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# Creep and Shrinkage of High Performance Concrete, and Prediction of Long-Term Camber of Prestressed Bridge Girders

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**Creep and shrinkage of high performance concrete and prediction of the long-term camber  
of prestressed bridge girders**

by

**Wenjun He**

A thesis submitted to the graduate faculty  
in partial fulfillment of the requirements for the degree of  
**MASTER OF SCIENCE**

Major: Civil Engineering (Structural Engineering)

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## ABSTRACT

The long-term camber of prestressed bridge girders is typically over-estimated by current Iowa Department of Transportation (IA DOT) methods at erection (typically 3 month after production of girders), especially for long-span bulb tee girders. This often leads to increased costs due to the haunch modifications in the field, and unnecessary delay of construction. Creep and shrinkage of concrete play an important role in the long-term camber of a prestressed bridge girder. The current models used to predict the creep and shrinkage yield large disparities with the actual behavior of concrete in prestressed girders cast using local materials in Iowa. In order to improve the accuracy of prediction of the camber of prestressed bridge girders, creep and shrinkage tests of concrete using local materials were performed. Seven mixes from three precast plants were investigated in this study, in which four of them were high performance concrete (HPC) that are currently used to cast prestressed bridge girders, and three of them were normal concrete (NC) that were utilized to produce prestressed bridge girders previously. Mineral admixtures including slag and fly ash are typically added into HPC. Half of the creep and shrinkage specimens were sealed with Sikagard 62 to minimize the evaporation of water, and the rest were unsealed. All creep and shrinkage specimens with 4 in. diameter and 8 in. height were monitored in an environmentally controlled chamber for one year. In addition, twenty-six prestressed bridge girders produced using HPC from three precast plants were monitored and the corresponding long-term camber was measured.

It was observed that due to the early age of loading and the use of slag and fly ash HPC had higher average creep coefficient and average shrinkage strain than NC for both sealed and unsealed specimens during 1 year. It was also found that sealed specimens represent the creep and shrinkage behavior of a full scale prestressed bridge girder much better than unsealed specimens, in agreement with some of the previous literature. It was also observed that the sealed creep coefficient and sealed shrinkage strain measured from the four HPC mixes were similar, and it was acceptable to use the average sealed creep coefficient and average sealed shrinkage strain of the four HPC mixes tested to predict long-term camber of prestressed bridge girders produced in Iowa.

Three simplified methods were applied to predict long-term camber of the prestressed bridge girders, including Tadros's Method (2011), Naaman's Method (2004) and an incremental method. Naamans' Method and the incremental method yielded similar results, and both methods yielded  $\pm 25\%$  errors relative to measured camber of 26 prestressed bridge girders, but Tadros's Method yielded up to  $\pm 50\%$  errors. The calculation of Naaman's Method was simpler than for the incremental method. Therefore, Naaman's Method was the recommended method to predict the long-term camber of prestressed bridge girders produced in Iowa.

## CHAPTER 1 INTRODUCTION

### 1.1 Background

The issue of inaccuracy of camber prediction at erection of prestressed bridge girders is found not only by Iowa Department of Transportation (IA DOT), but by other DOTs, including Washington DOT (2007), North Carolina DOT (2011) and Minnesota DOT (2012). For the camber prediction at erection of prestressed bridge girders, the current tolerance by IA DOT is  $\pm 30\%$ , and typically the actual situation is beyond this limit. It is found that the long-term camber of prestressed bridge girder at erection by using the current simple multipliers method by the IA DOT is typically over-estimated, especially for long span bulb tee girders that are frequently used in Iowa. The over-estimation of long-term camber at erection of girders typically results in field modifications of concrete haunches, leading to the increase of cost and increase of self-weight of the superstructure of the bridge. This over-estimation is possibly caused by different factors, including material properties and the current prediction method itself. IA DOT changed the concrete of prestressed bridge girders from normal concrete (NC) to high performance concrete (HPC) after 2006. In HPC slag and fly ash are utilized to replace a certain percent of Portland cement, which results in different material properties and further different camber behavior with NC. For the material properties of concrete, creep and shrinkage, modulus of elasticity and compressive strength for HPC and NC should be investigated and compared with the corresponding current models. For the current method of camber prediction at erection, only simple multipliers are used, and the accuracy of this method should be evaluated. Uncertainty of the duration between production and erection of girders leads to additional errors in camber prediction. After the clarification of causes of errors of camber prediction, a new simplified method should be proposed to predict long-term camber at erection with satisfactory accuracy.

## **1.2 Research Scopes**

The goal of this study is to improve the accuracy of long-term camber prediction of prestressed bridge girders. In order to realize this goal, material properties of concrete using local materials are investigated, and underlying reasons of inaccuracy of long-term camber prediction of IA DOT's current method are also quantified. A simplified method of long-term camber prediction is then proposed.

## **1.3 Research Objectives**

The objectives of this study are shown below:

- Monitor creep, shrinkage and development of elastic modulus and strength for 7 mixes, including 4 high performance concrete (HPC) mixes that are currently used to cast prestressed bridge girders, and 3 normal concrete (NC) mixes that were used to produce prestressed bridge girders previously.
- Identify practices and conditions that affect camber development in prestressed bridge girders
- Correlate the creep and shrinkage behavior between concrete specimens and a full size of prestressed bridge girder.
- Measure the long-term camber of 26 prestressed bridge girders that are cast by using HPC from three precast plants.
- Evaluate the current camber prediction method.
- Propose a simplified method to predict the long-term camber of prestressed bridge girders by using measured data of creep and shrinkage of HPC

## **1.4 Assumptions**

Assumptions applicable for reinforced concrete structures are also applied in this study, and two additional assumptions are utilized in this study, including the following:

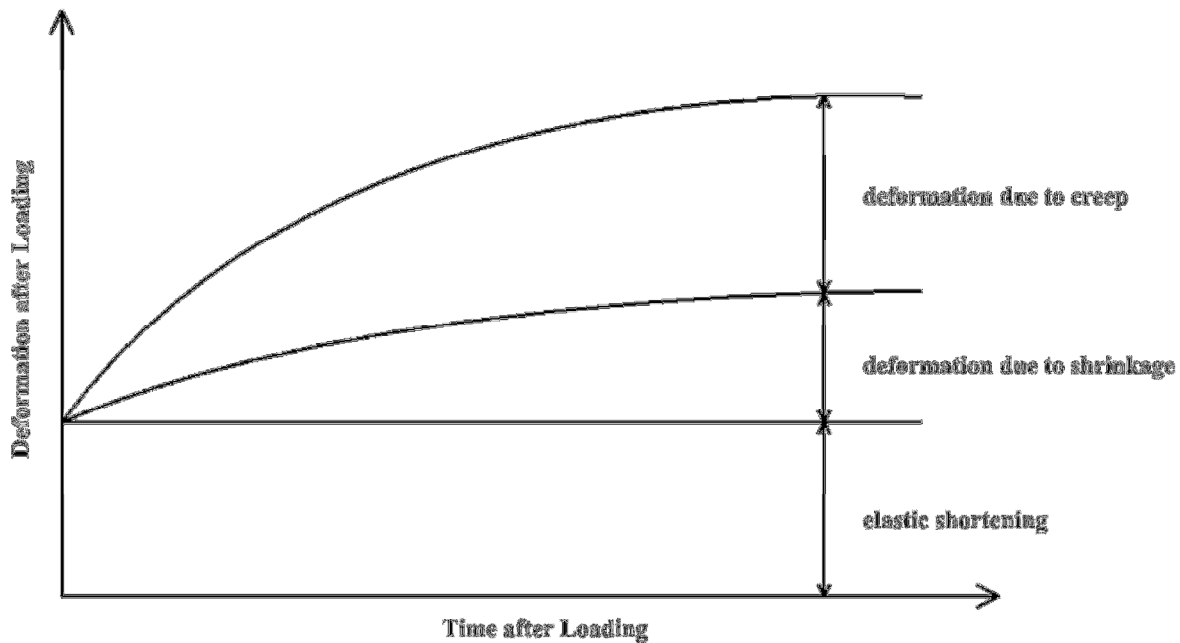
- In the creep and shrinkage test of concrete, elastic shortening, creep strain and shrinkage strain are additive;
- A prestressed bridge girder has the linear-elastic behavior of camber under the combined effect of prestressing forces and self-weight of the girder.

## CHAPTER 2 BACKGROUND INFORMATION

### 2.1 Creep of Concrete

#### 2.1.1 Introduction

Creep is the time-dependent increase of strain in the hardened concrete under sustained stress (ACI 209R, 1992). Creep is generally obtained by subtracting instantaneous strain after loading application and shrinkage strain in the non-loaded specimen, from the total measured strain with the change of time in a loaded specimen. Creep is classified into basic creep and drying creep. Basic creep occurs under conditions without moisture movement between the specimen and the environment. Drying creep is the additional creep due to the moisture movement between the specimen and the environment. Figure 2.1 shows the relation of deformation of concrete after loading application with time.



**Figure 2.1.** Relation of deformation after loading application versus time

### 2.1.2 Factors affecting creep of concrete

Creep in current study is on the creep behavior of concrete under compressive stress. Creep of concrete is influence by many factors, which are classified into intrinsic and extrinsic. Intrinsic factors consist of proportions and properties of materials in concrete. Extrinsic factors consist of size of concrete member, age of loading application, applied stress-strength ratio, curing conditions, ambient temperature and relative humidity surrounding concrete under load.

#### 2.1.2.1 Aggregate

Aggregates play an important role in creep of concrete. Aggregates provide restraining effect on the creep (Neville A. M., 1970). Generally higher aggregate content results in lower creep. Neville (1970) proposed equations to indicate the relation between aggregate content and creep shown below:

$$\log \frac{c_p}{c} = \alpha \log \frac{1}{1-g} \quad (\text{Eq 2-1})$$

$$\alpha = \frac{3(1-\mu)}{1 + \mu + 2(1-2\mu_a)E/E_a} \quad (\text{Eq 2-2})$$

where:

$c_p$  = creep of neat cement paste

$c$  = creep of concrete

$g$  = aggregate content

$\mu$  = Poisson's ratio of concrete

$\mu_a$  = Poisson's ratio of aggregate

$E$  = modulus of elasticity of concrete

$E_a$  = modulus of elasticity of aggregate

According to the study by Neville (1970), for concrete specimens loaded at 14 days with a stress-strength ratio of 0.5 stored in 90% relative humidity condition, a linear relationship was obtained between  $\log \frac{c_p}{c}$  and  $\log \frac{1}{1-g}$  after 28 days of loading for basic creep. The magnitude of  $\alpha$

was based on the age of initial loading and the change of modulus of elasticity of concrete with time after loading application. Similar observations were made by Polivka (1964) for both basic creep and drying creep of concrete.

Aggregate properties have a great influence on creep, including modulus of elasticity, porosity, roughness of surface, shape and size. Neville (1970) cited a study by Morlier, who investigated the creep of aggregates, and divided aggregates into three types, including elasto-brittle, visco-elastic and visco-plastic. Elasto-brittle aggregates consisted of magmatic, non-altered gneiss, hard limestone and quartzite, and this type of aggregates was typically used in concretes, and generally had small creep within 10% of elastic shortening deformation. Visco-elastic aggregates, such as calcareous minerals, shale, marl, porous limestone and granular gypsum, crept in a range of 12% to 40% of elastic shortening deformation. The first two types of aggregates had certain recoverable creep after the removal of the load. However, for visco-plastic aggregates such as chalk no reversible creep was observed.

Concretes made with different types of aggregates generally have different creep behavior. In the study by Davis (1931), six types of aggregates were used in concrete, including limestone, quartz, granite, gravel, basalt and sandstone. Concrete specimens were made with the same aggregate-cement ratio, water-cement ratio, the same applied stress and stored in the same condition. It was indicated that limestone concrete had the lowest creep, and sandstone concrete had the highest creep. Sandstone concrete crept as much as 2.5 times greater than limestone concrete. Kordina (1960) investigated the effect of eight types of aggregates on creep, and it was observed that concretes with different aggregates had different creep behavior, which confirmed the results from Davis. According to the study by Alexander (1996), the influence of 23 different aggregates on the properties of concrete was investigated, and they were divided into two series, including series 1 with 13 types of aggregates and series 2 with 10 types of aggregates. Series 1 and series 2 concretes, stored in water before loading and stored in air (23°C temperature and 60% relative humidity) after loading, were loaded approximately at the age of 600 days and 334 days respectively, because the change of mature concretes due to hydration of cement paste became mineral. It was found that creep coefficient of series 1 concretes varied from 1.29 to 2.97 after 11 months of loading, and that of series 2 concretes was in a range of 0.78 to 1.85 after 140 days of loading.



An explanation of aggregate type on creep of concrete provided by Neville (1970) was the modulus of elasticity of aggregate, and the higher modulus of elasticity of aggregate generally resulted in the higher restraining effect on cement paste, which caused lower creep. The study by Kordina (1960) and Alexander (1996) confirmed this explanation.

Porosity of aggregate has an influence on creep of concrete through elastic moduli of aggregate. In the study by Kordina (1960), the relation between absorption of eight types of aggregate and modulus of elasticity of aggregate was investigated. It was found that the higher absorption caused lower modulus of elasticity, which meant that higher porosity of aggregates resulted in lower elastic modulus of aggregate and higher creep of concrete.

The roughness of surface of aggregates also affects creep of concrete. The rougher the surface of aggregates, the better interface between aggregate and cement paste, and further the higher restraining effect of aggregate on cement paste, which results in lower creep.

Size of aggregate also has an effect on creep of concrete through aggregate content. Generally larger size of aggregates results in higher aggregate content and further causes lower creep. In the study by U.S. Army Engineers Laboratories (1958), sealed specimens were prepared by using two aggregate sizes including 1.5 inches and 6 inches. It was observed that concrete with 6 in. aggregate had 20% to 25% lower creep than concrete with 1.5 in. aggregate.

#### 2.1.2.2 Cement

Cement paste is the base of creep phenomenon (Neville A. M., 1970), so cement has a great influence on creep of concrete. According to Neville (1970), it was observed that creep was inversely proportional to the rate of hardening of cement. It was logical that the higher rate of hardening of cement, the more hydrated cement and the more restraining effect on creep. Typically the concrete with rapid-hardening Portland (Type III) cement results in lower creep than the concrete with standard Portland (Type I) cement for both dry-stored and wet-stored conditions (Glanville W. H., 1939), which was due to the higher strength of Type III Portland cement concrete at the age of loading comparing with Type I cement concrete. For high-alumina cement, it was treated by Neville (1970) as a special case than other types of cement. According to the observations by Hummel (1959), rate of creep of concretes with type I and type III cement decreased with time almost down zero after 3 years. However, the creep of concrete made by

high alumina cement had the largely different behavior with the rest of two types of cement concretes. After 1 year of loading application, the rate of creep of high alumina cement concrete increased sharply. It was also found by Hummel that the strength of high-alumina cement concrete decreased considerably with time, and for instance, concrete specimens at 3 years only had 60% strength comparing with that at 90 days. This behavior was confirmed and explained by Neville (1958) (1963). The micro-structure of hydrated high-alumina cement pastes changed with time from hexagonal to cubic form, which resulted in an increase of porosity of the hydrated pastes. A considerable decrease of strength occurred, which resulted in considerable increase of creep.

#### 2.1.2.3 Water to cementitious ratio

Typically creep increases with an increase of water to cementitious (w/c) ratio (Neville A. M., 1970). Lorman (1940) suggested that creep was approximately proportional to the square of the w/c ratio. This phenomenon was confirmed by Wagner and Hummel, whose results were cited by Neville (1970). From the study by Wagner, the effect of w/c ratio on creep was investigated, and specimens were prepared with constant cement paste content 20 percent by weight with w/c ratio ranging from 0.35 to 0.9. It was found that the higher w/c ratio, the higher ultimate specific creep. In another study by Hummel, all concretes had an aggregate-cement ratio of 5.4, and similar trend was found, and the ultimate specific creep with w/c ratio of 0.4 was approximately 10% higher than that with w/c ratio of 0.3.

#### 2.1.2.4 Chemical admixtures

Chemical admixtures such as plasticizers and superplasticizers are commonly used in high performance concrete (HPC). The effect of chemical admixtures highly depends on chemical compositions and dosages. According to the study by Brooks (1989), admixtures added in HPC typically increased creep and drying shrinkage of concrete. In this study two types of plasticizers and three types of superplasticizers were investigated. It was indicated that generally plasticizers and superplasticizers increased creep of concrete comparing with concrete without any admixture. The mean increase of concrete creep due to admixtures was about 20%. In another study by Ngataki (1978), decrease of creep of concrete was observed by using superplasticizers.

#### 2.1.2.5 Mineral admixtures

Mineral admixtures, including ground granulated blast furnace slag (GGBFS), fly ash and silica fume, are widely used as partial replacement of Portland cement in HPC. GGBFS is a glassy material with cementitious property formed when molten blast-furnace slag is rapidly cooled, such as by immersion in water, and slag mainly consists of silicates and aluminosilicates of calcium (ACI 233R, 2003). Fly ash is a by-product of coal combustion with both pozzolanic and cementitious properties (ACI 232.2R, 1996). Fly ash primarily consists of silicon dioxide, aluminum oxide and iron oxide. Silica fume is a by-product of the ferrosilicon industry consisting of very fine particles ( $4 \text{ to } 8 \times 10^{-6} \text{ in}$ ) with high pozzolanic property (ACI 234R, 2006), and silica fume consists primarily of non-crystalline silicon dioxide.

Neville (1975) investigated the effect of slag on properties of concrete. Concrete specimens, with three levels of replacement of Portland cement with slag including 0%, 30% and 50%, were loaded with the same stress after 28 days moist curing. It was indicated that slag decreased basic creep, and the higher level of slag replacement, the lower basic creep. It was also observed that slag resulted in slightly higher total creep under drying condition comparing with concrete without slag. Those behaviors of slag concrete were confirmed by Chern (1989). The effect of slag on creep highly depends on the age and strength of concrete at loading (Swamy, 1986). If slag concrete was loaded with the same stress at early ages such as 1-3 days, higher creep was observed under both dry and wet conditions. Reasonable explanation was that slag concrete developed strength more slowly comparing with concrete without slag, which resulted in higher stress-strength ratio at early age of loading and higher creep.

Fly ash is another type of mineral admixture commonly used in HPC. Fly ash is classified into Class F and Class C. Class F fly ash has pozzolanic properties but little or no cementitious properties, and Class C fly ash has pozzolanic properties and some autogenous cementitious properties. According to the studies by Ghosh (1981) and Lane (1982), when concrete with Class F fly ash and concrete without fly ash had similar strength at loading and similar applied stress, lower creep was observed for fly ash concrete due to higher rate of strength gain after loading application. Yuan and Cook (1983) investigated the effect of Class C fly ash on creep of concrete. There were four levels of replacement of Portland cement with fly ash, including 0%, 20%, 30% and 50%. It was indicated that 20% fly ash concrete had the

lowest creep during the first eight months of loading, and had comparable creep with 0% fly ash concrete after that until one year of loading. For 20%, 30% and 50% fly ash concrete, creep increased with an increase in the level of replacement.

In HPC silica fume is also used to partially replace Portland cement. Silica fume within certain percent decreases creep of concrete. In the study by Khatri and Sirivivatnanon (1995), significant decrease in creep was observed in the concrete with 10% silica fume comparing with concrete without silica fume. This behavior was due to the great increase of strength of the concrete with 10% silica fume at early days. According to the studies by Saucier (1984) and Buil (1985), it was indicated that concrete with both 15% and 33% silica fume had comparable creep with concrete without silica fume.

#### 2.1.2.6 Stress-strength ratio at loading

According to a wide range of investigations (Neville A. M., 1970), creep is proportional to the applied stress and inversely proportional to the strength at the time of application of load. Although some other researches indicated higher upper limit of stress-strength ratio to 0.75 or 0.80, generally the upper limit was approximately 0.60. In the study by Jones and Richart (1936), the measured creep of concrete specimens was proportional with stress-strength ratio up to 0.6, and beyond this limit creep increased more quickly than the increase of applied stress. Similar behavior of concrete was observed by Gvozdev (1966) for concrete specimens with different stress-strength ratio and different initial application of load. According to the study by L'Hermite and Mamilla (1968), the linear relation was obtained for concrete stored in water initially loaded at 7 days, 35 days, 70 days, 1 year and 5.5 years. In the study by Haranki (2009), linear limit was 0.5 for HPC after the loading of 91 days. The linear limit for creep in compression is 40% of concrete compressive strength in ASTM C512 (2002).

#### 2.1.2.7 Age at loading

The same concrete loaded at different ages undergoes a different growth in strength, so for the constant applied stress, creep depends on the age at loading. The strength of the younger concrete is lower, and the creep is higher, and the older concrete has the opposite characteristics. From the study by Yashin (1959), it was found that when the strength gain of concrete was smaller the creep was higher. Another study by Poivka (1964) confirmed this behavior, and for the same concrete, 18% higher creep was obtained for the concrete loaded at 1 day than 3 days

after the loading of 28 days. Loading age effect on creep of concrete also observed by Bryant (1987) for both unsealed and sealed specimens, and the earlier loading the higher creep. In the study by Khan (1997), the effect of age of loading on creep for normal concrete, medium concrete and high-strength concrete was investigated. It was found that the creep of high-strength concrete was more sensitive to the early age of loading than that of normal and medium concrete.

The extent of loading age of concrete also depends on the storage condition of concrete. In the study by Davis (1934), sustained stress was applied on all specimens during 80 days, and it was found that water-stored concrete specimens loaded at 7 days, 28 days and 3 months had the ratio of creep deformations at 3:2:1, but for dry-stored concrete specimens the effect of the age of loading was considerably smaller, and the creep of concrete loaded at 28 days was only 10% to 20% higher than that of concrete loaded at 3 months. Possible reason was that after 28 days of drying, the strength gain of concrete was very small. Davis also found that the earlier loaded concrete had higher rate of creep than later loaded concrete. Glanville (1933) found the similar behavior, and also that the rate of creep after one month was independent of the age at loading.

#### 2.1.2.8 Size effect

It is important for the shape and size of specimens to make a transition from the results obtained in laboratory to actual full-size concrete members under drying condition. Neville (1970) summarized several investigations and found that the measured creep decreased with an increase in the size of the concrete specimens, but when the specimen thickness was greater than 3 ft. (90 cm) the size effect became negligible. Generally the influence of size on creep under drying condition is great during the initial period (first several weeks) after the application of load, but after that the rate of creep is comparable for all specimens with different sizes. In the study by Weil cited by Neville (1970), size effect of specimens with different diameters ranging from 3.9 in. (10 cm) to 23.6 in. (60 cm) on creep of concrete under drying condition was investigated. It was found that during the first two months after initial load application larger size of specimens resulted in lower creep and lower rate of creep, but after two months all specimens had similar rate of creep up to three years. L'Hermite (1968) observed the similar behavior. In this study specimens with 7 and 20 cm thickness were loaded at the age of 7 days, it was found that after three months all specimens had similar rate of creep up to three years. Size

effect on creep of concrete under drying condition was also observed by Bryant (1987), and it was found that increase of effective thickness of concrete member resulted in decrease of creep of concrete.

The loss of water from specimens to the ambient environment is an explanation of the effect of size on creep, which is correct for unsealed specimens, but not applicable for sealed specimens without moisture movement. According to study by Hansen and Mattock (1966), size effect was absent for sealed specimens, which indicated that basic creep was independent of size and shape. ACI Committee 209R (2008) confirmed this conclusion.

#### 2.1.2.9 Curing conditions

Curing condition has a great effect on creep of concrete. Low-pressure steam curing is frequently used for the construction of prestressed concrete with the consideration of efficiency and economy. Generally low-pressure steam curing results in lower creep of concrete than moist curing, which is due to the accelerated hydration of cement causing higher strength of concrete at the age of loading (Neville A. M., 1970). According to the study by ACI Committee 517 (1963), the effect of two curing conditions was investigated, including steam curing at 150 °F (66 °F) for 13 hours and moist curing at 75°F (24 °F) for 5 or 6 days. It was observed that steam-cured concrete had lower specific creep by 30 to 50% comparing with moist-cured concrete loaded at the same stress-strength level. This behavior was confirmed by Hanson (1964), from which it was additionally indicated that type III Portland cement resulted in lower creep of concrete at the same steam curing condition comparing with type I Portland cement. According to the study by Townsend (2003), the effect of 1-day steam curing and 7-day moist curing on creep and shrinkage of HPC stored in an environmental-controlled chamber with 50% relative humidity was investigated. HPC contained 40% replacement of Portland cement with slag with 0.3 w/c ratio. It was found that steam-cured concrete had 5% lower creep strain at the storage of 1 week than moist-cured concrete but had 19% higher creep strain at the storage of 14 weeks. It was indicated that steam curing decreased initial creep strain of HPC, but increased it afterwards. It was additionally found that steam-cured concrete had similar creep coefficient with moist-cured concrete during 1 week, but higher creep coefficient afterwards, up to about 30% higher after the storage of 14 weeks.

#### 2.1.2.10 Relative humidity

Relative humidity is an important extrinsic factor affecting creep of concrete. Typically higher relative humidity during loading application results in lower creep due to the decrease of drying effect of concrete (Neville A. M., 1970). In the study by Troxell (1958), 4 by 14 in. cylindrical specimens were prepared and after 28-day moist-curing loaded at relative humidity of 50%, 70% and 100%. It was observed that the creep of concrete specimens at 50% relative humidity was 2 to 3 times higher than that of concretes at a relative humidity of 100% after 25 years. Concrete at 70% relative humidity had the moderate creep. Concrete at 50% relative humidity had the highest rate of creep during the first 2 years, and the rate of creep decreased with an increase in relative humidity. However, after 2 years, concretes with three levels of relative humidity had comparable rate of creep. L'Hermite (1968) found the similar behavior of concrete specimens at the relative humidity of 50%, 75% and 100%. The effect of change of relative humidity on creep decreased with an increase in the size of concrete specimens, which was recognized by Troxell (1958) and confirmed by Keeton (1960).

The actual structures usually are under alternating humidity, which has an influence on creep of concrete. In the study by L'Hermite (1968), the difference of deformations of concrete specimens between laboratory and open air was observed. 8 by 8 by 24 in. concrete specimens were prepared and constant stress was applied. Half specimens were placed in the laboratory with constant 50% relative humidity, and the rest were located in the open air with humidity ranging from 60% to 90%. During 600 days of loading it was indicated that specimens in the laboratory had lower total deformation under load but higher deformation without load than specimens in the open air. If the additive theory was used to calculate creep by subtracting the unloaded deformation from total deformation, it was found that the creep of specimens in the laboratory was lower than those specimens stored in the open air. In another study by Muller and Pristl (1993) slightly lower total strain was observed for concretes stored at 65% relative humidity condition comparing with concretes stored at relative humidity ranging from 40 to 90%. Glucklich (1968) gave a possible explanation of the increase in creep due to the sudden wetting and drying. Sudden wetting induced the crack on the surface of solid with the absorption of water, and the crack resulted in reduced surface tension of the solid. This reduction led to the re-propagation of stable cracks, which further increased creep. Sudden drying induced not only the

cracks due to the moisture gradient but also the reduction of the effective cross-section of concrete, which resulted in higher creep.

#### 2.1.2.11 Temperature under load

Temperature under load is another extrinsic factor affecting creep. Generally the higher temperature results in higher creep during the certain temperature range (Neville A. M., 1970). This behavior was confirmed by Hannant (1967). In this study it was observed that the specific creep of sealed specimens had the linear relationship with temperature ranging from 81 to 176°F (27 to 80°C) with duration of loading of 733 days. Nasser and Neville (1965) took another study to investigate the influence of temperature on creep of concrete. All specimens were submerged into the water all the time, and they were loaded at the age of 14 days. After 15 months under load linear behavior was observed between creep and temperature at the stress-strength ratio 0.35 for the temperature in the range of 115 to 205°F (46 to 96°C). According to the study by Brooks (1991), the effect of change of temperature within a certain range on basic creep of normal concrete and slag concrete was insignificant. Concrete specimens with three levels of replacement of Portland cement with slag were prepared, including 0%, 50% and 70%. After the comparison of specimens stored at constant temperature (40°C) and increasing and decreasing temperature within a certain range (40-65°C for normal concrete, 40-61°C for 50% slag concrete and 40-53°C for 70% slag concrete), it was found that the effect of change of temperature on basic creep of concrete in compression was negligible.

### **2.1.3 Prediction of creep of concrete**

For the prediction of creep of concrete without actual measurements of local material mixtures, the following five models are commonly used, including AASHTO LRFD 2010, ACI 209R-90, ACI 209R Modified by Huo, CEB-FIP 90 and Bazant B3. CEB-FIP 90 also provides the relation between temperature and maturity of concrete. Therefore, if concrete is steam-cured, the maturity of concrete after steam-curing could be calculated, and the adjusted age of concrete could be used in creep and shrinkage models.



### 2.1.3.1 AASHTO LRFD (2010)

Equations provided by AASHTO LRFD 2010 Specification are applicable for concrete strength up to 15.0 ksi. The expression for the creep coefficient is given as:

$$\Phi(t, t_i) = 1.9 \cdot k_{vs} \cdot k_{hc} \cdot k_f \cdot k_{td} \cdot t_i^{-0.118} \quad (\text{Eq 2-3})$$

in which:

$t$  = maturity of concrete (day), defined as the age of concrete between time of loading for creep calculations, or end of curing for shrinkage calculations, and time being considered for analysis of creep or shrinkage effect

$t_i$  = age of concrete when load is initially applied (day)

$k_{vs}$  = factor for the effect of the volume-to-surface ratio of the component

$$k_{vs} = 1.45 - 0.13(V/S) \geq 1.0 \quad (\text{Eq 2-4})$$

or for the detailed equation is

$$k_{vs} = \left[ \frac{\frac{t}{26e^{0.0142(V/S)+t}}}{\frac{t}{45+t}} \right] \left[ \frac{1.80 + 1.77e^{-0.0213(V/S)}}{2.587} \right] \quad (\text{Eq 2-5})$$

$V/S$  is volume to surface ratio, and maximum is 6 in.

$k_{hc}$  = humidity factor for creep

$$k_{hc} = 1.56 - 0.008H \quad (\text{Eq 2-6})$$

$H$  is relative humidity of ambient condition in percent

$k_f$  = factor for the effect of concrete strength

$$k_f = \frac{35}{7 + f'_{ci}} \quad (\text{Eq 2-7})$$

$f'_{ci}$  = specified compressive strength of concrete at time of prestressing for

pretensioned members and at time of initial loading for nonprestressed member

$k_{td}$  = time development factor

$$k_{td} = \frac{t}{61 - 0.58f'_{ci} + t} \quad (\text{Eq 2-8})$$

### 2.1.3.2 ACI 209R (1992)

The expression for creep coefficient at the standard condition is given as:

$$\nu_t = \frac{t^{0.60}}{10 + t^{0.60}} \nu_u \quad (\text{Eq 2-9})$$

This equation is applicable for both 1-3 days steam cured concrete and 7-dat moist-cured concrete.

Where:

$t$  = days after loading

$\nu_t$  = creep coefficient after  $t$  days of loading

$\nu_u$  = ultimate creep coefficient, and the average value suggested  $\nu_u = 2.35 \gamma_c$

$\gamma_c$  = correction factors for conditions other than the standard concrete composition, which is defined as:

$$\gamma_c = \gamma_{la} \cdot \gamma_{\lambda} \cdot \gamma_{vs} \cdot \gamma_s \cdot \gamma_p \cdot \gamma_a \quad (\text{Eq 2-10})$$

in which:

$\gamma_{la}$  = correction factor for loading age, which is defined as

$$\gamma_{la} = 1.25t^{-0.118} \text{ for loading ages later than 7 days for moist cured concrete} \quad (\text{Eq 2-11})$$

$$\gamma_{la} = 1.13t^{-0.094} \text{ for loading ages later than 1-3 days for steam cured concrete} \quad (\text{Eq 2-12})$$

$\gamma_{\lambda}$  = correction factor for ambient relative humidity, which is defined as

$$\gamma_{\lambda} = 1.27 - 0.0067\lambda, \text{ for } \lambda > 40, \text{ where } \lambda \text{ is relative humidity in percent} \quad (\text{Eq 2-13})$$

$\gamma_{vs}$  = correction factor for average thickness of member or volume-to-surface ratio. When average thickness of member is other than 6 in. (150 mm) or volume-to-surface ratio is other than 1.5 in. (38 mm), two methods are offered

(a) Average thickness method

For average thickness of member less than 6 in. (150 mm), the factors are given in Table 2.5.5.1 in ACI 209R-92. For average thickness of members greater than 6 in. (150 mm) and up to about 12 to 15 in (300 to 380 mm), equations are given:

$$\gamma_{vs} = 1.14 - 0.023h \quad \text{during the first year after loading} \quad (\text{Eq 2-14})$$

$$\gamma_{vs} = 1.10 - 0.017h \quad \text{for ultimate values} \quad (\text{Eq 2-15})$$

Where  $h$  is the average thickness of the member in inches

(b) Volume-surface ratio method

For members with volume-to-surface area other than 1.5 in. (38 mm), the equations are given:

$$\gamma_{vs} = \frac{2}{3} [1 + 1.13e^{-0.54(\frac{v}{s})}] \quad \text{where } v/s \text{ is the volume-surface ratio in inches} \quad (\text{Eq 2-16})$$

$\gamma_s$  = correction factor for slump, and equations are given as:

$$\gamma_s = 0.82 + 0.067s \quad \text{where } s \text{ is the observed slump in inches} \quad (\text{Eq 2-17})$$

$\gamma_p$  = correction factor for fine aggregate percentage, which is defined as:

$$\gamma_p = 0.88 + 0.0024p \quad (\text{Eq 2-18})$$

where  $p$  is the ratio of the fine aggregate to total aggregate by weight expressed as percentage

$\gamma_a$  = correction factor for air content, which is defined as

$$\gamma_a = 0.46 + 0.09a \geq 1.0 \quad \text{where } a \text{ is the air content in percent} \quad (\text{Eq 2-19})$$

### 2.1.3.3 ACI-Modified by Huo (2001)

This model is the same as ACI 209-90, and additional modification factors for compressive strength are taken into account:

$$\nu_t = \frac{t^{0.60}}{K_C + t^{0.60}} \nu_u \quad (K_C = 12 - 0.50f'_c) \quad (\text{Eq 2-20})$$

$\gamma_{st,c}$  = correction factor for compressive strength of concrete

$$\gamma_{st,c} = 1.18 - 0.045f'_c \quad (\text{Eq 2-21})$$

$f'_c$  = 28-day compressive strength in ksi

#### 2.1.3.4 CEB-FIP (1990)

The expression for creep coefficient is given:

$$\varphi(t, t_0) = \varphi_0 \cdot \beta_c(t - t_0) \quad (\text{Eq 2-22})$$

where

$t$  = age of concrete (days) at the moment considered

$t_0$  = age of concrete at loading (days)

$\varphi_0$  = notional creep coefficient

$\beta_c$  = coefficient to describe the development of creep with time after loading

The expression for notional creep coefficient is given:

$$\varphi_0 = \varphi_{RH} \cdot \beta(f_{cm}) \cdot \beta(t_0) \quad (\text{Eq 2-23})$$

where

$\varphi_{RH}$  = coefficient for relative humidity and the dimension of member, and the expression is given:

$$\varphi_{RH} = 1 + \frac{1 - RH/RH_0}{0.46 \cdot (h/h_0)^{1/3}} \quad (\text{Eq 2-24})$$

where:

$RH$  = relative humidity of the ambient environment in percent (%)

$RH_0 = 100\%$

$h$  = notational size of member (mm), and the expression is  $h = 2A_c/u$ , where  $A_c$  is the area of

cross section, and  $u$  is the perimeter of the member in constant with the atmosphere

$h_0 = 100 \text{ mm}$

$$\beta(f_{cm}) = \frac{5.3}{(f_{cm}/f_{cmo})^{0.5}} \quad (\text{Eq 2-25})$$

where

$f_{cm}$  = the mean compressive strength of concrete at the age of 28 days (MPa)

$f_{cmo} = 10$  MPa

$$\beta(t_0) = \frac{1}{0.1 + (t_0/t_1)^{0.2}} \quad (\text{Eq 2-26})$$

where  $t_1 = 1$  day

The expression for the development of creep with time is given:

$$\beta_c(t - t_0) = \left[ \frac{(t - t_0)/t_1}{\beta_H + (t - t_0)/t_1} \right]^{0.3} \quad (\text{Eq 2-27})$$

with

$$\beta_H = 150 \cdot \left\{ 1 + 1.2 \left( \frac{RH}{RH_0} \right)^{18} \right\} \cdot \frac{h}{h_0} + 250 \leq 1500 \quad (\text{Eq 2-28})$$

where:  $t_1 = 1$  day,  $RH_0 = 100\%$ , and  $h_0 = 100$  mm

If concrete undergoes elevated or reduced temperature, the maturity of concrete could be calculated by using the following equation:

$$t_T = \sum_{i=1}^n \Delta t_i \exp \left[ 13.65 - \frac{4000}{273 + T(\Delta t_i)/T_0} \right] \quad (\text{Eq 2-29})$$

where:

$t_T$  is the maturity of concrete which can be used in creep and shrinkage models

$\Delta t_i$  = number of days where a temperature  $T$  prevails

$T(\Delta t_i)$  = temperature ( $^{\circ}\text{C}$ ) during the time of period  $\Delta t_i$

$T_0 = 1^{\circ}\text{C}$

### 2.1.3.5 Bazant B3 (2000)

The compliance function for loaded specimens is expressed as:

$$J(t, t') = q_1 + C_0(t, t') + C_d(t, t', t_0) \quad (\text{Eq 2-30})$$

where

$q_1$  = instantaneous strain due to unit stress

$$q_1 = 10^6/E_{ci} \text{ or } (0.6 \times 10^6)/E_{c28} \quad (\text{Eq 2-31})$$

$$E_{ci} = 57000\sqrt{f'_{ci}} \quad (f'_{ci} \text{ is compressive strength at the age of loading, psi}) \quad (\text{Eq 2-32})$$

$$E_{c28} = 57000\sqrt{f'_{c28}} \quad (f'_{c28} \text{ is 28-day compressive strength, psi}) \quad (\text{Eq 2-33})$$

$C_0(t, t')$  = compliance function for basic creep (in/in/psi)

$$C_0(t, t') = q_2 Q(t, t') + q_3 \ln[1 + (t - t')^n] + q_4 \ln(t/t') \quad (\text{Eq 2-34})$$

$t$  = age of concrete after casting (days)

$t'$  = age of concrete at loading (days)

$t_0$  = age of concrete at the beginning of shrinkage (days)

$$q_2 = 451.4c^{0.5}(f'_{c28})^{-0.9} \quad (c \text{ is cement content in pcf}) \quad (\text{Eq 2-35})$$

$$Q(t, t') = Q_f(t') \left[ 1 + \left( \frac{Q_f(t')}{Z(t, t')} \right)^{\gamma(t')} \right]^{1/\gamma(t')} \quad (\text{Eq 2-36})$$

$$Q_f(t') = [0.086(t')^{2/9} + 1.21(t')^{4/9}]^{-1} \quad (\text{Eq 2-37})$$

$$Z(t, t') = (t')^{-m} \ln(1 + (t - t')^n) \quad (m=0.5, n=0.1) \quad (\text{Eq 2-38})$$

$$\gamma(t') = 1.7(t')^{0.12} + 8 \quad (\text{Eq 2-39})$$

$C_d(t, t', t_0)$  = additional compliance function due to simultaneous drying (in/in/psi)

$$C_d(t, t', t_0) = q_5 [\exp\{-8H(t)\} - \exp\{-8H(t')\}]^{1/2} \quad (\text{Eq 2-40})$$

$$q_5 = 7.57 \times 10^5 (f'_{c28})^{-1} \text{ABS}(\varepsilon_{sh\infty})^{-0.6} \quad (\text{Eq 2-41})$$

$$\varepsilon_{sh\infty} = \alpha_I \alpha_2 [26\omega^{2.1} (f'_{c28})^{-0.28} + 270] \quad (\omega \text{ is water content in pcf}) \quad (\text{Eq 2-42})$$

$$\alpha_I = \begin{cases} 1.0 & \text{for type I cement} \\ 0.85 & \text{for type II cement} \\ 1.1 & \text{for type III cement} \end{cases}$$

and

$$\alpha_2 = \begin{cases} 0.75 & \text{for steam – curing} \\ 1.2 & \text{for sealed or normal curing in air with initial protection against drying} \\ 1.0 & \text{for curing in water or at 100% relative humidity} \end{cases}$$

$$H(t) = 1 - (1 - h)S(t) \quad (h \text{ is relative humidity}) \quad (\text{Eq 2-43})$$

$$S(t) = \tanh[(t - t_0)/\tau_{sh}]^{1/2} \quad (\text{Eq 2-44})$$

$$\tau_{sh} = K_t (K_s D)^2 \quad (\text{Eq 2-45})$$

$$D = 2v/s \quad (\text{Eq 2-46})$$

$$K_t = 190.8(t_0)^{-0.08} (f'_{c28})^{-0.25} \quad (\text{Eq 2-47})$$

$$K_s = 1.00 \text{ for infinite slab}$$

$$= 1.15 \text{ for infinite cylinder}$$

$$= 1.25 \text{ for infinite square prism}$$

$$= 1.30 \text{ for sphere}$$

$$= 1.55 \text{ for cube}$$

$$= 1.00 \text{ for undefined member}$$

$$H(t') = 1 - (1 - h)S(t') \quad (h \text{ is relative humidity}) \quad (\text{Eq 2-48})$$

$$S(t') = \tanh[(t' - t_0)/\tau_{sh}]^{1/2} \quad (\text{Eq 2-49})$$

Creep strain should be calculated as:

$$\varepsilon_{cr} = [C_0(t, t') + C_d(t, t', t_0)]\sigma \quad (\sigma \text{ is the applied stress, psi}) \quad (\text{Eq 2-50})$$

Creep coefficient should be expressed as:

$$\varphi(t, t') = \frac{\varepsilon_{cr}}{q_1 \sigma} \quad (\text{Eq 2-51})$$

Total strain may be expressed as:

$$\varepsilon_{total} = J(t, t') \sigma + \varepsilon_{sh} \quad (\text{Eq 2-52})$$

where  $\varepsilon_{sh}$  = shrinkage strain in section 2.2.3.5

#### 2.1.3.6 Comparison of five models

The considered parameters in each model and corresponding ranges are shown in Table 2.1.

**Table 2.1.** Comparison of Five Models for Prediction of Creep of Concrete

| Considered Parameters                        | AASHTO LRFD 2010 | ACI 209R-92  | ACI-Modified by Huo | CEB-FIP 90     | Bazant B3      |
|--|------------------|--------------|---------------------|----------------|----------------|
| $f_{cm28}$ , psi                             | up to 15,000     | -            | up to 12360         | 2900 to 13,000 | 2500 to 10,000 |
| Aggregate to cement ratio, $a/c$             | -                | -            | -                   | -              | 2.5 to 13.5    |
| Water to cementitious ratio, $w/c$           | -                | -            | -                   | -              | 0.35 to 0.85   |
| Cement content, pound per cubic yard         | -                | Considered   | Considered          | -              | 270 to 1215    |
| Relative humidity, %                         | 35 to 100        | 40 to 100    | 40 to 100           | 40 to 100      | 40 to 100      |
| Type of cement                               | I, II, III       | I or III     | I, II, III          | I, II, III     | I, II, III     |
| Age of steam curing before loading           | 1 to 3 days      | 1 to 3 days  | 1 to 3 days         | -              | -              |
| Age of moist curing before loading           | $\geq 1$ day     | $\geq 1$ day | $\geq 1$ day        | $\leq 14$ days | $\geq 1$ day   |
| Age of loading                               | $\geq 1$ day     | $\geq 1$ day | $\geq 1$ day        | $\geq 1$ day   | $\geq 1$ day   |
| Fine aggregate content in total aggregate, % | -                | Considered   | Considered          | -              | -              |
| Air content                                  | -                | Considered   | Considered          | -              | -              |
| Slump  | -                | Considered   | Considered          | -              | -              |
| Size effect                                  | Considered       | Considered   | Considered          | Considered     | Considered     |



## 2.2 Shrinkage of Concrete

### 2.2.1 Introduction

Shrinkage is the decrease in volume of hardened concrete with time. Shrinkage of hardened concrete is divided into drying shrinkage, autogenous shrinkage and carbonation shrinkage (ACI 209R, 1992). Drying shrinkage is caused by the moisture loss in the concrete. Autogenous shrinkage (or basic shrinkage or chemical shrinkage) is due to the hydration of cement. Autogenous shrinkage typically is negligible in concrete with a higher water to cement (w/c) ratio, but it becomes an issue for concrete with a lower w/c ratio such as high performance concrete (Nishiyama, 2009). Carbonation shrinkage results from the carbonation of cement hydration products in the presence of carbon dioxide. Bazant (2000) found that in good concrete carbonation occurs only in the surface layer with the thickness of several millimeters, so the carbonation shrinkage is negligible. This was confirmed by Persson (1998) and Malhotra (2000). For high performance concrete used for prestressed bridge girders, carbonation shrinkage is negligible comparing with drying shrinkage and autogenous shrinkage.

### 2.2.2 Factors affecting shrinkage of concrete

Shrinkage of concrete is influenced by intrinsic and extrinsic factors similar with creep. Intrinsic factors contain the proportions and properties of mixtures. Extrinsic factors consist of size of concrete, age of concrete exposure to the ambient condition, curing conditions, ambient temperature and relative humidity after exposure.

#### 2.2.2.1 Aggregate

Aggregate has a significant effect on shrinkage of concrete. Aggregate provides the restraining effect of shrinkage (Neville A. M., 1981), and the more aggregate the higher restraining effect and the lower shrinkage. Pickett (1956) proposed an equation to describe the effect of aggregate content on shrinkage of concrete:

$$\text{Shrinkage ratio} = \frac{S_c}{S_p} = (1 - a)^n \quad (\text{Eq 2-53})$$

where:

$S_c$  = shrinkage of concrete

$S_p$  = shrinkage of neat paste

a = percent aggregate content by volume

n = experimental exponent, and typically between 1.2 to 1.7 (L' Hermite R. G., 1968)

In this study, six levels of percent aggregate content by volume were used with a range from 0% to 62%. It was found that shrinkage decreased with an increase in aggregate content, and data fit the equation above when  $n = 1.7$ .

The effect of aggregate type on shrinkage of concrete under drying condition was investigated by Alexander (1996). In this study, two groups of concretes with 23 different types of aggregates were prepared, including shrinkage only specimens exposure to the air at 28 days and shrinkage specimens for creep exposure at the same age with creep specimens (600 days for series 1, 334 days for series 2). It was observed that shrinkage in the shrinkage only test was in a range of 86 to 463 microstrain at 28 days, and 247 to 841 microstrain at 6 months. It was also found that shrinkage for creep test varied from 83 to 561 microstrain at 28 days and from 236 to 826 microstrain for series 1 at 325 days, and from 140 to 459 microstrain for series 2 at the age of 140 days. It was additionally indicated that shrinkage for creep test had lower magnitude than shrinkage only test, because unloaded concretes for creep test had longer curing duration.

Modulus of elasticity of aggregate also has a great effect on shrinkage of concrete, and the higher modulus of elasticity of aggregate, the higher restraining effect on shrinkage and the lower shrinkage (Neville A. M., 1981). Hobbs (1974) also proposed equations to illustrate the effect of properties of aggregate including aggregate content and modulus of elasticity on the ratio of shrinkage of concrete and shrinkage of cement paste. Other properties of aggregate such as size and grading are indirect factors, and they affect shrinkage through aggregate content (Neville A. M., 1981).

#### 2.2.2.2 Cement

Cement type and fineness have a slightly influence on shrinkage of concrete (Neville A. M., 1981). According to the studies by Swayze (1960), the finer cement typically resulted in higher shrinkage of cement pastes, but not necessarily caused higher shrinkage of concrete.

Similar conclusion was also made by Bennett (1970). Typically rapid-hardening (Type III) Portland cement and other mineral admixtures such as slag and fly ash resulted in higher autogenous shrinkage of concrete (Khayat, 2009).

#### 2.2.2.3 Water to cementitious ratio

Water to cementitious (w/c) ratio is another factor influencing both drying shrinkage and autogenous shrinkage. Higher w/c ratio typically causes higher drying shrinkage, which is due to the reduction of the effective volume of restraining aggregate caused by higher water content (Neville A. M., 1981). In the study by ODman (1968), the effect of w/c ratio on shrinkage of concrete was investigated, and it was found that shrinkage of concrete increased with an increase of w/c ratio in drying condition. Similar behaviors were observed by Soraka (1979).

Water to cementitious ratio has the opposite effect on autogenous shrinkage, and autogenous shrinkage becomes a concern with lower w/c ratio such as HPC. According to the study by Miyazawa (1997), it was observed that total shrinkage of cement paste almost kept constant with w/c ratio from 0.3 to 0.6, but increased significantly with w/c ratio of 0.2 due to the great increase of autogenous shrinkage. Autogenous shrinkage of cement paste was smaller than 100 microstrain when w/c ratio was 0.5 or greater at 90 days, and it increased with a decrease of w/c ratio from 0.5 to 0.2. Autogenous shrinkage of cement paste at 90 days was about half of total shrinkage with a w/c ratio of 0.3, and it became about three quarters with w/c ratio of 0.2. Those behaviors were consistent with observations by Tazawa (1997) and Persson (1998). Although the extent of effect of autogenous shrinkage of cement paste on autogenous shrinkage of concrete highly depends on properties of aggregate, typically higher autogenous shrinkage of cement paste means higher autogenous shrinkage of concrete. The relation between shrinkage of cement paste and shrinkage of concrete were proposed by Pickett (1956) and Hobbs (1974).

#### 2.2.2.4 Chemical admixtures

Chemical admixtures are widely used in HPC, and the effect on shrinkage of concrete highly depends on the chemical compositions and dosages. According to the study by Keene (1960), it was found that air-entrainment agent had no effect on the shrinkage of concrete under drying condition. This was confirmed by Kosmatka (2008). In the study by Brooks (1989), seven sets of data on drying shrinkage of concrete were summarized, and it was indicated that plasticizers and superplasticizers typically increased drying shrinkage of concrete by 20%.

However, some other investigators had the opposite conclusion, and decreased shrinkage of concrete was observed due to the use of high-range water reducing agents (Nagataki, 1978).

#### 2.2.2.5 Mineral admixtures

Slag, fly ash and silica fume are three types of partial replacement materials of Portland cement used in HPC. They also influence the behavior of shrinkage of concrete.

Slag has an effect on shrinkage of concrete. In the study by Tazawa (1989), there were three levels of replacement of Portland cement with slag, including 0%, 35% and 55%. It was observed that slag decreased shrinkage of concrete under drying condition after 28 days of storage, and the higher slag content the lower shrinkage of concrete. It was additionally found that the extent of effect of slag on shrinkage under drying condition also depended on the curing duration, and the longer curing time the lower effect of slag on shrinkage of concrete. Another study by Sakai (1992), the effect of four levels of replacement of Portland cement with slag including 50%, 60%, 70% and 80% in concrete was investigated. It was indicated that shrinkage of concrete under drying condition increased with an increase of slag content from 50% to 60%, then decreased with an increase of slag content from 70% and 80%. Similar behavior of shrinkage of concrete with high slag content was also observed by Brooks (1992). According to a later study by Tazawa (1997), the effect of slag content in the range of 0%, 25%, 50% and 70% and three levels of fineness of slag particles on autogenous shrinkage was investigated. It was indicated that slag with lowest fineness decreased autogenous shrinkage of cement paste slightly with an increase of slag content from 0% to 70%, but for slags with higher fineness autogenous shrinkage increased significantly with an increase of slag content. It was found that cement paste with 70% slag content and the highest fineness resulted in the highest autogenous shrinkage. It was additionally found that cement paste and concrete had the similar trend of autogenous shrinkage for the effect of slag. Similar behavior of autogenous of slag concrete was observed by Lim (2000). In the study by Saric-Coric (2003), it was found that autogenous shrinkage of cement paste increased with an increase of slag content. Both studies by Lim and Saric-Coric confirmed Tazawa's observations.

Generally partial replacement of Portland cement with fly ash has no significant influence on shrinkage of concrete under a given drying condition (ACI 232.2R, 1996), but affects autogenous shrinkage. According to the study by Naik (2007), the effect of Class C fly ash of 0%

and 30% replacement of Portland cement on shrinkage of concrete was investigated. It was observed that fly ash decreased early age autogenous shrinkage of concrete and increased it at later ages. Fly ash concrete only had 64% autogenous shrinkage at 7 days comparing with concrete without fly ash, but was 164% at 56 days. Fly ash increased shrinkage of concrete slightly under drying condition. Class F fly ash used in HPC with 20% replacement of Portland cement increased autogenous shrinkage (Khayat, 2009).

Silica fume is typically used in HPC. According to the study by Mazloom (2004), four levels of replacement of Portland cement with silica fume were used, including 0%, 6%, 10% and 15%. It was observed that total shrinkage of HPC with fixed w/c ratio of 0.35 under drying condition decreased slightly with an increase of silica fume, but autogenous shrinkage of HPC measured from sealed specimens increased with an increase of replacement level of silica fume. It was found that autogenous shrinkage of concrete increased from 37% to 58% of total shrinkage with an increase of silica fume from 0% to 15% at the age of 587 days. Calculated drying shrinkage of concrete decreased with an increase of silica fume content. Similar behaviors were also found previously by Roy (1993) and Tazawa (1993) with silica fume content below 10%. When replacement level up to 20%, it was indicated that shrinkage of concrete increased slightly (ACI 234R, 2006).

#### 2.2.2.6 Size effect

Size of a specimen has a significant effect on shrinkage of concrete under drying condition. In the study by Carlson (1937), mass concrete was stored in the air with 50% relative humidity. It was observed that drying thickness was about 3 inches from the surface after one month, and about 9 inches after one year and about 24 inches after ten years, which indicated the size effect on drying process of concrete. Hansen (1966) reported that volume to surface (v/s) ratio was a reasonable indicator of size effect on drying shrinkage, and it was observed that higher v/s ratio typically resulted in lower drying shrinkage during 1200 days. It was additionally indicated that the effect of shape of concrete members on drying shrinkage is small when specimens had similar v/s ratios. It was also found that concrete stored in water had very small shrinkage comparing with concrete stored in the air with 50% relative humidity, which indicated size effect on autogenous shrinkage of concrete was not significant. In the study by Bryant (1987), thickness of a concrete member was used to account for the size effect on

shrinkage, and it was found that the shrinkage under drying condition decreased with an increase of thickness of concrete members. It was also indicated that the shrinkage of sealed specimens were much smaller than unsealed specimens, which confirmed the observations by Hansen (1966).

#### 2.2.2.7 Curing conditions

Curing condition is an extrinsic factor affecting shrinkage of concrete. Steam curing is widely used for HPC of prestressed members. In the study by Townsend (2003), it was observed that steam-cured concrete had 45% higher shrinkage than moist-cured concrete at storage of 1 week under drying condition, but after 14 weeks this value became 11%. It was indicated that steam curing increased initial shrinkage of concrete significantly, and decreased the rate of shrinkage at later ages. According to the study by Haranki (2009), it was found that concretes with 14-day moist-curing had smaller shrinkage under drying condition comparing with concretes with 7-day moist-curing, which was due to the higher maturity of concrete after 14-day moist curing.

#### 2.2.2.8 Relative humidity

Relative humidity of storage has a great influence on shrinkage under drying condition. Concrete swells in the water or in the air with 100% relative humidity, and shrinks when the relative humidity is below 94% (Neville A. M., 1981). In the study by Troxell (1958), concrete specimens were stored in three conditions of relative humidity, including 50%, 70% and 100% (in water). It was observed that the concrete in water swelled with time with relatively small strain, and shrinkage increased with a decrease of relative humidity for concretes from 50% and 70% conditions. Concrete stored at the condition of 50% relative humidity had 30% higher shrinkage at 1 year and 45% higher shrinkage at 25 years comparing with concrete stored at the condition of 70% relative humidity. Similar conclusion was made by Bissonnette (1999).

### **2.2.3 Prediction of shrinkage of concrete**

For the prediction of shrinkage of concrete without actual measurements of local material mixtures, the following five models are typically used, including AASHTO LRFD 2010, ACI 209R-90, ACI 209R Modified by Huo, CEB-FIP 90 and Bazant B3.

### 2.2.3.1 AASHTO LRFD (2010)

The expression for the shrinkage strain is given as:

$$\varepsilon_{sh} = k_{vs} \cdot k_{hs} \cdot k_f \cdot k_{td} (0.48) \times 10^{-3} \quad (\text{Eq 2-54})$$

In this equation, the ultimate shrinkage strain is taken as 0.00048 in. /in.

in which:

$$k_{vs} = 1.45 - 0.13(V/S) \geq 1.0 \quad (\text{Eq 2-55})$$

or the detailed equation is:

$$k_{vs} = \left[ \frac{\frac{t}{26 \cdot e^{0.0142(\frac{V}{S}) + t}}}{45 + t} \right] \left[ \frac{1064 - 3.7(\frac{V}{S})}{923} \right] \quad (\text{maximum } V/S \text{ is } 6 \text{ in.}) \quad (\text{Eq 2-56})$$

$k_{hs}$  = humidity factor for shrinkage

$$k_{hs} = 2.00 - 0.014H \quad (\text{Eq 2-57})$$

### 2.2.3.2 ACI 209R (1992)

The expression for shrinkage strain at the standard condition is given as:

$$(\varepsilon_{sh})_t = \frac{t}{35+t} (\varepsilon_{sh})_u \quad \text{shrinkage after 7 days for moist cured concrete} \quad (\text{Eq 2-58})$$

$$(\varepsilon_{sh})_t = \frac{t}{55+t} (\varepsilon_{sh})_u \quad \text{shrinkage after 1-3 days for steam cured concrete} \quad (\text{Eq 2-59})$$

where:

$t$  = days after the end of the initial wet curing

$(\varepsilon_{sh})_t$  = shrinkage strain after  $t$  days

$(\varepsilon_{sh})_u$  = ultimate shrinkage strain, and the average value suggested for

$$(\varepsilon_{sh})_u = 780 \gamma_{sh} \times 10^{-3} \text{ in./in., (mm./mm.)}$$

$\gamma_{sh}$  = correction factors for conditions other than the standard concrete composition,

which is defined as:

$$\gamma_{sh} = \gamma_{\lambda} \cdot \gamma_{vs} \cdot \gamma_s \cdot \gamma_{\rho} \cdot \gamma_c \cdot \gamma_a \quad (\text{Eq 2-60})$$

in which:

$\gamma_{\lambda}$  = correction factor for ambient relative humidity, which is defined as

$$\gamma_{\lambda} = 1.40 - 0.0102\lambda, \text{ for } 40 \leq \lambda \leq 80, \text{ where } \lambda \text{ is relative humidity in percent} \quad (\text{Eq 2-61})$$

$$\gamma_{\lambda} = 3.00 - 0.030\lambda, \text{ for } 80 < \lambda \leq 100, \text{ where } \lambda \text{ is relative humidity in percent} \quad (\text{Eq 2-62})$$

$\gamma_{vs}$  = correction factor for average thickness of member or volume-to-surface ratio. When average thickness of member is other than 6 in. (150 mm) or volume-to-surface ratio is other than 1.5 in. (38 mm), two methods are offered

(a) Average thickness method

For average thickness of member less than 6 in. (150 mm), the factors are given in Table 2.5.5.1 in ACI 209R-92. For average thickness of members greater than 6 in. (150 mm) and up to about 12 to 15 in (300 to 380 mm), equations are given:

$$\gamma_{vs} = 1.23 - 0.038h \quad \text{during the first year after loading} \quad (\text{Eq 2-63})$$

$$\gamma_{vs} = 1.17 - 0.029h \quad \text{for ultimate values} \quad (\text{Eq 2-64})$$

Where  $h$  is the average thickness of the member in inches

(b) Volume-surface ratio method

For members with volume-to-surface area other than 1.5 in. (38 mm), the equations are given:

$$\gamma_{vs} = 1.2e^{-0.12(\frac{v}{s})} \quad \text{where } v/s \text{ is the volume-surface ration in inches} \quad (\text{Eq 2-65})$$

$\gamma_s$  = correction factor for slump, and equations are given as:

$$\gamma_s = 0.89 + 0.041s \quad \text{where } s \text{ is the observed slump in inches} \quad (\text{Eq 2-66})$$

$\gamma_{\rho}$  = correction factor for fine aggregate percentage, which is defined as:

$$\gamma_{\rho} = 0.30 + 0.014\rho \quad \text{where } \rho \leq 50 \text{ percent} \quad (\text{Eq 2-67})$$

$$\gamma_{\rho} = 0.90 + 0.002\rho \quad \text{where } \rho > 50 \text{ percent} \quad (\text{Eq 2-68})$$



where  $\rho$  is the ratio of the fine aggregate to total aggregate by weight expressed as percentage

$\gamma_c$  = correction factor for cement content, which is defined as

$$\gamma_c = 0.75 + 0.00036c \quad \text{where } c \text{ is the cement content in lb/yd}^3 \quad (\text{Eq 2-69})$$

$\gamma_a$  = correction factor for air content, which is defined as

$$\gamma_a = 0.95 + 0.008a \quad \text{where } a \text{ is the air content in percent} \quad (\text{Eq 2-70})$$

### 2.2.3.3 ACI-Modified by Huo (2001)

$$v_t = \frac{t}{K_S + t} (\varepsilon_{sh})_u \quad (K_S = 45 - 2.5f'_c) \quad (\text{Eq 2-71})$$

$\gamma_{st,s}$  = correction factor for compressive strength of concrete

$$\gamma_{st,s} = 1.20 - 0.05f'_c \quad (\text{Eq 2-72})$$

$f'_c$  = 28-day compressive strength in ksi

### 2.2.3.4 CEB-FIP (1990)

The expression for the shrinkage strain in compression is given:

$$\varepsilon_{cs}(t, t_s) = \varepsilon_{cso} \cdot \beta_s(t - t_s) \quad (\text{Eq 2-73})$$

where

$\varepsilon_{cso}$  = the notional shrinkage coefficient

$\beta_s$  = the coefficient to describe the development of shrinkage with time

$t$  = the age of concrete (days)

$t_s$  = the age of concrete (days) at the beginning of shrinkage

The notional shrinkage coefficient is given:

$$\varepsilon_{cso} = \varepsilon_s(f_{cm}) \cdot \beta_{RH} \quad (\text{Eq 2-74})$$

within

$$\varepsilon_s(f_{cm}) = [160 + 10 \cdot \beta_{sc}(9 - f_{cm}/f_{cmo})] \cdot 10^{-6} \quad (\text{Eq 2-75})$$

where:

$f_{cm}$  is the mean compressive strength of concrete at the age of 28 days (MPa)

$$f_{cm0} = 10 \text{ MPa}$$

$\beta_{sc}$  is the coefficient which depends on the type of cement:  $\beta_{sc} = 4$  for slowly hardening cements SL,  $\beta_{sc} = 5$  for normal or rapid hardening cements N and R, and  $\beta_{sc} = 8$  for rapid hardening high strength cements RS

$$\beta_{RH} = -1.55 \cdot \beta_{sRH} \text{ for } 40\% \leq RH \leq 99\% \quad (\text{Eq 2-76})$$

$$\beta_{RH} = +0.25 \quad \text{for } RH \geq 99\% \quad (\text{Eq 2-77})$$

$$\text{where } \beta_{sRH} = 1 - \left(\frac{RH}{RH_0}\right)^3 \quad (\text{Eq 2-78})$$

with

$RH$  is the relative humidity of the ambient atmosphere (%)

$$RH_0 = 100\%$$

The development of shrinkage with time is given by

$$\beta_s(t - t_s) = \left[ \frac{(t - t_s)/t_1}{350 \cdot (h/h_0)^2 + (t - t_s)/t_1} \right]^{0.5} \quad (\text{Eq 2-79})$$

where

$h$  = notational size of member (mm), and the expression is  $h = 2A_c/u$ , where  $A_c$  is the area of cross section, and  $u$  is the perimeter of the member in constant with the atmosphere

$$h_0 = 100 \text{ mm}$$

$$t_1 = 1 \text{ day}$$

#### 2.2.3.5 Bazant B3 Model (2000)

The shrinkage strain is expressed as:

$$\varepsilon_{sh}(t, t') = \varepsilon_{sh\infty} K_h S(t) \quad (\text{Eq 2-80})$$

where  $\varepsilon_{sh\infty}$  could be calculated by using Eq 2-45 and  $S(t)$  could be calculated by using Eq 2-47,

and

$$K_h = \begin{cases} 1 - h^3 & \text{for } h < 0.98 \\ -0.2 & \text{for } h = 1 \\ \text{use linear interpolation for } 0.98 < h < 1 \end{cases}$$

## 2.3 Modulus of Elasticity of Concrete

### 2.3.1 Introduction

Modulus of elasticity is an important property of hardened concrete. Concrete is a composite material, including aggregate and cement paste. Modulus of elasticity of concrete highly depends on properties and proportions of mixture materials. ASTM Standard C469 provides the method to measure static modulus of elasticity of concrete in compression. Elastic modulus of concrete has a significant effect on behavior of prestressed bridge girders, such as camber. In the following sections, factors affecting modulus of elasticity of concrete and four prediction models are presented.

### 2.3.2 Factors affecting modulus of elasticity of concrete

Modulus of elasticity of concrete is greatly influenced by the material properties and mineral admixtures, and the effect of other factors is not significant.

#### 2.3.2.1 Material properties

Concrete is a composite of aggregate and cement paste, and it is typically a composite soft material due to higher modulus of elasticity of aggregate than cement paste (Neville A. M., 1970). Neville (1970) cited two equations for elastic moduli of composite shown below:

$$E = (1-g) E_m + gE_p \quad (\text{composite hard material when } E_m > E_p) \quad (\text{Eq 2-81})$$

$$E = \left( \frac{1-g}{E_m} + \frac{g}{E_p} \right)^{-1} \quad (\text{composite soft material when } E_m < E_p) \quad (\text{Eq 2-82})$$

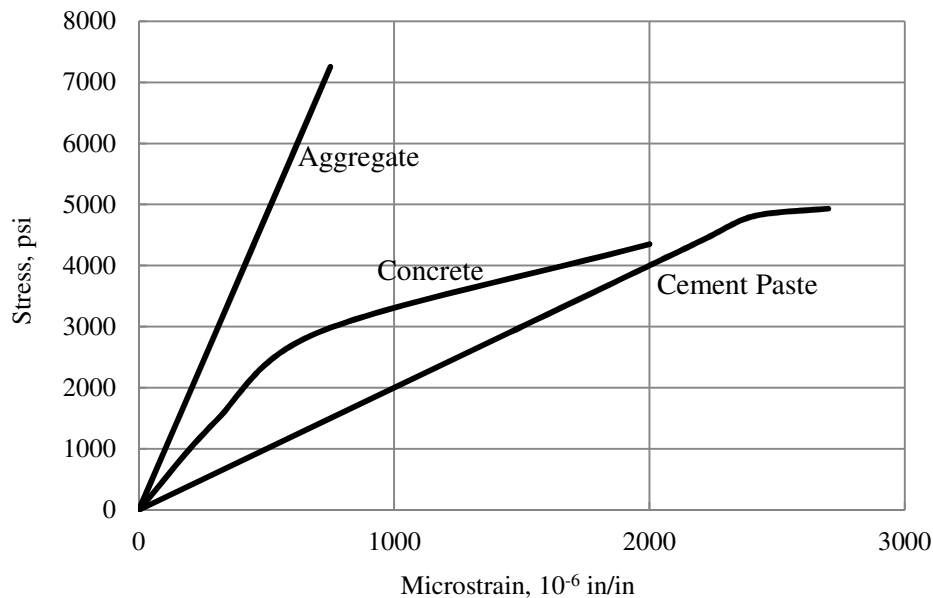
Where:

$E$  is modulus of elasticity of the composite material;  $E_m$  is modulus of elasticity of the matrix phase;  $E_p$  is modulus of elasticity of the particle phase;  $g$  = fractional volume of the particles.

Aggregate plays an important role in the modulus of elasticity of concrete. Typically higher aggregate content and higher modulus of elasticity of aggregate result in higher elastic

moduli of concrete. Those conclusions were confirmed by Hirsch (1962) and Hansen (1965), and also empirical equations were proposed.

The relations of stress and strain for aggregate, cement paste and concrete are shown in Figure 2.1 (Neville A. M., 1981). A reasonable explanation for the curved shape of concrete was given by Neville (1981). The rate of increase of induced strain at the interface of aggregate and cement paste was much higher than the rate of applied stress development beyond a certain range. Further explanation of the effect of bond of aggregate and cement paste on elastic modulus of concrete was also provided by Neville (1997). The difference of modulus of elasticity between aggregate and cement paste plays an important role in modulus of elasticity of concrete. In HPC the difference of modulus of elasticity between aggregate and cement paste was smaller than normal concrete, which resulted in better bond of aggregate and cement and higher modulus of elasticity of concrete. In HPC the linear part in a stress & strain curve as high as 85% of ultimate strength or even higher was observed.



**Figure 2.2.** Stress-strain relations for aggregate, cement paste and concrete

#### 2.3.2.2 Mineral admixtures

Mineral admixtures are typically added in HPC as partial replacement materials of Portland cement. The influence of slag on modulus of elasticity of concrete is small (ACI 233R, 2003). In the study by Brooks (1992), the effect of 0%, 30%, 50% and 70% slag replacement of

Portland cement on the property of concrete was investigated. No significant influence of slag on elastic moduli was observed. It was indicated that dry-stored slag concrete had higher elastic moduli at early ages, but lower at later ages comparing with concrete without slag, and the opposite trend was found for water-stored concrete. Fly ash has also slightly influence on modulus of elasticity of concrete, including Class F fly ash (Lane, 1982) and Class C fly ash (Yildirim, 2011). Silica fume increases elastic moduli of concrete within certain content. According to the study by Alfes (1992), it was indicated that 10% silica fume as the replacement of Portland cement increased elastic moduli of concrete by 12% at 28 days, but 20% silica fume increased it by 7% at 28 days comparing with concrete without silica fume. In the study by Mazloom (2004), effect of four levels of replacement of Portland cement with silica fume including 0%, 6%, 10% and 15% on modulus of elasticity of concrete was investigated. It was found that elastic moduli increased within 10% at 7 days and 28 days with an increase of silica fume content.

### 2.3.3 Prediction of elastic modulus of elasticity of concrete

Typically the relation between modulus of elasticity of concrete and corresponding compressive strength is provided, which is not due to a direct relation between elastic moduli and compressive strength, but because of the convenience of measurement of compressive strength. The following four models are commonly used for the prediction of modulus of elasticity when the actual measurements are not available.

#### 2.3.3.1 AASHTO LRFD (2010)

In the absence of measured data, the modulus of elasticity,  $E_c$ , for concretes with unit densities between 90 and 155 pcf and specified compressive strengths up to 15.0 ksi may be taken as:

$$E_c = 33 K_I w_c^{1.5} \sqrt{f'_c} \quad (\text{Eq 2-83})$$

Where:

$E_c$  = elastic modulus of elasticity of concrete (psi)

$K_I$  = correction factor for source of aggregate to be taken as 1.0 unless determined by physical test, and as approved by the authority of jurisdiction

$w_c$  = unit density of concrete (lb/ft<sup>3</sup>)

$f'_c$  = specified compressive strength of concrete (psi)

### 2.3.3.2 ACI 363R (1992)

According to the study by Martinez (1982), it was found that the expression of Eq 2-83 overestimated the modulus of elasticity for high performance concretes with compressive strength between 6000 psi and 12000 psi. A correlation between the modulus of elasticity  $E_c$  and compressive strength  $f'_c$  for normal weight concretes was reported below:

$$E_c = (40,000 \sqrt{f'_c} + 1.0 \times 10^6) \left(\frac{w_c}{145}\right)^{1.5} \quad (3,000 \text{ psi} < f'_c < 12,000 \text{ psi}) \quad (\text{Eq 2-84})$$

where:

$f'_c$  = specified compressive strength of concrete (psi)

$w_c$  = the density of concrete (lb/ft<sup>3</sup>)

### 2.3.3.3 CEB-FIP (1990)

Values of the modulus of elasticity for normal weight concrete can be estimated from the specified characteristic strength by using:

$$E_{ci} = E_{co} [(f_{ck} + \Delta f) / f_{cmo}]^{1/3} \quad (\text{Eq 2-85})$$

where

$E_{ci}$  = the modulus of elasticity (MPa) at a concrete age of 28 days

$E_{co} = 2.15 \times 10^4 \text{ MPa}$

$f_{ck}$  = the characteristic strength (MPa) mentioned at Table 2.1.1 in CEB-FIP 1990

$\Delta f = 8 \text{ MPa}$

$f_{cmo} = 10 \text{ MPa}$

When the actual compressive strength of concrete at an age of 28 days  $f_{cm}$  is known,  $E_{ci}$  may be estimated from:

$$E_{ci} = E_{co}[f_{cm}/f_{cmo}]^{1/3} \quad (\text{Eq 2-86})$$

When only an elastic analysis of a concrete structure is carried out, a reduced modulus of elasticity  $E_c$  can be calculated in order to account for initial plastic strain shown below:

$$E_c = 0.85 E_{ci} \quad (\text{Eq 2-87})$$

#### 2.3.3.4 Tadros (2003)

The modulus of elasticity of high performance concrete can be expressed as:

$$E_c = 33,000 K_1 K_2 \left(0.140 + \frac{f'_c}{1000}\right)^{1.5} \sqrt{f'_c} \quad (E_c \text{ is in ksi, and } f'_c \text{ is in ksi}) \quad (\text{Eq 2-88})$$

Where:

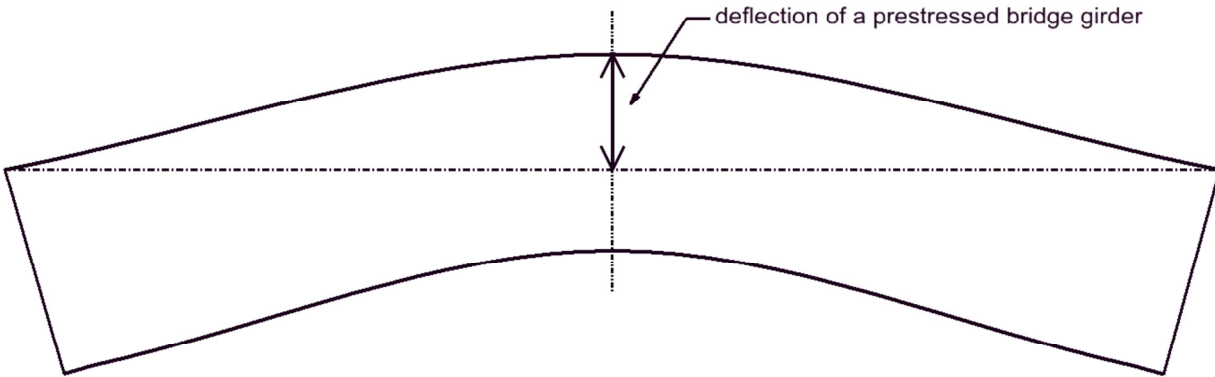
$K_1$  = correction factor for local material variability, and  $K_1 = 1.0$  for the average of all data obtained by Tadros (2003).

$K_2$  = correction factor based on the 90th percentile upper-bound and the 10th percentile lower-bound for all data, and for the average of all data  $K_2 = 0.777$  (10th percentile) and  $K_2 = 1.224$  (90th percentile).



## 2.4 Long-Term Camber of Prestressed Bridge Girders

Camber of a prestressed bridge girder is the elevation difference between the midspan and the end of the girder. Figure 2.3 shows the detail below. Typically elevation is measured from the top flange by using an accurate laser level.



**Figure 2.3.** Camber of a prestressed bridge girder

### 2.4.1 Factors affecting long-term camber of prestressed bridge girders

#### 2.4.1.1 Introduction

Long-term camber of a prestressed bridge girder is affected by camber at transfer, self-weight, creep, prestress forces and losses, and cross section properties.

#### 2.4.1.2 Camber at transfer

For a prestressed bridge girder after strands are cut, instantaneous upward camber occurs. Instantaneous camber varies for different types of girders, and it is influenced by prestress forces, self-weight, modulus of elasticity of concrete and cross section of the girder.

#### 2.4.1.3 Camber due to self-weight

Camber of a prestressed girder due to self-weight is significantly influenced by the length of an overhang. Overhang length is the distance from the end of girder to the center of the support.

If there is no overhang, the camber at midspan relative to the end of the girder due to self-weight can be calculated by using:

$$\Delta_{sw} = \frac{5w_{sw}L^4}{384E_{ce}I} \quad (\text{Eq 2-89})$$

where:

$w_{sw}$  = self-weight per unit length

$L$  = length of a girder

$I$  = moment of inertia of cross section

If there is an overhang, the camber at midspan respect to the end of the girder due to self-weight can be calculated:

$$\Delta_{sw} = \Delta_{overhang} + \Delta_{midspan} \quad (\text{Eq 2-90})$$

$$\Delta_{overhang} = \frac{\omega_{sw}L_c}{24E_{ce}I} [3L_c^2 (L_c + 2L_n) - L_n^3] \quad (\text{Eq 2-91})$$

$$\Delta_{midspan} = \frac{\omega_{sw}L_n^2}{384E_{ce}I} [5L_n^2 - 24L_c^2] \quad (\text{Eq 2-92})$$

where:

$\Delta_{overhang}$  = the camber of the end of overhang relative to the support

$\Delta_{midspan}$  = the camber at the midspan relative to the support

$L_c$  = length of overhang

$L_n$  = distance between two supports

Time dependent camber of a prestressed bridge girder with overhang can be adjusted to the camber without overhang by using the Eq 2-90, 2-91 and 2-92.

#### 2.4.1.4 Camber due to creep

After transfer for a prestressed girder, prestressing force and self-weight result in different stresses along the cross section of concrete of a girder, and the applied stress increases the upward camber. This additional camber is due to creep of concrete.

#### 2.4.1.5 Prestress losses

##### *2.4.1.5.1 Introduction*

Prestress losses of prestressed bridge girders before deck is placed consist of short-term losses and long-term losses. Short-term losses are due to anchorage set at jacking, relaxation before transfer and elastic shortening at transfer. Long-term losses result from creep, shrinkage and relaxation after transfer. Prestress losses result in a decrease of camber of a girder.

AASHTO LRFD (2010) provides refined estimations of time-dependent prestress losses:

$$\Delta f_p = \Delta f_{pA} + \Delta f_{pRI} + \Delta f_{pES} + \Delta f_{pC} + \Delta f_{pSH} + \Delta f_{pR2} \quad (\text{Eq 2-93})$$

##### *2.4.1.5.2 Prestress loss due to anchorage set*

Anchorage set loss is due to the movement of the strand prior to seating the anchorage gripping device. This is a major loss before transfer comparing with relaxation loss. The magnitude of this movement depends on the prestressing system used in precast factory, and AASHTO LRFD 2010 provides a common value of 0.375 inch. Anchorage set loss stress is expressed as:

$$\Delta f_{pA} = \frac{\Delta_{set}}{L_p} E_p \quad (\text{Eq 2-94})$$

$\Delta_{set}$  = anchorage set at jacking, which is provided by manufacturer of prestressing system, in

$L_p$  = total length of prestressing strand, in

$E_p$  = modulus of elasticity of strand (typical value is 28,500 ksi)

##### *2.4.1.5.3 Prestress loss due to relaxation*

When a strand is stressed, the magnitude of stress decreases with time, which is relaxation loss. Relaxation loss occurs not only between jacking and transfer, and also after transfer for a long-term.

Relaxation loss for stress-relieved strand from jacking to transfer:

$$\Delta f_{pRI} = \frac{\log(24.0t)}{10.0} \left[ \frac{f_{pi}}{f_{py}} - 0.55 \right] f_{pi} \quad (\text{Eq 2-95})$$

Relaxation loss for low-relaxation strand from jacking to transfer:

$$\Delta f_{pRI} = \frac{\log(24.0t)}{40.0} \left[ \frac{f_{pi}}{f_{py}} - 0.55 \right] f_{pi} \quad (\text{Eq 2-96})$$

where:

t = time between initial jacking and transfer (days)

$f_{pi}$  = strand stress after jacking (ksi)

$f_{py}$  = yield strength of strand (ksi)

$f_{py} = 0.85f_{pu}$  for stress-relieved strand, and  $f_{py} = 0.90f_{pu}$  for low-relaxation strand

Relaxation loss for stress-relieved strand after transfer:

$$\Delta f_{pR2} = 20.0 - 0.4\Delta f_{pES} - 0.2 (\Delta f_{pSR} + \Delta f_{pCR}) \quad (\text{Eq 2-97})$$

Relaxation loss for low-relaxation strand after transfer:

$$\Delta f_{pR2} = 6.0 - 0.12\Delta f_{pES} - 0.06 (\Delta f_{pSR} + \Delta f_{pCR}) \quad (\text{Eq 2-98})$$

where:

$\Delta f_{pES}$  is loss due to elastic shortening at transfer

$\Delta f_{pSR}$  is loss due to shrinkage

$\Delta f_{pCR}$  is loss due to creep.

According to the study by Tadros (2003), relaxation loss after transfer is between 1.8 to 3.0 ksi, which is relatively a small part of total prestressing losses.

#### 2.4.1.5.4 Prestress loss due to elastic shortening

A direct solution method to calculate elastic shortening loss was proposed by Cole (2000).

Equations are shown below:

$$\Delta f_{pES} = \text{abs}(f_{cgp}) \frac{E_P}{E_{ci}} \quad (\text{Eq 2-99})$$

where:

$$f_{cgp} = -\frac{P_{at}}{A} - \frac{P_{at} e^2}{I} + \frac{M_g e}{I} \quad (\text{Eq 2-100})$$

$$P_{at} = f_{pat} A_{ps} \quad (\text{Eq 2-101})$$

$$f_{pat} = f_{pbt} - \Delta f_{pES} \quad (\text{Eq 2-102})$$

where:

$f_{cgp}$  = concrete stress at the level of the strands due to the weight of the girder and the prestressing force after transfer (ksi)

$A$  = area of cross section (in<sup>2</sup>)

$I$  = moment of inertia of cross section (in<sup>4</sup>)

$A_{ps}$  = total area of strands (in<sup>2</sup>)

$e$  = eccentricity of strands with respect to centroid of girder (in)

$M_g$  = moment due to the self-weight of the girder (kip-in)

$E_{ci}$  = modulus of elasticity of concrete at transfer (ksi)

It is necessary to do iterations to obtain the appropriate  $\Delta f_{pES}$ , and for the initial assumption  $f_{pat} = 0.9f_{pbt}$ .

#### 2.4.1.5.5 Prestress loss due to creep

Prestress loss due to creep from transfer to deck placement is shown below:

$$\Delta f_{pCR} = \Delta f_{pES} \Phi_{bid} K_{id} \quad (\text{Eq 2-103})$$

where:

$$K_{id} = \frac{1}{1 + \frac{E_P A_{ps}}{E_{ci} A} \left(1 + \frac{A e_{pg}^2}{I}\right) [1 + 0.7 \Phi_{bif}]} \quad (\text{Eq 2-104})$$

$\Phi_{bid}$  = specified creep coefficient of concrete

$\Phi_{bif}$  = ultimate creep coefficient of concrete

$A_{ps}$  = total area of prestressing strands (in<sup>2</sup>)

$A$  = area of cross section (in<sup>2</sup>)

$I$  = moment of inertia of cross section (in<sup>4</sup>)

$e_{pg}$  = eccentricity of the strand with respect to the centroid of girder (in)

#### 2.4.1.5.6 Prestress loss due to shrinkage

Prestress loss due to shrinkage from transfer and to deck placement shown below:

$$\Delta f_{pSH} = E_p \varepsilon_{bid} K_{id} \quad (\text{Eq 2-105})$$

where:

$\varepsilon_{bid}$  = specified shrinkage strain (10<sup>-6</sup> in/in)

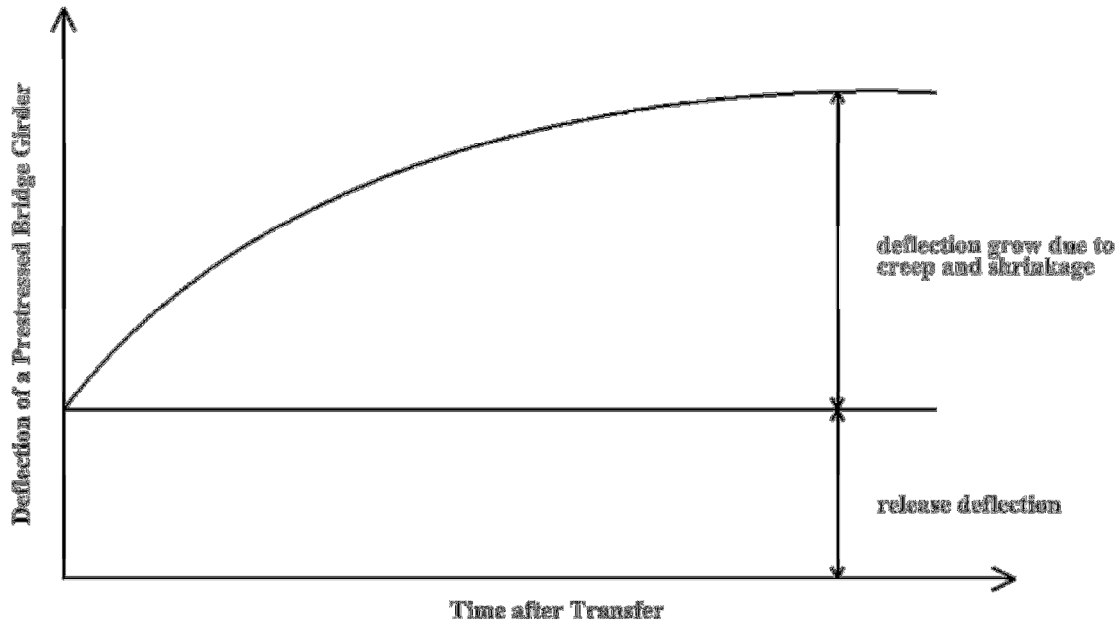
#### 2.4.1.6 Cross section properties

Cross section of a prestressed bridge girder has two types of properties, including gross section property and transformed section property. It is easier to calculate gross section property. Transformed section properties are dependent on the ratio of modulus of elasticity of strands and concrete, strand locations and strand quantities. Transformed section property is widely used for reinforced concrete. Short-term and long-term cambers of girders by using gross section and transformed section properties are compared in Section 5.8.4.

### 2.4.2 Calculation of long-term camber of prestressed bridge girders

#### 2.4.2.1 Introduction

For a prestressed bridge girder, creep increases camber, and prestress losses decreases camber, and the combination of these two effects typically results in an increase of camber. Figure 2.4 shows the camber of prestressed girder after transfer. Moment area method, Tadros's Method, Naaman's Method and Incremental method are discussed in the following sections, which are used to calculate long-term camber of a prestressed bridge girder in this study.



**Figure 2.4.** Camber of a prestressed bridge girder versus time after transfer

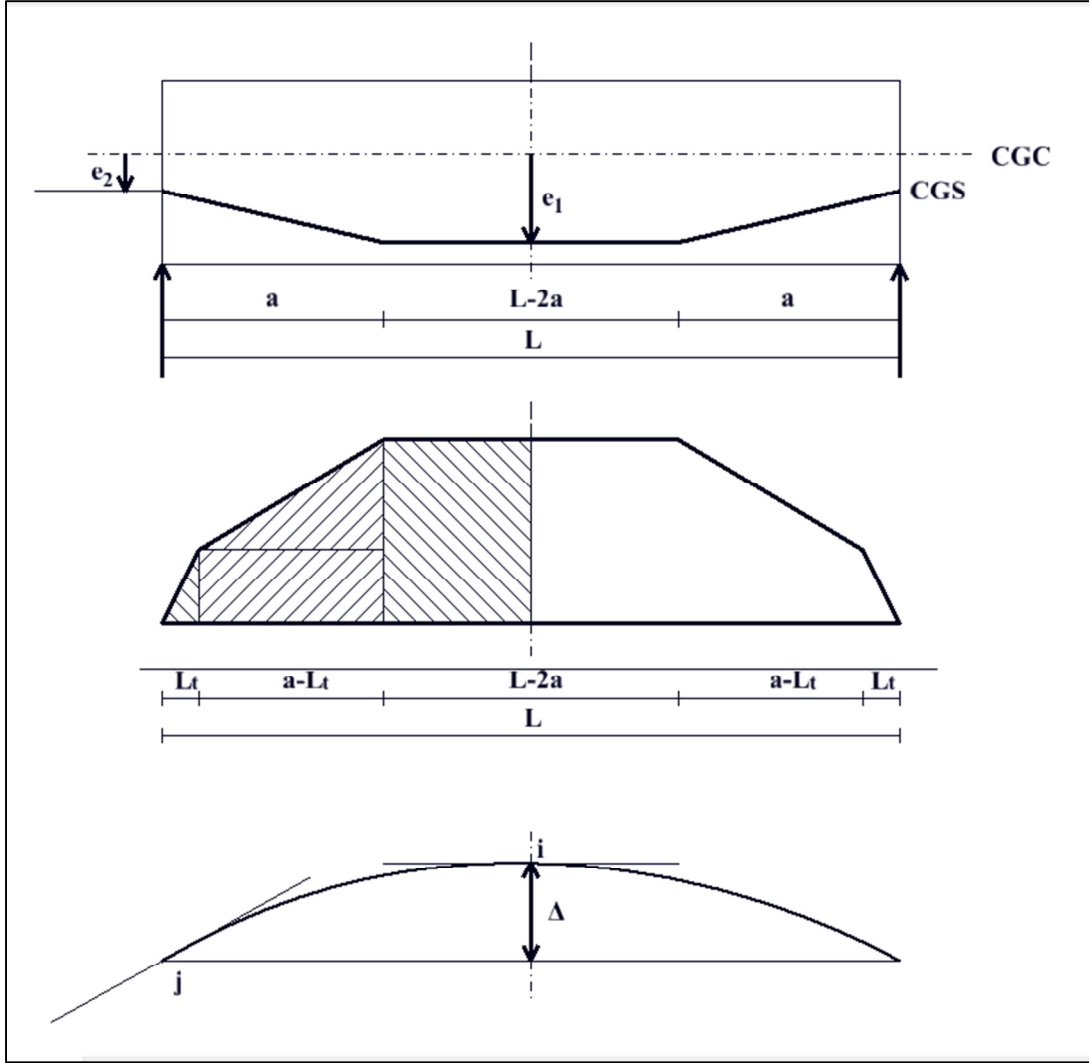
#### 2.4.2.2 Moment area mothod

Second moment-area theorem (or camber theorem) is typically used to calculate the camber of beam members. The expression of camber at point j relative to point i is shown below:

$$\Delta_{j/i} = \int_{x_i}^{x_j} x \left( \frac{M}{EI} \right) dx \quad (\text{Eq 2-106})$$

For prestressed girders, it is convenient to choose midspan as point i and end span as point j. Figure 2.5 below shows the typical strand layout of a prestressed girder, curvature diagram and deflected shape of a girder. Naaman's method and Incremental method are based on this theorem.

Transfer length of a prestressed girder is typically about 3 ft. (e.g. 60 times 0.6 in. diameter of strand) in this study according to AASHTO LRFD 2010. The effect of transfer length on camber of girder is very small mentioned in the study by Tadros (2011), and it can be neglected if necessary.



**Figure 2.5.** Moment area method for a prestressed bridge girder

#### 2.4.2.3 Tadros's Method

Tadros (2011) provided a simplified method to calculate the long-term camber of prestressed bridge girders before the placement of deck, and expression is shown below:

$$\Delta_{long-term} = (1 + \Phi_{bid}) \Delta_{release} - (1 + 0.7\Phi_{bid}) \Delta_{loss} \quad (\text{Eq 2-107})$$

where:

$\Delta_{long-term}$  = long-term camber of a prestressed girder before the placement of deck (in)

$\Delta_{release}$  = release camber of a prestressed girder (in)



$\Delta_{loss}$  = camber loss due to prestress losses resulting from creep, shrinkage and relaxation between the time of transfer to the time of placement of deck (in)

$$= \frac{\Delta f}{f} \Delta_{release}$$

Where:

$\Delta f$  = long-term prestress losses due to creep, shrinkage and relaxation (ksi)

$f$  = prestress stress after transfer (ksi)

$\Phi_{bid}$  = specified creep coefficient of concrete

In this equation, 0.7 is an aging coefficient used to calculate the camber loss due to prestress losses, which is based on considerations of  $v/s$  ratio, relative humidity and loading age.

#### 2.4.2.4 Naaman's Method

Naaman (2004) proposed another simplified method to calculate long-term camber of prestressed girders. Equivalent modulus is used for the calculation of camber shown as follows:

$$E_{ce}(t, t_A) = \frac{E_c(t)}{1 + C_C(\tau)} \quad (\text{Eq 2-108})$$

where:

$E_c(t)$  = time-dependent modulus of elasticity of concrete

$$= \sqrt{\frac{t}{b+ct}} E_c(28)$$

Moist-curing:  $b = \begin{cases} 4.0 & \text{for Type I cement} \\ 2.3 & \text{for Type III cement} \end{cases}$  and  $c = \begin{cases} 0.85 & \text{for Type I cement} \\ 0.92 & \text{for Type III cement} \end{cases}$

Steam-curing:  $b = \begin{cases} 1.0 & \text{for Type I cement} \\ 0.7 & \text{for Type III cement} \end{cases}$  and  $c = \begin{cases} 0.95 & \text{for Type I cement} \\ 0.98 & \text{for Type III cement} \end{cases}$

$C_C(\tau)$  = specified creep coefficient of concrete

$t$  = age of concrete (days)

$t_A$  = age of concrete at transfer (days)

Long-term camber of a prestressed girder shown in Figure 2.5 can be calculated by using the following equations:

$$\Delta_{long-term} = \frac{FL^2}{8 Ece(t, t_A) I} [e_1 + (e_2 - e_1) \frac{4a^2}{3L^2}] \quad (\text{Eq 2-109})$$

where:

$F$  = prestressing force in strands;  $I$  = moment of inertia of cross section

or

$$\Delta_{long-term} = (\phi_1 - \phi_2) \frac{a^2}{6} - \phi_1 \frac{L^2}{8} \quad (\text{Eq 2-110})$$

where:

$\phi_1$  = curvature at the midspan of the girder due prestressing force and self-weight

$$\phi_1 = \frac{M_{ps1} + M_{sw1}}{Ece(t, t_A) I} \quad (\text{Eq 2-111})$$

where  $M_{ps1}$  is the moment due to prestressing force at midspan of a girder, and  $M_{sw1}$  is the moment due to self-weight at midspan

$\phi_2$  = curvature at the end of the girder due prestressing force and self-weight

$$\phi_2 = \frac{M_{ps2} + M_{sw2}}{Ece(t, t_A) I} \quad (\text{Eq 2-112})$$

where  $M_{ps2}$  is the moment due to prestressing force at end of a girder, and  $M_{sw2}$  is the moment due to self-weight at end (for a simply supported girder, this value equals zero).

#### 2.4.2.5 Incremental Method

For incremental method, a girder is divided into 1 in. sections, and properties of each section are analyzed, including cross section properties and applied moments and stresses.

Curvature of each section is calculated by using time-dependent equivalent modulus, and the camber of a girder is obtained by integrating curvature along half span of the girder:

$$\Delta_{long-term} = \int_0^{L/2} \frac{M_i}{E_{ce}(t, t_A) I_i} dx \quad (\text{Eq 2-113})$$

where:

$i$  = number of 1 in. section of half span of a prestressed girder

$M_i$  = applied moment on the section of  $i$  due to prestress force and self-weight of a girder, in which time-dependent prestress losses are calculated section by section by using time-dependent cross section properties

$E_{ce}(t, t_A)$  = equivalent modulus of concrete, which can be calculated by using Eq 2-108

$I_i$  = moment of inertia on the section of  $i$

### **2.4.3 Three previous studies of the prediction of the long-term camber of prestressed bridge girders**

Three previous studies of the prediction of the long-term camber of prestressed bridge girders were reviewed and summarized in the following sections, including Washington Report (2007), North Carolina Report (2011) and Minnesota Report (2012).

#### **2.4.3.1 Washington Report (2007)**

This study indicated that in order to improve the accuracy of prediction of the long-term camber of prestressed bridge girders, properties of concrete of local materials should be taken, which were used to calibrate the camber, and also the time effect should be also taken into account to calculate camber of a girder by using time-step method. A computer program was developed to calculate long-term camber of prestressed girders, in which time-step method was used to calculate time-dependent camber with the consideration of time-dependent material properties including concrete and prestressing steel. Two adjustment factors were used to calibrate the calculated camber of a girder, including 1.15 for elastic modulus of AASHTO model and 1.4 for creep coefficient of AASHTO model. Refined method of prestress loss

calculations from AASHTO LRFD 2006 was recommended for the prediction of long-term camber of girders. Creep and shrinkage tests were taken by using local materials of concretes, but the unexpected elongation of some shrinkage specimens were observed, which could result in errors of calculation of creep strain and camber of the girder.

#### 2.4.3.2 North Carolina Report (2011)

In this study in order to improve the accuracy of the prediction of the long-term camber of prestressed bridge girders, adjustment factors of concrete properties were recommended, including 1.25 for design compressive strength at release and 1.45 for design compressive strength at 28-day, and 0.85 for elastic modulus of AASHTO model, and also approximate method and refined method for the prediction of camber of girders were proposed. Simply multipliers from PCI were used as approximate method, and refined method of calculation of prestressed losses from AASHTO LRFD 2010 was used to calculate the camber of a girder at 28-day and 1-year as the refined method of camber calculation. Temperature gradient effect on the measurement of girders was recognized, and it was recommended to take the measurement of girder before dawn. It was also found that the transfer length of the prestressed girder had effect on the camber of the girder. Creep and shrinkage tests of concretes of local materials were not taken, and AASHTO LRFD 2010 creep and shrinkage model was used.

#### 2.4.3.3 Minnesota Report (2012)

In this study in order to improve the accuracy of the prediction of the long-term camber of prestressed bridge girders, adjustments of concrete properties were used, including 1.15 for design release compressive strength and change of elastic modulus prediction from ACI 363 to AASHTO model. Additional prestress losses due to relaxation and thermal effect were considered for the calculation of camber of a girder. Creep and shrinkage tests of concretes of local materials were not taken, and ACI 209R 1992 creep and shrinkage model was selected for the calculation of prestressed losses and camber of the girders. Effect of relative humidity and temperature on creep and shrinkage were taken into account to calculate time-dependent camber of the girder. A computer program was used to predict time-dependent camber of a girder all the consideration of factors discussed above. Also simple multipliers were also proposed to predict long-term camber of a girder.

#### 2.4.3.4 Comparison of three studies

According to the three studies, it was found that inaccuracy of prediction of concrete properties, including compressive strength, elastic modulus and creep and shrinkage was one important cause of errors of camber of a prestressed girder. In three studies, compressive strength and elastic modulus tests were taken, and adjustment factors of material properties were provided. Three studies also provided the prediction method of time dependent camber of the prestressed girder by using computer programs or time-dependent equations. For two studies simple multipliers were also proposed for the prediction of camber. Three studies indicated that AASHTO LRFD 2010 refined method for prestress losses provided a good prediction of the camber of girders. Creep and shrinkage tests were only taken in Washington DOT study.

## **CHAPTER 3 EXPERIMENTS**

### **3.1 Introduction**

Each procedure involved in this study was performed according to the appropriate ASTM specification. Materials and specimens of concrete are discussed in section 3.2. Compressive strength test, creep test and shrinkage test are presented in section 3.3, 3.4 and 3.5 respectively. Shrinkage of 4-ft. beam section and measurements of long-term cambers of the prestressed bridge girders are discussed in section 3.6 and 3.7.

### **3.2 Materials and Specimens**

A total of 7 mixtures of concrete specimens were prepared by three precast plants. Four of seven were high performance concretes (HPC) currently used to cast prestressed bridge girders, and the rest of them were normal concretes (NC) used in girders in the past. In HPC slag and fly ash were added as partial replacement materials of Portland cement. NC concretes didn't contain those materials. 4 by 8 in. cylindrical concrete specimens were used in this study and all of them were cast by the quality control staffs of three precast plants. Specimens of HPC were made and stored in the mold along with steam-cured prestressed bridge girders, and NC specimens were cast and stored in the mold in the quality control room in precast plants. HPC 1 and NC 1 were prepared by precast plant A, and HPC 2, HPC 4 and NC 2 were cast by precast plant B, and HPC 3 and NC 3 were provided by precast plant C.

Typically prestressed bridge girders were released after 1-day steam curing, so specimens at the age of 1 day for both HPC and NC were transported from precast plants to the laboratory on campus during the early morning of the day of girder release. Sometimes girders were kept on the bed of fabrication during the weekend, and those girders were released at the age of 2 – 4 days.

Totally 14 cylindrical specimens for each mix were brought in the laboratory. 3 specimens were used for 1-day compressive strength test, 3 for 28-day compressive strength test, 4 for creep test, and 4 for shrinkage test. For the creep and shrinkage test, half specimens were sealed by using a type of coating material, and the rest were unsealed. All specimens were sulfur-capped (ASTM C617, 2009) for compressive strength test, creep and shrinkage tests. Photos of sealed and unsealed specimens are shown in Figure A.1 in Appendix A.

### **3.3 Compressive Strength Test**

Compressive strength test was performed according to ASTM C39 (2004). For each mix, three sulfur-capped 4 by 8 in. cylindrical specimens were used for the compressive strength test at 1 day and 28 days, respectively. Three specimens for 28 days compressive strength test were stored in the same chamber of creep and shrinkage tests before the test. Photos of the compressive strength test are shown in Figure A. 2 in Appendix A.

### **3.4 Creep Test**

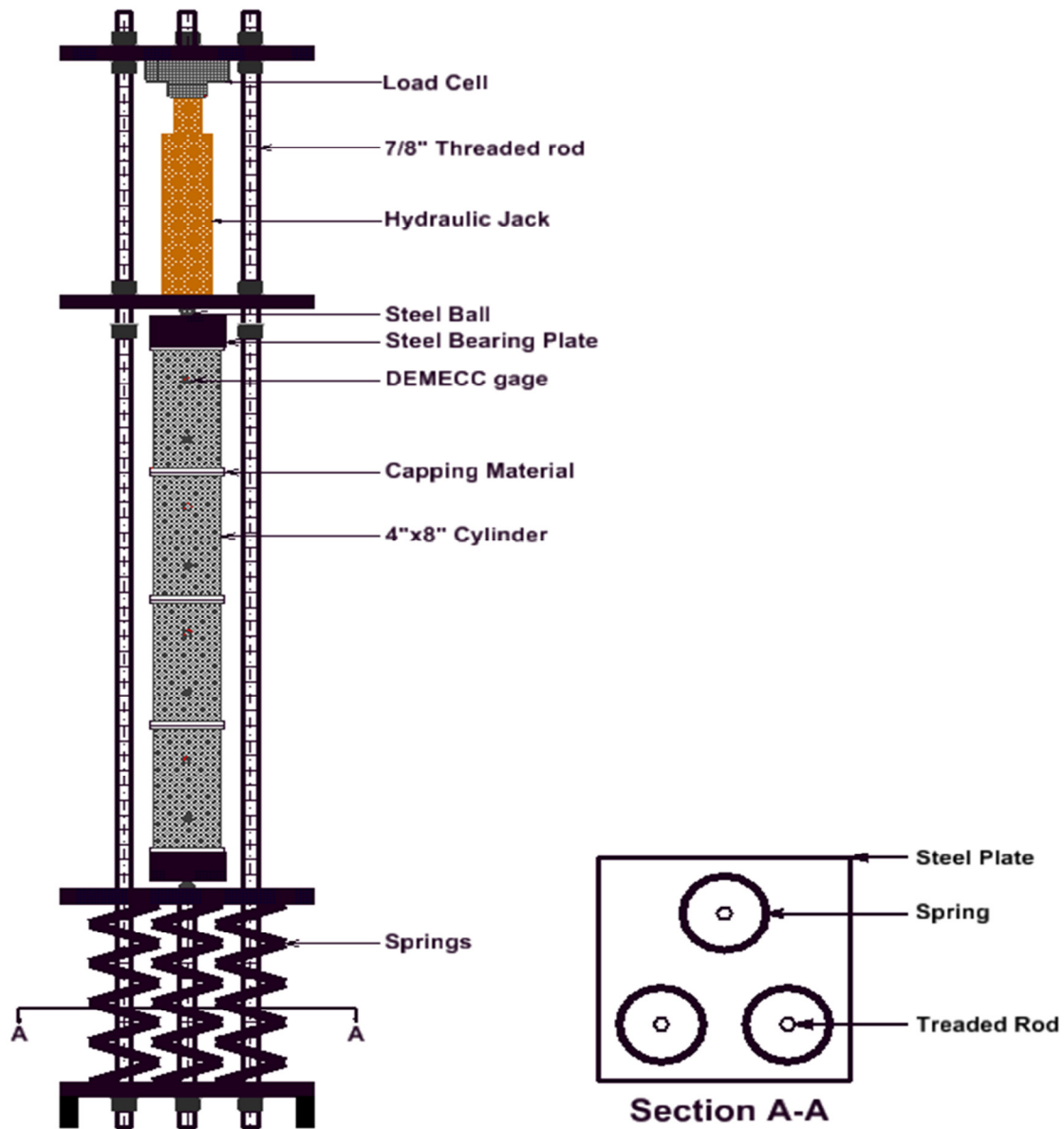
#### **3.4.1 Introduction**

Creep test in compression was performed according to ASTM C 512 (2002). Creep frame, loading of creep test, storage of specimens, device and method of measurements are presented in the following sections.

#### **3.4.2 Creep frame**

Creep frame was designed and assembled in accordance with ASTM C512 (2002). Figure 3.1 shows the details of a creep frame. For each steel plate in the creep frame the locations of three holes for thread rods and the geometry center of the triangle of three holes

were carefully determined. Steel nuts were also carefully selected in order to minimize the relaxation of the frame after loading application.



**Figure 3.1.** Details of a creep frame



### 3.4.3 Loading of creep test

Constant stress was applied in all creep frames, and the magnitude was 2125 psi. A load cell and a hydraulic jack were used to apply the load in the creep frame shown in Figure 3.1, and they were removed after loading application. In order to apply the load at the same location each time, a circle that fit the bottom shape of the hydraulic jack was drawn. Load was re-applied every time before measurements due to the relaxation of creep frame after loading application, and the tolerance of load variation was 2% according to ASTM C512 (2002).

### 3.4.4 Storage condition of specimens

Specimens for creep test, shrinkage test and 28-day compressive strength test were stored in an environmentally controlled chamber, in which the temperature was  $73.4 \pm 2.0$  °F ( $23.0 \pm 1.1$  °C) and the relative humidity was  $50 \pm 4$  %. For each mix four 4 by 8 in. cylindrical specimens were stacked in each creep frame and four specimens were placed on the wood shelf without loading. Photos of creep test and shrinkage test are shown in Figure A. 3 and Figure A. 4 in Appendix A.

### 3.4.5 Device and method of measurements

Demountable mechanical (DEMEC) strain gauge was used to measure the change of length between two vertical gage points with a length of 4 inches. The DEMEC gage had the precision of 0.00005 in. On each specimen three sides of vertical gage points were located. For each measurement, three instantaneous readings were obtained from each side of gage points, and the average was used as the reading of this side. If the difference of those three readings was greater than 0.00010 in, additional three measurements were taken and the average of total six readings was used as the reading of the two gage points. Photos of DEMEC gage and measurement are shown in Figure A. 5 in Appendix A.

Strain was the quotient of the change of length and the initial length between two gage points. Strain measured in loaded specimens in the creep frame was total strain, and strain measured in unloaded specimens was shrinkage strain. Sealed and unsealed creep strain could be calculated by subtracting sealed and unsealed shrinkage strain from total sealed and unsealed

strain with a change of time. Creep coefficient was the ratio of creep strain and instantaneous strain after loading application.

### **3.5 Shrinkage Test**

Shrinkage specimens were unloaded specimens stored in the same chamber with loaded specimens. Shrinkage strain was measured in the unloaded specimens at the same time with total strain in the loaded specimens.

### **3.6 Shrinkage Behavior of 4-ft Beam Section**

In order to correlate the shrinkage behavior of actual beam and specimens in the laboratory, a BTB beam section with a length of 4 feet was cast and stored in the yard of precast plant A. Strands in the beam section were debonded by using plastics and grease. DEMEC gauge and gage points were used to measure the strain of the beam section. Each group of two gage points was glued on the surface of the middle part of the beam section horizontally, and there were 6 groups of gage points along one side and 7 groups along the other side. Four temperature sensing thermistor probes attached with wires were located in the beam section when the beam section was cast. Three probes were laid at the bottom flange, web and top flange along the center of the cross section at the center of beam section, and the rest was placed near the end of the top flange. A handled thermistor thermometer was used to obtain the reading from the thermistor probes. Photo of this beam section is shown in Figure A. 6 in Appendix A.

Four 4 by 8 in. cylindrical specimens were also cast along with the beam section, and those specimens were transported to the laboratory for shrinkage tests at the same day of the release of the beam section. Two cylindrical specimens were sealed and the other two were unsealed.

### **3.7 Measurements of Long-Term Camber of Prestressed Girders**

The long-term cambers of 26 prestressed bridge girders were monitored after the production at the precast plant until the bridge deck was placed. The camber of a prestressed bridge girder was the difference of elevation between the midspan and the two edges of the girder. The elevations were measured at the top flange of a girder by using an accurate laser level. For the measurement of each section three readings were taken along the width of the top flange, including two edges and middle of the top flange. The average of three readings was used as the effective elevation at that section, and elevation difference between the midspan and the average of two ends of the girder was the measured camber of a girder.

The measured camber changed with time. Before the girder was shipped to the construction site, it was stored in the yard of the precast plant. Typically wood supports were not located at the end of a girder, and there existed an overhang with a varying length from the center of the support to the end of a girder. The overhang length of a girder stored in the yard could be changed by the precast plant to adjust the camber of a girder. If the camber was smaller than the desired value, the length of overhang could be increased to increase the camber during a certain period. Overhang length could also be decreased to decrease the camber. Sometimes a certain weight could be applied at the top flange of a girder to decrease the camber quickly within a certain period. The overhang had an influence of the camber of a girder, which was discussed in 2.4.1.3. The length of an overhang was measured, and it was used to adjust the measured camber of a girder for comparison with the camber without an overhang.

## CHAPTER 4 RESULTS

### 4.1 Introduction

This chapter discusses the results of tests and measurements. Compressive strength and modulus of elasticity are presented in Section 4.2 and Section 4.3. Measurements of creep and shrinkage tests are shown in Section 4.4. Results of long-term cambers of 26 prestressed girders are presented in Section 4.5.

### 4.2 Compressive Strength

For each mix 1-day and 28-day compressive strength were measured, and the results shown below are the average magnitude, standard deviation and maximum difference in percent of three measurements. Table 4.1 shows the results of the 1-day compressive strength test, and Table 4.2 summarizes the results of 28-day compressive strength test. Maximum difference of three specimens ranges from 4% to 11% for 1-day compressive strength test, and from 2% to 10% for 28-day compressive strength, which are less than the limit value of 14% according to ASTM C39 (2004). The results of compressive strength tests are acceptable.

**Table 4.1.** Results of 1-day compressive strength test

| Mix I.D.                              | HPC 1 | HPC 2 | HPC 3 | HPC 4 | NC 1 | NC 2 | NC 3 |
|---------------------------------------|-------|-------|-------|-------|------|------|------|
| Average 1-Day Strength, psi           | 6784  | 6247  | 5417  | 6640  | 8902 | 6547 | 9750 |
| Standard Deviation, psi               | 182   | 116   | 132   | 91    | 89   | 55   | 123  |
| Maximum Difference of Three Specimens | 9%    | 8%    | 11%   | 6%    | 4%   | 4%   | 5%   |

**Table 4.2.** Results of 28-day compressive strength test

| Mix I.D.                              | HPC 1 | HPC 2 | HPC 3 | HPC 4 | NC 1  | NC 2 | NC 3  |
|---------------------------------------|-------|-------|-------|-------|-------|------|-------|
| Average 28-Day Strength, psi          | 8750  | 7938  | 6884  | 8212  | 10215 | 7545 | 11020 |
| Standard Deviation, psi               | 86    | 35    | 161   | 106   | 58    | 132  | 227   |
| Maximum Difference of Three Specimens | 4%    | 2%    | 10%   | 6%    | 5%    | 7%   | 9%    |

### 4.3 Modulus of Elasticity

Elastic modulus of elasticity is the quotient of applied stress and elastic shortening measured in the creep test immediately before and after the loading application at 1-day. The average magnitude and standard deviation for each mix are summarized in Table 4.3 for sealed specimens and Table 4.4 for unsealed specimens.

**Table 4.3.** Results of modulus of elasticity for sealed specimens

| Mix I.D.                   | HPC 1 | HPC 2 | HPC 3 | HPC 4 | NC 1 | NC 2 | NC 3 |
|----------------------------|-------|-------|-------|-------|------|------|------|
| Modulus of Elasticity, ksi | 4870  | 5596  | 5226  | 5629  | 5425 | 4399 | 4671 |
| Standard Deviation, ksi    | 306   | 593   | 517   | 389   | 369  | 202  | 442  |

**Table 4.4.** Results of modulus of elasticity for unsealed specimens

| Mix I.D.                   | HPC 1 | HPC 2 | HPC 3 | HPC 4 | NC 1 | NC 2 | NC 3 |
|----------------------------|-------|-------|-------|-------|------|------|------|
| Modulus of Elasticity, ksi | 3216  | 3105  | 4080  | 5129  | 5602 | 5027 | 4297 |
| Standard Deviation, ksi    | 91    | 233   | 324   | 413   | 543  | 480  | 302  |

## 4.4 Creep and Shrinkage

Table 4.5 summarizes the stress-strength ratio of creep tests. It is found that stress-strength ratio has a range from 0.31 to 0.39 for four HPC mixes, and from 0.22 to 0.32 for three NC mixes. Stress-strength ratios are less than 0.40, which is the limit of linear theory provided by ASTM C512 (2002) mentioned previously. Detailed results of creep and shrinkage tests for seven mixes are shown from Table 4.9 to Table 4.16. In those tables, there are two “0” values for “Time after Loading”, which stand for before and after loading application.

**Table 4.5.** Stress-strength ratio of creep tests

| Mix I.D.                    | HPC 1 | HPC 2 | HPC 3 | HPC 4 | NC 1 | NC 2 | NC 3 |
|-----------------------------|-------|-------|-------|-------|------|------|------|
| Average 1-Day Strength, psi | 6784  | 6247  | 5417  | 6640  | 8902 | 6547 | 9750 |
| Applied Stress, psi         | 2125  | 2125  | 2125  | 2125  | 2125 | 2125 | 2125 |
| Stress-strength Ratio       | 0.31  | 0.34  | 0.39  | 0.32  | 0.24 | 0.32 | 0.22 |

From Table 4.6 to Table 4.8, the results of creep and shrinkage tests are shown, including 3-month, 6-month and 1-year. According to those data, the following are observed:

- Unsealed total strain for each mix is higher than sealed total strain ranging from 6% to 52% at 3-month, from 5% to 53% at 6-month and from 0% to 63% at 1-year;
- Unsealed shrinkage strain for each mix is higher than sealed shrinkage strain with a range from 17% to 106%, from 17% to 120% and from 18% to 169%;
- Unsealed total strain of HPC 4 mix is higher than the rest of six mixes ranging from 3% to 43% at 3-month, and unsealed total strain of HPC 2 is higher than the rest of six mixes ranging from 2% to 45% at 6-month and ranging from 4% to 51% at 1-year. HPC 3 mix has the lowest unsealed total strain at 3-month, 6-month and 1-year;
- Sealed total strain of HPC 1 mix is higher than the rest of six mixes ranging from 19% to 29% at 3-month, from 19% to 28% at 6-month and from 6% to 19% at 1-year. NC 2 mix has the lowest sealed total strain at 3-month and 6-month, and NC 1 mix has the lowest sealed total strain at 1-year;
- Unsealed shrinkage strain of HPC 3 mix is higher than the rest of six mixes ranging from 14% to 59% at 3-month and from 12% to 41% at 6-month, and unsealed shrinkage strain

of HPC 1 is higher than the rest of six mixes in a range from 8% to 63% at 1-year. HPC 2 mix has the lowest unsealed shrinkage strain at 3-month, HPC 4 mix has the lowest unsealed shrinkage strain at 6-month and at 1-year;

- Sealed shrinkage strain of HPC 3 mix is higher than the rest of six mixes ranging from 40% to 101% at 3-month, from 12% to 117% at 6-month, and from 27% to 92% at 1-year. NC 2 mix has the lowest sealed shrinkage strain at 3-month and 6-month, and HPC 1 mix has the lowest sealed shrinkage strain at 1-year;
- HPC 2 mix has the highest unsealed and sealed creep coefficient during one year. HPC 2 mix has higher unsealed creep coefficient ranging from 13% to 163% and higher sealed creep coefficient ranging from 23% to 96% than the rest of six mixes at 3-month. HPC 2 mix has higher unsealed creep coefficient ranging from 20% to 165% and higher sealed creep coefficient ranging from 15% to 87% than the rest of six mixes at 6-month. HPC 2 mix has higher unsealed creep coefficient ranging from 35% to 154% and higher sealed creep coefficient ranging from 9% to 84% than the rest of six mixes at 1-year;
- Unsealed creep coefficient of NC 3 is lowest than the rest of six mixes at 3-month, and unsealed creep coefficient of HPC 3 is the lowest at 6-month and 1-year;
- Sealed creep coefficient of NC 3 is lowest than the rest of six mixes at 3-month, and unsealed creep coefficient of NC 1 is the lowest at 6-month and 1-year.

**Table 4.6.** Results of creep and shrinkage tests for seven mixes at 3-month

| Mix I.D. | Unsealed Total Strain, $10^{-6}$ in/in | Sealed Total Strain, $10^{-6}$ in/in | Unsealed Shrinkage Strain, $10^{-6}$ in/in | Sealed Shrinkage Strain, $10^{-6}$ in/in | Unsealed Creep Coefficient | Sealed Creep Coefficient |
|----------|--|--------------------------------------|--|--|----------------------------|--------------------------|
| HPC 1    | 1596                                   | 1292                                 | 353  | 171                                      | 0.62695                    | 0.84151                  |
| HPC 2    | 1587                                   | 1054                                 | 254  | 185                                      | 0.88825                    | 1.03454                  |
| HPC 3    | 1151                                   | 1088                                 | 404  | 344                                      | 0.37776                    | 0.73522                  |
| HPC 4    | 1650                                   | 1086                                 | 306  | 229                                      | 0.78334                    | 0.81871                  |
| NC 1     | 1196                                   | 1076                                 | 287  | 246                                      | 0.59498                    | 0.55266                  |
| NC 2     | 1254                                   | 979                                  | 315  | 157                                      | 0.47820                    | 0.58374                  |
| NC 3     | 1126                                   | 1005                                 | 278  | 204                                      | 0.33835                    | 0.52824                  |

**Table 4.7.** Results of creep and shrinkage tests for seven mixes at 6-month

| Mix I.D. | Unsealed Total Strain, $10^{-6}$ in/in | Sealed Total Strain, $10^{-6}$ in/in | Unsealed Shrinkage Strain, $10^{-6}$ in/in | Sealed Shrinkage Strain, $10^{-6}$ in/in | Unsealed Creep Coefficient | Sealed Creep Coefficient |
|----------|--|--------------------------------------|--|--|----------------------------|--------------------------|
| HPC 1    | 1698                                   | 1370                                 | 414  | 188                                      | 0.68093                    | 0.94038                  |
| HPC 2    | 1756                                   | 1149                                 | 344  | 260                                      | 0.99976                    | 1.08155                  |
| HPC 3    | 1212                                   | 1152                                 | 465  | 373                                      | 0.37749                    | 0.81697                  |
| HPC 4    | 1716                                   | 1145                                 | 330  | 251                                      | 0.83552                    | 0.88930                  |
| NC 1     | 1422                                   | 1178                                 | 391  | 333                                      | 0.80871                    | 0.57925                  |
| NC 2     | 1345                                   | 1068                                 | 358  | 172                                      | 0.56235                    | 0.71463                  |
| NC 3     | 1260                                   | 1190                                 | 375  | 277                                      | 0.40353                    | 0.72637                  |

**Table 4.8.** Results of creep and shrinkage tests for seven mixes at 1-year

| Mix I.D. | Unsealed Total Strain, $10^{-6}$ in/in | Sealed Total Strain, $10^{-6}$ in/in | Unsealed Shrinkage Strain, $10^{-6}$ in/in | Sealed Shrinkage Strain, $10^{-6}$ in/in | Unsealed Creep Coefficient | Sealed Creep Coefficient |
|----------|--|--------------------------------------|--|--|----------------------------|--------------------------|
| HPC 1    | 1942                                   | 1448                                 | 576  | 214                                      | 0.78800                    | 1.02522                  |
| HPC 2    | 2027                                   | 1245                                 | 429  | 324                                      | 1.26346                    | 1.15647                  |
| HPC 3    | 1345                                   | 1234                                 | 533  | 410                                      | 0.49840                    | 0.92176                  |
| HPC 4    | 1820                                   | 1249                                 | 353  | 263                                      | 0.93464                    | 1.06521                  |
| NC 1     | 1506                                   | 1217                                 | 443  | 344                                      | 0.86399                    | 0.62822                  |
| NC 2     | 1507                                   | 1353                                 | 425  | 360                                      | 0.73004                    | 0.88432                  |
| NC 3     | 1358                                   | 1360                                 | 375  | 285                                      | 0.54098                    | 1.01115                  |



**Table 4.9.** Results of creep and shrinkage test for HPC 1

| Time after Loading, days | Unsealed Total Strain, 10 <sup>-6</sup> in/in | Sta. Dev., 10 <sup>-6</sup> in/in | Sealed Total Strain, 10 <sup>-6</sup> in/in | Sta. Dev., 10 <sup>-6</sup> in/in | Unsealed Shrinkage, 10 <sup>-6</sup> in/in | Sta. Dev., 10 <sup>-6</sup> in/in | Sealed Shrinkage, 10 <sup>-6</sup> in/in | Sta. Dev., 10 <sup>-6</sup> in/in | Unsealed Creep Coefficient | Sealed Creep Coefficient |
|--------------------------|---|-----------------------------------|---|-----------------------------------|--|-----------------------------------|--|-----------------------------------|----------------------------|--------------------------|
| 0                        | 0   | 0                                 | 0   | 0                                 | 0  | 0                                 | 0  | 0                                 | 0.00000                    | 0.00000                  |
| 0                        | 764   | 66                                | 609   | 46                                | 0  | 0                                 | 0  | 0                                 | 0.00000                    | 0.00000                  |
| 1                        | 898   | 53                                | 744   | 51                                | 98   | 8                                 | 31                                       | 23                                | 0.04613                    | 0.17186                  |
| 2                        | 1002  | 64                                | 794   | 55                                | 163  | 9                                 | 62                                       | 25                                | 0.09829                    | 0.20138                  |
| 3                        | 1031  | 50                                | 824   | 68                                | 166  | 7                                 | 59                                       | 21                                | 0.13338                    | 0.25699                  |
| 7                        | 1145  | 59                                | 916   | 64                                | 219  | 13                                | 74                                       | 18                                | 0.21138                    | 0.38265                  |
| 14                       | 1268  | 95                                | 1005  | 65                                | 276  | 13                                | 101                                      | 16                                | 0.29875                    | 0.48378                  |
| 21                       | 1323  | 97                                | 1041  | 65                                | 285  | 16                                | 115                                      | 19                                | 0.35857                    | 0.52042                  |
| 28                       | 1379  | 101                               | 1077  | 66                                | 295  | 19                                | 129                                      | 18                                | 0.41839                    | 0.55707                  |
| 60                       | 1543  | 117                               | 1227  | 73                                | 319  | 25                                | 151                                      | 21                                | 0.60306                    | 0.76635                  |
| 90                       | 1596  | 117                               | 1292  | 89                                | 353  | 27                                | 171                                      | 22                                | 0.62695                    | 0.84151                  |
| 120                      | 1631  | 119                               | 1330  | 96                                | 373  | 28                                | 180                                      | 25                                | 0.64573                    | 0.88788                  |
| 150                      | 1663  | 120                               | 1359  | 97                                | 392  | 29                                | 187                                      | 22                                | 0.66325                    | 0.92430                  |
| 180                      | 1698  | 122                               | 1370  | 92                                | 414  | 29                                | 188                                      | 23                                | 0.68093                    | 0.94038                  |
| 210                      | 1737  | 126                               | 1382  | 93                                | 433  | 29                                | 192                                      | 24                                | 0.70615                    | 0.95341                  |
| 240                      | 1760  | 128                               | 1388  | 93                                | 443  | 34                                | 197                                      | 24                                | 0.72343                    | 0.95564                  |
| 270                      | 1786  | 129                               | 1395  | 94                                | 453  | 29                                | 205                                      | 23                                | 0.74416                    | 0.95299                  |
| 300                      | 1867  | 129                               | 1420  | 93                                | 500  | 30                                | 213                                      | 25                                | 0.78917                    | 0.98059                  |
| 330                      | 1905  | 130                               | 1434  | 94                                | 538  | 38                                | 214                                      | 26                                | 0.78859                    | 1.00290                  |
| 360                      | 1942  | 132                               | 1448  | 95                                | 576  | 42                                | 214                                      | 32                                | 0.78800                    | 1.02522                  |
|                          | Average                                       | 103                               | Average                                     | 78                                | Average                                    | 22                                | Average                                  | 21                                |                            |                          |

**Table 4.10.** Results of creep and shrinkage test for HPC 2

| Time after Loading, days | Unsealed Total Strain, 10 <sup>-6</sup> in/in | Sta. Dev., 10 <sup>-6</sup> in/in | Sealed Total Strain, 10 <sup>-6</sup> in/in | Sta. Dev., 10 <sup>-6</sup> in/in | Unsealed Shrinkage, 10 <sup>-6</sup> in/in | Sta. Dev., 10 <sup>-6</sup> in/in | Sealed Shrinkage, 10 <sup>-6</sup> in/in | Sta. Dev., 10 <sup>-6</sup> in/in | Unsealed Creep Coefficient | Sealed Creep Coefficient |
|--------------------------|---|-----------------------------------|---|-----------------------------------|--|-----------------------------------|--|-----------------------------------|----------------------------|--------------------------|
| 0                        | 0   | 0                                 | 0   | 0                                 | 0  | 0                                 | 0  | 0                                 | 0.00000                    | 0.00000                  |
| 0                        | 706   | 47                                | 427   | 52                                | 0  | 0                                 | 0  | 0                                 | 0.00000                    | 0.00000                  |
| 1                        | 831   | 66                                | 535   | 62                                | 51   | 7                                 | 20                                       | 2                                 | 0.10519                    | 0.20649                  |
| 2                        | 880   | 70                                | 573   | 70                                | 76   | 11                                | 30                                       | 3                                 | 0.13924                    | 0.27289                  |
| 3                        | 976   | 66                                | 657   | 73                                | 125  | 13                                | 46                                       | 10                                | 0.20651                    | 0.42961                  |
| 7                        | 1092  | 68                                | 712   | 72                                | 132  | 17                                | 50                                       | 8                                 | 0.36018                    | 0.55016                  |
| 14                       | 1254  | 88                                | 789   | 71                                | 142  | 23                                | 54                                       | 9                                 | 0.57533                    | 0.71894                  |
| 21                       | 1365  | 108                               | 842   | 71                                | 150  | 29                                | 61                                       | 10                                | 0.72104                    | 0.82920                  |
| 28                       | 1429  | 119                               | 874   | 71                                | 157  | 33                                | 68                                       | 11                                | 0.80130                    | 0.88609                  |
| 60                       | 1530  | 123                               | 985   | 82                                | 216  | 38                                | 131                                      | 10                                | 0.86230                    | 0.99837                  |
| 90                       | 1587  | 136                               | 1054  | 76                                | 254  | 37                                | 185                                      | 10                                | 0.88825                    | 1.03454                  |
| 120                      | 1650  | 144                               | 1092  | 74                                | 287  | 37                                | 216                                      | 12                                | 0.93161                    | 1.05018                  |
| 150                      | 1707  | 143                               | 1127  | 69                                | 319  | 39                                | 245                                      | 12                                | 0.96715                    | 1.06514                  |
| 180                      | 1756  | 138                               | 1149  | 65                                | 344  | 40                                | 260                                      | 13                                | 0.99976                    | 1.08155                  |
| 210                      | 1805  | 133                               | 1166  | 65                                | 366  | 40                                | 269                                      | 13                                | 1.03922                    | 1.10117                  |
| 240                      | 1851  | 126                               | 1186  | 66                                | 383  | 40                                | 279                                      | 14                                | 1.07995                    | 1.12276                  |
| 270                      | 1884  | 123                               | 1203  | 65                                | 396  | 40                                | 290                                      | 14                                | 1.10826                    | 1.13770                  |
| 300                      | 1938  | 139                               | 1213  | 69                                | 404  | 45                                | 302                                      | 25                                | 1.17376                    | 1.13435                  |
| 330                      | 1979  | 137                               | 1231  | 70                                | 418  | 45                                | 313                                      | 26                                | 1.21172                    | 1.15021                  |
| 360                      | 2027  | 145                               | 1245  | 72                                | 429  | 48                                | 324                                      | 36                                | 1.26346                    | 1.15647                  |
|                          | Average                                       | 111                               | Average                                     | 69                                | Average                                    | 31                                | Average                                  | 13                                |                            |                          |

**Table 4.11.** Results of creep and shrinkage test for HPC 3

| Time after Loading, days | Unsealed Total Strain, 10 <sup>-6</sup> in/in | Sta. Dev., 10 <sup>-6</sup> in/in | Sealed Total Strain, 10 <sup>-6</sup> in/in | Sta. Dev., 10 <sup>-6</sup> in/in | Unsealed Shrinkage, 10 <sup>-6</sup> in/in | Sta. Dev., 10 <sup>-6</sup> in/in | Sealed Shrinkage, 10 <sup>-6</sup> in/in | Sta. Dev., 10 <sup>-6</sup> in/in | Unsealed Creep Coefficient | Sealed Creep Coefficient |
|--------------------------|---|-----------------------------------|---|-----------------------------------|--|-----------------------------------|--|-----------------------------------|----------------------------|--------------------------|
| 0                        | 0   | 0                                 | 0   | 0                                 | 0  | 0                                 | 0  | 0                                 | 0.00000                    | 0.00000                  |
| 0                        | 542   | 44                                | 429   | 38                                | 0  | 0                                 | 0  | 0                                 | 0.00000                    | 0.00000                  |
| 1                        | 687   | 60                                | 533   | 36                                | 105  | 9                                 | 36                                       | 6                                 | 0.07272                    | 0.15996                  |
| 2                        | 852   | 82                                | 657   | 38                                | 147  | 7                                 | 73                                       | 12                                | 0.30072                    | 0.36042                  |
| 3                        | 873   | 79                                | 685   | 38                                | 164  | 11                                | 90                                       | 16                                | 0.30802                    | 0.38626                  |
| 7                        | 997   | 62                                | 856   | 47                                | 265  | 10                                | 195                                      | 15                                | 0.35181                    | 0.54134                  |
| 14                       | 1009  | 55                                | 885   | 46                                | 277  | 10                                | 214                                      | 13                                | 0.35113                    | 0.56266                  |
| 21                       | 1026  | 50                                | 925   | 44                                | 295  | 10                                | 242                                      | 12                                | 0.35019                    | 0.59250                  |
| 28                       | 1048  | 54                                | 977   | 41                                | 317  | 10                                | 277                                      | 14                                | 0.34897                    | 0.63087                  |
| 60                       | 1088  | 63                                | 1033  | 45                                | 351  | 16                                | 311                                      | 13                                | 0.35959                    | 0.68287                  |
| 90                       | 1151  | 85                                | 1088  | 62                                | 404  | 16                                | 344                                      | 13                                | 0.37776                    | 0.73522                  |
| 120                      | 1165  | 83                                | 1103  | 61                                | 418  | 16                                | 352                                      | 14                                | 0.37773                    | 0.75161                  |
| 150                      | 1192  | 80                                | 1129  | 59                                | 445  | 17                                | 365                                      | 15                                | 0.37764                    | 0.78198                  |
| 180                      | 1212  | 80                                | 1152  | 55                                | 465  | 19                                | 373                                      | 16                                | 0.37749                    | 0.81697                  |
| 210                      | 1226  | 79                                | 1170  | 52                                | 478  | 21                                | 381                                      | 19                                | 0.38106                    | 0.84013                  |
| 240                      | 1247  | 78                                | 1179  | 50                                | 486  | 23                                | 389                                      | 16                                | 0.40511                    | 0.84229                  |
| 270                      | 1274  | 87                                | 1196  | 60                                | 500  | 21                                | 392                                      | 15                                | 0.42800                    | 0.87278                  |
| 300                      | 1296  | 90                                | 1207  | 62                                | 509  | 24                                | 399                                      | 18                                | 0.45176                    | 0.88203                  |
| 330                      | 1321  | 102                               | 1221  | 71                                | 522  | 29                                | 404                                      | 20                                | 0.47493                    | 0.90544                  |
| 360                      | 1345  | 112                               | 1234  | 77                                | 533  | 26                                | 410                                      | 22                                | 0.49840                    | 0.92176                  |
|                          | Average                                       | 75                                | Average                                     | 52                                | Average                                    | 16                                | Average                                  | 14                                |                            |                          |

**Table 4.12.** Results of creep and shrinkage test for HPC 4

| Time after Loading, days | Unsealed Total Strain, 10 <sup>-6</sup> in/in | Sta. Dev., 10 <sup>-6</sup> in/in | Sealed Total Strain, 10 <sup>-6</sup> in/in | Sta. Dev., 10 <sup>-6</sup> in/in | Unsealed Shrinkage, 10 <sup>-6</sup> in/in | Sta. Dev., 10 <sup>-6</sup> in/in | Sealed Shrinkage, 10 <sup>-6</sup> in/in | Sta. Dev., 10 <sup>-6</sup> in/in | Unsealed Creep Coefficient | Sealed Creep Coefficient |
|--------------------------|---|-----------------------------------|---|-----------------------------------|--|-----------------------------------|--|-----------------------------------|----------------------------|--------------------------|
| 0                        | 0   | 0                                 | 0   | 0                                 | 0  | 0                                 | 0  | 0                                 | 0.00000                    | 0.00000                  |
| 0                        | 814   | 53                                | 525   | 32                                | 0  | 0                                 | 0  | 0                                 | 0.00000                    | 0.00000                  |
| 1                        | 870   | 55                                | 540   | 27                                | 22   | 9                                 | 17                                       | 5                                 | 0.20137                    | 0.21487                  |
| 2                        | 919   | 57                                | 579   | 29                                | 33   | 11                                | 26                                       | 7                                 | 0.22125                    | 0.24085                  |
| 3                        | 959   | 60                                | 604   | 34                                | 51   | 12                                | 40                                       | 9                                 | 0.24892                    | 0.26184                  |
| 7                        | 1145  | 77                                | 719   | 60                                | 133  | 14                                | 103                                      | 14                                | 0.37690                    | 0.35891                  |
| 14                       | 1334  | 99                                | 874   | 60                                | 229  | 16                                | 160                                      | 15                                | 0.49110                    | 0.54802                  |
| 21                       | 1459  | 108                               | 959   | 67                                | 286  | 35                                | 212                                      | 19                                | 0.57438                    | 0.61062                  |
| 28                       | 1493  | 107                               | 983   | 63                                | 293  | 38                                | 220                                      | 24                                | 0.60676                    | 0.63966                  |
| 60                       | 1581  | 109                               | 1044  | 51                                | 296  | 42                                | 225                                      | 28                                | 0.71138                    | 0.74767                  |
| 90                       | 1650  | 120                               | 1086  | 52                                | 306  | 40                                | 229                                      | 33                                | 0.78334                    | 0.81871                  |
| 120                      | 1683  | 128                               | 1113  | 51                                | 312  | 38                                | 235                                      | 27                                | 0.81742                    | 0.86035                  |
| 150                      | 1701  | 131                               | 1133  | 65                                | 319  | 36                                | 244                                      | 23                                | 0.83024                    | 0.87970                  |
| 180                      | 1716  | 143                               | 1145  | 73                                | 330  | 48                                | 251                                      | 29                                | 0.83552                    | 0.88930                  |
| 210                      | 1732  | 151                               | 1155  | 81                                | 341  | 46                                | 259                                      | 36                                | 0.84156                    | 0.89390                  |
| 240                      | 1750  | 158                               | 1174  | 86                                | 344  | 49                                | 260                                      | 38                                | 0.86018                    | 0.92817                  |
| 270                      | 1768  | 162                               | 1197  | 97                                | 342  | 57                                | 257                                      | 43                                | 0.88508                    | 0.97726                  |
| 300                      | 1785  | 164                               | 1214  | 104                               | 345  | 59                                | 259                                      | 46                                | 0.90160                    | 1.00658                  |
| 330                      | 1802  | 167                               | 1230  | 109                               | 351  | 61                                | 262                                      | 48                                | 0.91603                    | 1.03095                  |
| 360                      | 1820  | 172                               | 1249  | 114                               | 353  | 63                                | 263                                      | 45                                | 0.93464                    | 1.06521                  |
|                          | Average                                       | 117                               | Average                                     | 66                                | Average                                    | 33                                | Average                                  | 25                                |                            |                          |

**Table 4.13.** Results of creep and shrinkage test for NC 1

| Time after Loading, days | Unsealed Total Strain, 10 <sup>-6</sup> in/in | Sta. Dev., 10 <sup>-6</sup> in/in | Sealed Total Strain, 10 <sup>-6</sup> in/in | Sta. Dev., 10 <sup>-6</sup> in/in | Unsealed Shrinkage, 10 <sup>-6</sup> in/in | Sta. Dev., 10 <sup>-6</sup> in/in | Sealed Shrinkage, 10 <sup>-6</sup> in/in | Sta. Dev., 10 <sup>-6</sup> in/in | Unsealed Creep Coefficient | Sealed Creep Coefficient |
|--------------------------|---|-----------------------------------|---|-----------------------------------|--|-----------------------------------|--|-----------------------------------|----------------------------|--------------------------|
| 0                        | 0   | 0                                 | 0   | 0                                 | 0  | 0                                 | 0  | 0                                 | 0.00000                    | 0.00000                  |
| 0                        | 570   | 91                                | 515   | 68                                | 0  | 0                                 | 0  | 0                                 | 0.00000                    | 0.00000                  |
| 1                        | 604   | 92                                | 538   | 69                                | 25   | 7                                 | 19                                       | 6                                 | 0.06025                    | 0.03997                  |
| 2                        | 665   | 113                               | 596   | 109                               | 40   | 9                                 | 30                                       | 8                                 | 0.09649                    | 0.08978                  |
| 3                        | 714   | 126                               | 654   | 117                               | 68   | 11                                | 59                                       | 13                                | 0.13272                    | 0.13959                  |
| 7                        | 845   | 137                               | 797   | 123                               | 150  | 18                                | 130                                      | 15                                | 0.21936                    | 0.26657                  |
| 14                       | 901   | 189                               | 869   | 142                               | 185  | 23                                | 161                                      | 16                                | 0.25714                    | 0.33955                  |
| 21                       | 928   | 212                               | 890   | 153                               | 193  | 27                                | 167                                      | 18                                | 0.28914                    | 0.36494                  |
| 28                       | 944   | 206                               | 903   | 162                               | 199  | 31                                | 171                                      | 24                                | 0.30834                    | 0.38016                  |
| 60                       | 1105  | 217                               | 1025  | 172                               | 253  | 39                                | 216                                      | 27                                | 0.49544                    | 0.51619                  |
| 90                       | 1196  | 231                               | 1076  | 182                               | 287  | 37                                | 246                                      | 28                                | 0.59498                    | 0.55266                  |
| 120                      | 1295  | 230                               | 1114  | 200                               | 328  | 38                                | 278                                      | 29                                | 0.69625                    | 0.56393                  |
| 150                      | 1379  | 225                               | 1150  | 193                               | 369  | 41                                | 312                                      | 32                                | 0.77192                    | 0.56711                  |
| 180                      | 1422  | 227                               | 1178  | 197                               | 391  | 42                                | 333                                      | 37                                | 0.80871                    | 0.57925                  |
| 210                      | 1442  | 226                               | 1190  | 189                               | 397  | 49                                | 338                                      | 39                                | 0.83287                    | 0.59197                  |
| 240                      | 1455  | 228                               | 1195  | 210                               | 406  | 50                                | 339                                      | 34                                | 0.83909                    | 0.59922                  |
| 270                      | 1464  | 254                               | 1197  | 208                               | 417  | 59                                | 338                                      | 36                                | 0.83635                    | 0.60374                  |
| 300                      | 1478  | 267                               | 1204  | 194                               | 426  | 69                                | 340                                      | 43                                | 0.84556                    | 0.61190                  |
| 330                      | 1493  | 284                               | 1212  | 186                               | 434  | 69                                | 343                                      | 48                                | 0.85776                    | 0.62097                  |
| 360                      | 1506  | 289                               | 1217  | 203                               | 443  | 67                                | 344                                      | 47                                | 0.86399                    | 0.62822                  |
|                          | Average                                       | 202                               | Average                                     | 162                               | Average                                    | 36                                | Average                                  | 26                                |                            |                          |

**Table 4.14.** Results of creep and shrinkage test for NC 2

| Time after Loading, days | Unsealed Total Strain, 10 <sup>-6</sup> in/in | Sta. Dev., 10 <sup>-6</sup> in/in | Sealed Total Strain, 10 <sup>-6</sup> in/in | Sta. Dev., 10 <sup>-6</sup> in/in | Unsealed Shrinkage, 10 <sup>-6</sup> in/in | Sta. Dev., 10 <sup>-6</sup> in/in | Sealed Shrinkage, 10 <sup>-6</sup> in/in | Sta. Dev., 10 <sup>-6</sup> in/in | Unsealed Creep Coefficient | Sealed Creep Coefficient |
|--------------------------|---|-----------------------------------|---|-----------------------------------|--|-----------------------------------|--|-----------------------------------|----------------------------|--------------------------|
| 0                        | 0   | 0                                 | 0   | 0                                 | 0  | 0                                 | 0  | 0                                 | 0.00000                    | 0.00000                  |
| 0                        | 666   | 75                                | 489   | 36                                | 0  | 0                                 | 0  | 0                                 | 0.00000                    | 0.00000                  |
| 1                        | 791   | 83                                | 564   | 46                                | 130  | 14                                | 70                                       | 8                                 | -0.00768                   | 0.00779                  |
| 2                        | 841   | 94                                | 604   | 49                                | 161  | 16                                | 73                                       | 11                                | 0.02393                    | 0.07495                  |
| 3                        | 940   | 110                               | 685   | 53                                | 225  | 20                                | 77                                       | 14                                | 0.08715                    | 0.20926                  |
| 7                        | 984   | 117                               | 727   | 56                                | 236  | 22                                | 91                                       | 17                                | 0.14514                    | 0.25892                  |
| 14                       | 1069  | 118                               | 802   | 55                                | 259  | 27                                | 122                                      | 25                                | 0.25188                    | 0.33585                  |
| 21                       | 1108  | 124                               | 835   | 66                                | 271  | 28                                | 139                                      | 30                                | 0.30063                    | 0.36312                  |
| 28                       | 1138  | 129                               | 862   | 83                                | 279  | 30                                | 141                                      | 33                                | 0.33857                    | 0.40630                  |
| 60                       | 1214  | 131                               | 936   | 89                                | 299  | 34                                | 150                                      | 40                                | 0.43608                    | 0.52148                  |
| 90                       | 1254  | 135                               | 979   | 95                                | 315  | 39                                | 157                                      | 47                                | 0.47820                    | 0.58374                  |
| 120                      | 1280  | 135                               | 1008  | 98                                | 330  | 40                                | 161                                      | 46                                | 0.49850                    | 0.62707                  |
| 150                      | 1321  | 119                               | 1053  | 91                                | 352  | 45                                | 165                                      | 44                                | 0.53189                    | 0.70029                  |
| 180                      | 1345  | 123                               | 1068  | 103                               | 358  | 55                                | 172                                      | 46                                | 0.56235                    | 0.71463                  |
| 210                      | 1381  | 129                               | 1136  | 115                               | 373  | 59                                | 218                                      | 45                                | 0.60038                    | 0.75244                  |
| 240                      | 1411  | 135                               | 1203  | 107                               | 387  | 60                                | 265                                      | 49                                | 0.62798                    | 0.78744                  |
| 270                      | 1437  | 149                               | 1236  | 119                               | 396  | 69                                | 286                                      | 53                                | 0.65742                    | 0.80916                  |
| 300                      | 1465  | 152                               | 1292  | 122                               | 408  | 69                                | 325                                      | 56                                | 0.68564                    | 0.83973                  |
| 330                      | 1492  | 158                               | 1337  | 136                               | 419  | 68                                | 354                                      | 52                                | 0.71447                    | 0.86587                  |
| 360                      | 1507  | 164                               | 1353  | 144                               | 425  | 77                                | 360                                      | 59                                | 0.73004                    | 0.88432                  |
|                          | Average                                       | 125                               | Average                                     | 88                                | Average                                    | 40                                | Average                                  | 35                                |                            |                          |

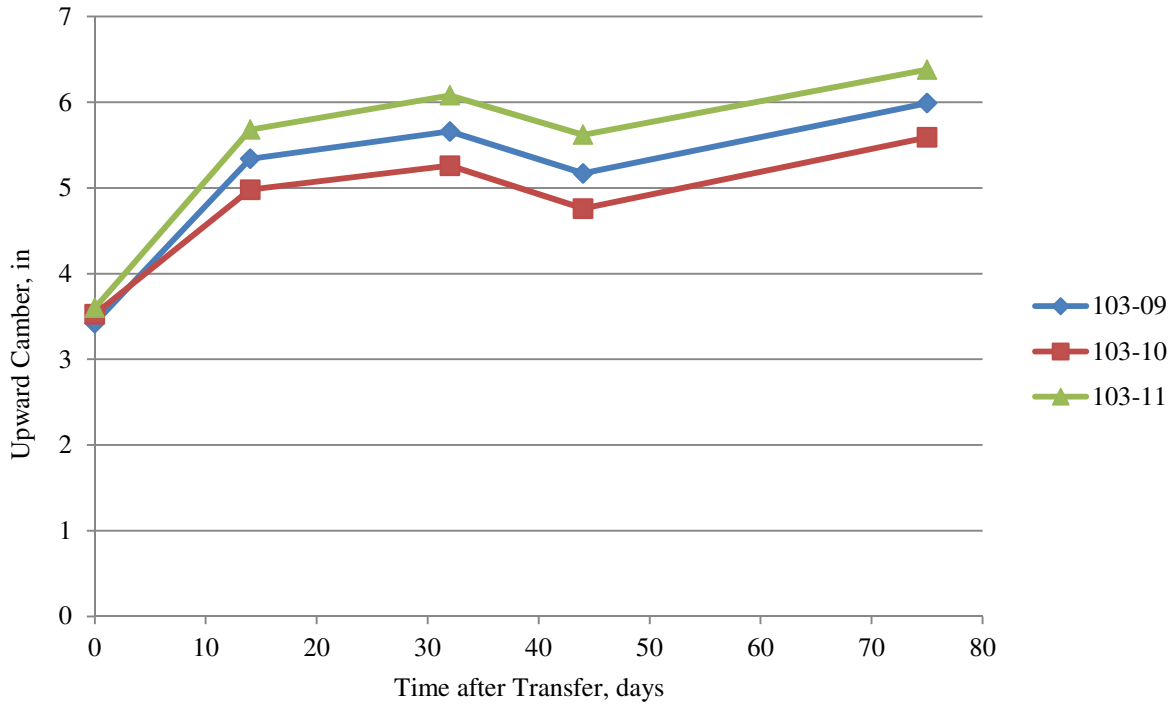
**Table 4.15.** Results of creep and shrinkage test for NC 3

| Time after Loading, days | Unsealed Total Strain, 10 <sup>-6</sup> in/in | Sta. Dev., 10 <sup>-6</sup> in/in | Sealed Total Strain, 10 <sup>-6</sup> in/in | Sta. Dev., 10 <sup>-6</sup> in/in | Unsealed Shrinkage, 10 <sup>-6</sup> in/in | Sta. Dev., 10 <sup>-6</sup> in/in | Sealed Shrinkage, 10 <sup>-6</sup> in/in | Sta. Dev., 10 <sup>-6</sup> in/in | Unsealed Creep Coefficient | Sealed Creep Coefficient |
|--------------------------|---|-----------------------------------|---|-----------------------------------|--|-----------------------------------|--|-----------------------------------|----------------------------|--------------------------|
| 0                        | 0   | 0                                 | 0   | 0                                 | 0  | 0                                 | 0  | 0                                 | 0.00000                    | 0.00000                  |
| 0                        | 655   | 75                                | 499   | 28                                | 0  | 0                                 | 0  | 0                                 | 0.00000                    | 0.00000                  |
| 1                        | 677   | 77                                | 545   | 32                                | 14   | 9                                 | 9  | 5                                 | 0.01379                    | 0.06562                  |
| 2                        | 694   | 84                                | 578   | 39                                | 28   | 11                                | 18                                       | 8                                 | 0.01916                    | 0.10648                  |
| 3                        | 711   | 91                                | 610   | 43                                | 42   | 14                                | 27                                       | 11                                | 0.02452                    | 0.14733                  |
| 7                        | 753   | 98                                | 667   | 46                                | 67   | 19                                | 48                                       | 15                                | 0.05440                    | 0.21115                  |
| 14                       | 839   | 108                               | 753   | 55                                | 104  | 25                                | 88                                       | 21                                | 0.14018                    | 0.29153                  |
| 21                       | 876   | 117                               | 777   | 69                                | 126  | 24                                | 99                                       | 22                                | 0.16816                    | 0.31410                  |
| 28                       | 1012  | 109                               | 864   | 73                                | 204  | 24                                | 140                                      | 27                                | 0.26889                    | 0.39536                  |
| 60                       | 1084  | 123                               | 946   | 79                                | 252  | 28                                | 180                                      | 37                                | 0.31187                    | 0.46723                  |
| 90                       | 1126  | 127                               | 1005  | 84                                | 278  | 29                                | 204                                      | 41                                | 0.33835                    | 0.52824                  |
| 120                      | 1179  | 139                               | 1074  | 89                                | 315  | 32                                | 233                                      | 43                                | 0.36531                    | 0.60072                  |
| 150                      | 1230  | 127                               | 1145  | 96                                | 353  | 34                                | 261                                      | 47                                | 0.38972                    | 0.67654                  |
| 180                      | 1260  | 149                               | 1190  | 99                                | 375  | 29                                | 277                                      | 43                                | 0.40353                    | 0.72637                  |
| 210                      | 1270  | 143                               | 1203  | 117                               | 383  | 31                                | 281                                      | 42                                | 0.40667                    | 0.74236                  |
| 240                      | 1298  | 155                               | 1252  | 103                               | 387  | 38                                | 282                                      | 45                                | 0.44864                    | 0.82635                  |
| 270                      | 1313  | 167                               | 1283  | 114                               | 383  | 34                                | 280                                      | 48                                | 0.48179                    | 0.88451                  |
| 300                      | 1331  | 156                               | 1311  | 135                               | 391  | 49                                | 283                                      | 51                                | 0.49901                    | 0.92715                  |
| 330                      | 1347  | 162                               | 1341  | 149                               | 392  | 52                                | 283                                      | 46                                | 0.52618                    | 0.97949                  |
| 360                      | 1358  | 178                               | 1360  | 157                               | 395  | 61                                | 285                                      | 53                                | 0.54098                    | 1.01115                  |
|                          | Average                                       | 126                               | Average                                     | 85                                | Average                                    | 27                                | Average                                  | 30                                |                            |                          |

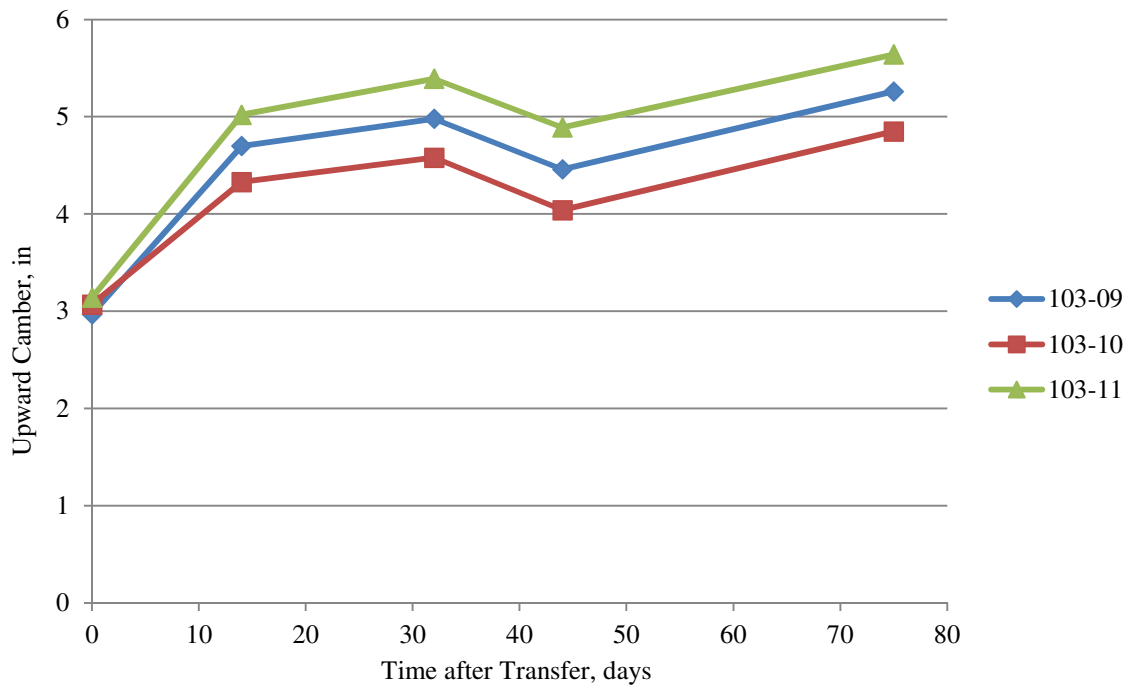
## 4.5 Long-term Camber of Prestressed Bridge Girders

Measured cambers of 26 prestressed bridge girders with overhang and adjusted cambers without overhang are shown from Figure 4.1 to Figure 4.8, including 3 BTC 120 girders produced by plant A, 9 BTE 110 girders and 6 BTE 145 girders cast by precast plant B, and 8 BTD 135 girders made by plant C. The equivalent modulus is used to adjust the measured upward camber, which is discussed in Section 2.4.1.3. It is found that overhang increases upward camber with time, and the extent of the effect increases with an increase of the length of overhang. The cross section properties and material properties of four types of girders are shown in Appendix E, in which figures of cross sections of girders are obtained from *Beam Standards Issued by Iowa DOT* (2012).

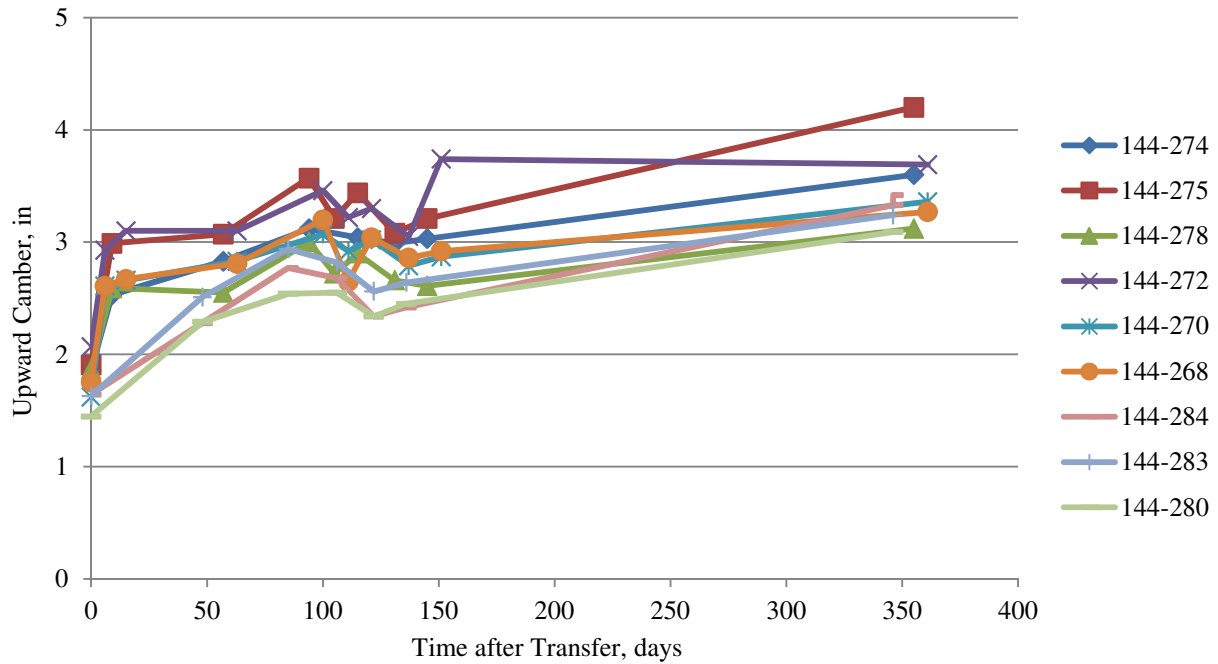




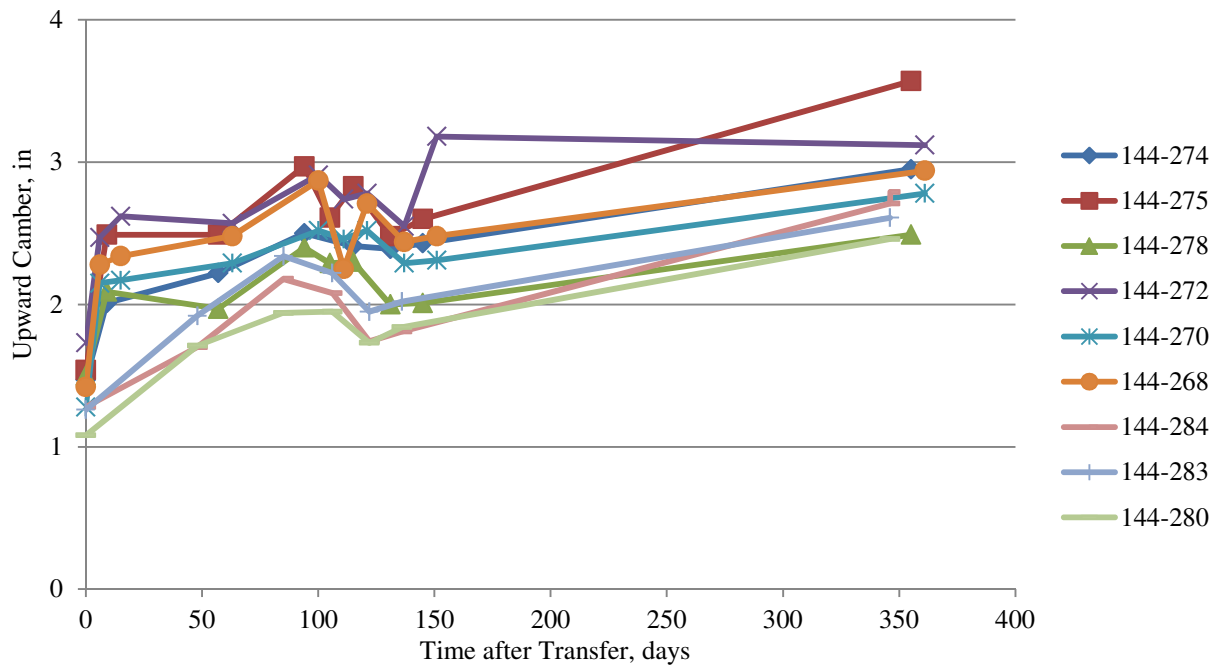
**Figure 4.1.** Measured upward camber of 3 BTC 120 prestressed bridge girders at plant A



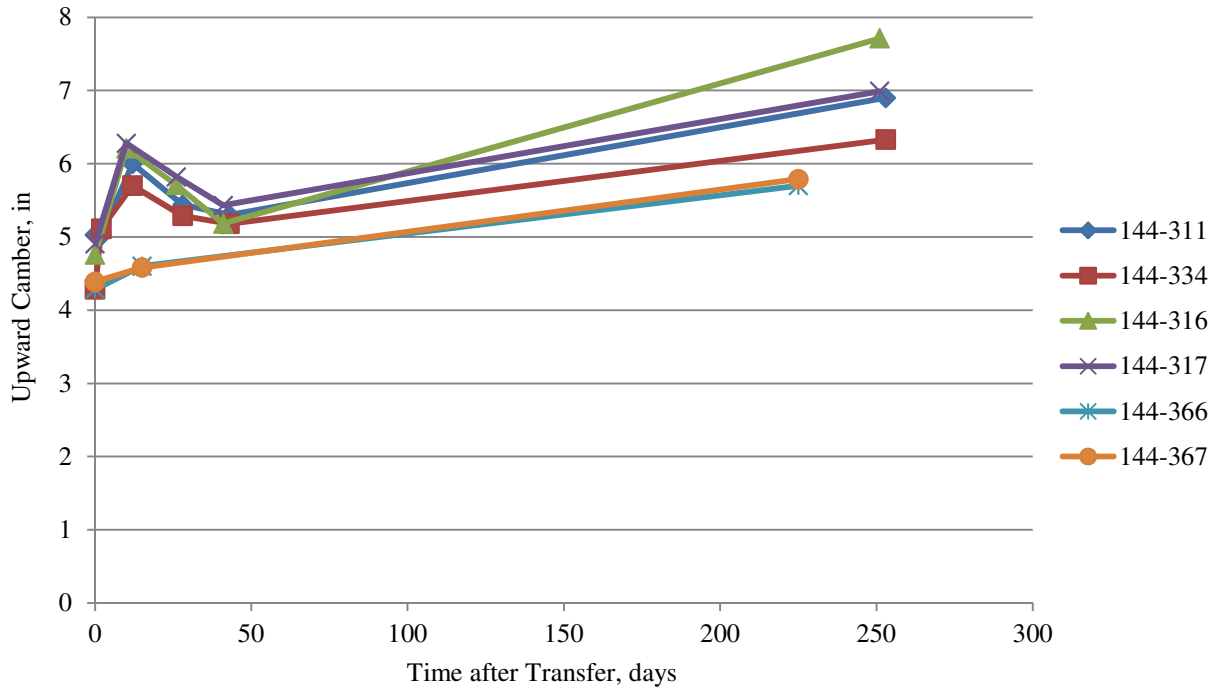
**Figure 4.2.** Adjusted upward camber of 3 BTC 120 prestressed bridge girders at plant A



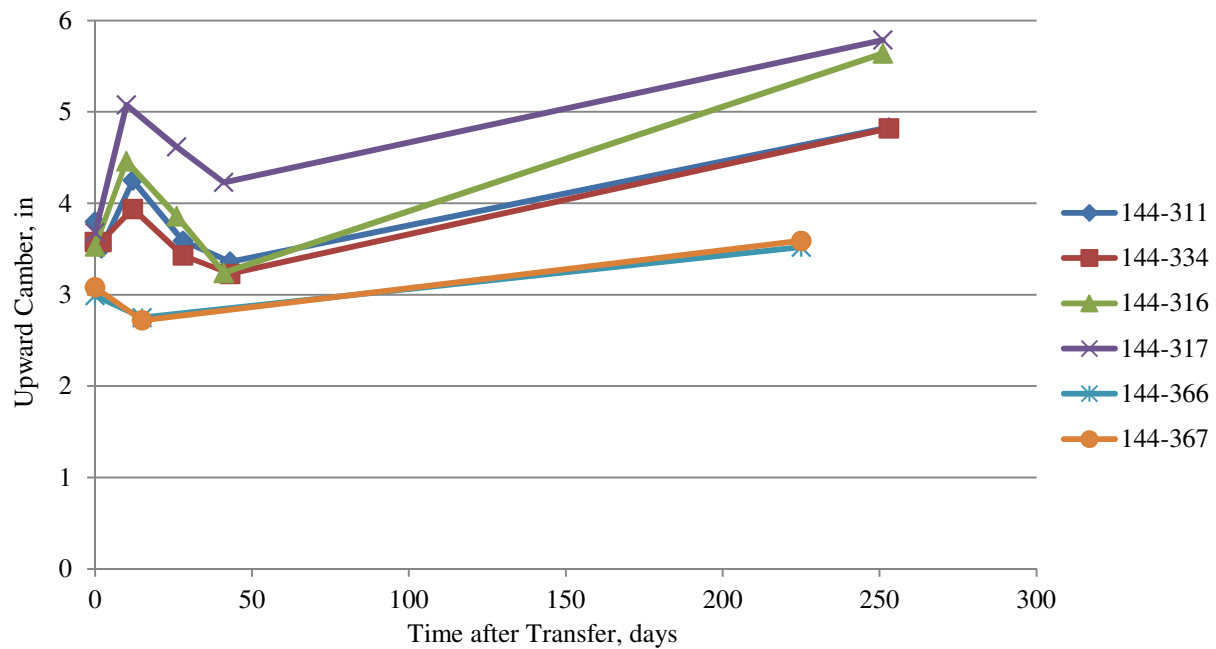
**Figure 4.3** Measured upward camber of 9 BTE 110 prestressed bridge girders at plant B



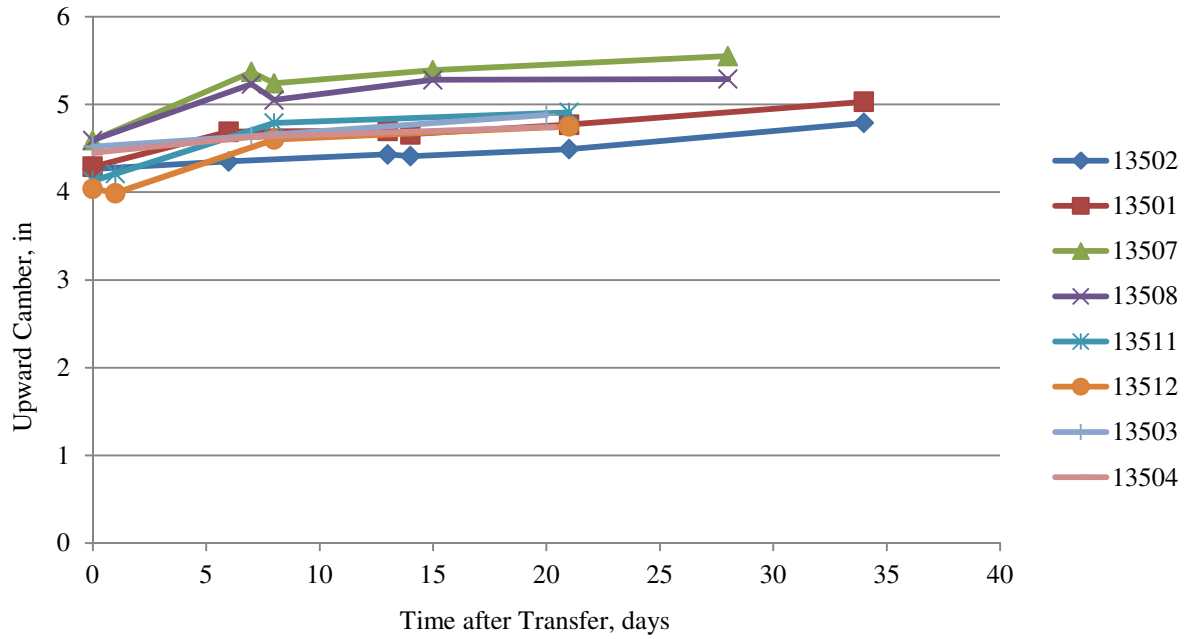
**Figure 4.4** Adjusted upward camber of 9 BTE 110 prestressed bridge girders at plant B



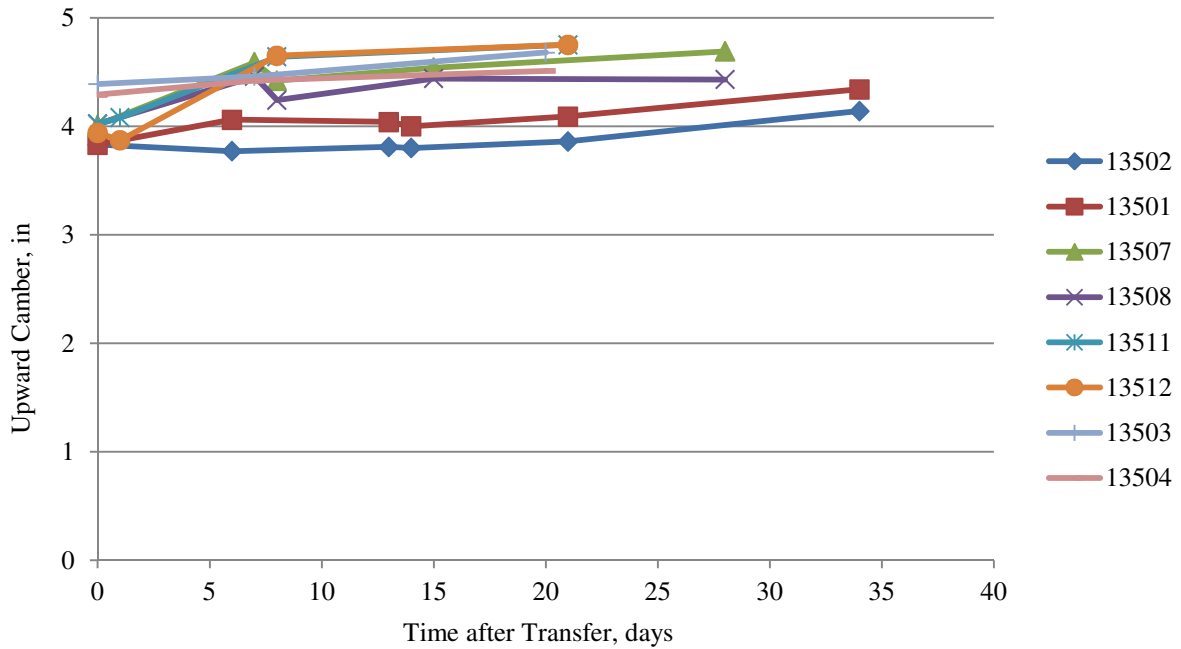
**Figure 4. 5** Measured upward camber of 6 BTE 145 prestressed bridge girders at plant B



**Figure 4. 6** Adjusted upward camber of 6 BTE 145 prestressed bridge girders at plant B



**Figure 4.7.** Measured upward camber of 8 BTD 135 prestressed bridge girders at plant C



**Figure 4.8.** Adjusted upward camber of 8 BTD 135 prestressed bridge girders at plant C

## CHAPTER 5 ANALYSIS AND DISCUSSION

### 5.1 Introduction

In this chapter, the analysis and discussion on compressive strength and modulus of elasticity are performed in the section 5.2 and 5.3. Comparison of measured results of creep and shrinkage tests and five models is presented in section 5.4. Equations of sealed creep coefficient and sealed shrinkage obtained according to the measured data are proposed in section 5.5. Section 5.6 discusses the prediction of long-term camber of prestressed girders.

### 5.2 Compressive Strength

Average compressive strength of four HPC mixes is 6272 psi at 1-day, 7946 psi at 28-day. Average compressive strength of three NC mixes is 8400 psi at 1-day, 9593 psi at 28-day. Average compressive strength of three NC mixes is higher 34% at 1-day and 21% at 28-day than that of four HPC mixes. The values of strength gain in percent from 1-day to 28-day for HPC and NC are shown in Table 5.1. It is observed that HPC has a higher rate of strength gain from 1-day to 28-day than NC, which is due to the effect of slag and fly ash in HPC. This result is consistent with previous studies, including Brooks (1992), Baalbaki (1992) and Wainwright (2000).

**Table 5.1.** Strength gain from 1-day to 28-day for HPC and NC

| Mix I.D.                                   | HPC 1 | HPC 2 | HPC 3 | HPC 4 | NC 1  | NC 2 | NC 3  |
|--|-------|-------|-------|-------|-------|------|-------|
| Average 1-Day Strength, psi                | 6784  | 6247  | 5417  | 6640  | 8902  | 6547 | 9750  |
| Average 28-Day Strength, psi               | 8750  | 7938  | 6884  | 8212  | 10215 | 7545 | 11020 |
| Strength Gain from 1-Day to 28-Day         | 29%   | 27%   | 27%   | 24%   | 15%   | 15%  | 13%   |
| Average Strength Gain from 1-Day to 28-Day | 27%   |       |       |       | 14%   |      |       |

### 5.3 Modulus of Elasticity

Comparison of modulus of elasticity of concrete at the age of loading between the measured values and four models is shown in Table 5.2. Table 5.3 and Table 5.4 summarize the percent difference of modulus of elasticity between measured values and four models for sealed specimens and unsealed specimens respectively. Measured values of modulus of elasticity versus compressive strength of HPC from five different research projects are summarized in Figure 5.1, including Haranki (2009), Schindler (2007), Townsend (2003), Wang (2013) and the current research.

It is found that for sealed specimens AASHTO and Tadros (2003) models have a good agreement with measured values, and ACI 363R model has the largest difference with measured values. It is observed that for unsealed specimens ACI 363R model has a good prediction, and CEB-FIP 90 model has the largest difference with measured data.

As discussed previously because sealed specimens represent the behavior of mass concrete such as bridge girders better than unsealed specimens, AASHTO model provides a good prediction of elastic modulus of sealed specimens. Tadros's model also has a good agreement with AASHTO model in a certain range of compressive strength from 5000 psi to 11000 psi, which was the range of observed release strength for different types of prestressed bridge girders.

In Figure 5.1, average density of all concrete mixtures is used for AASHTO model. It is observed that most data points are within or close with the boundary of  $\pm 20\%$  AASHTO model, which means AASHTO model provides a good prediction of modulus of elasticity according to corresponding compressive strength of HPC. AASHTO model for modulus of elasticity is acceptable for the calculation of camber of prestressed bridge girders.

**Table 5.2.** Comparison of measured modulus of elasticity and four models (ksi)

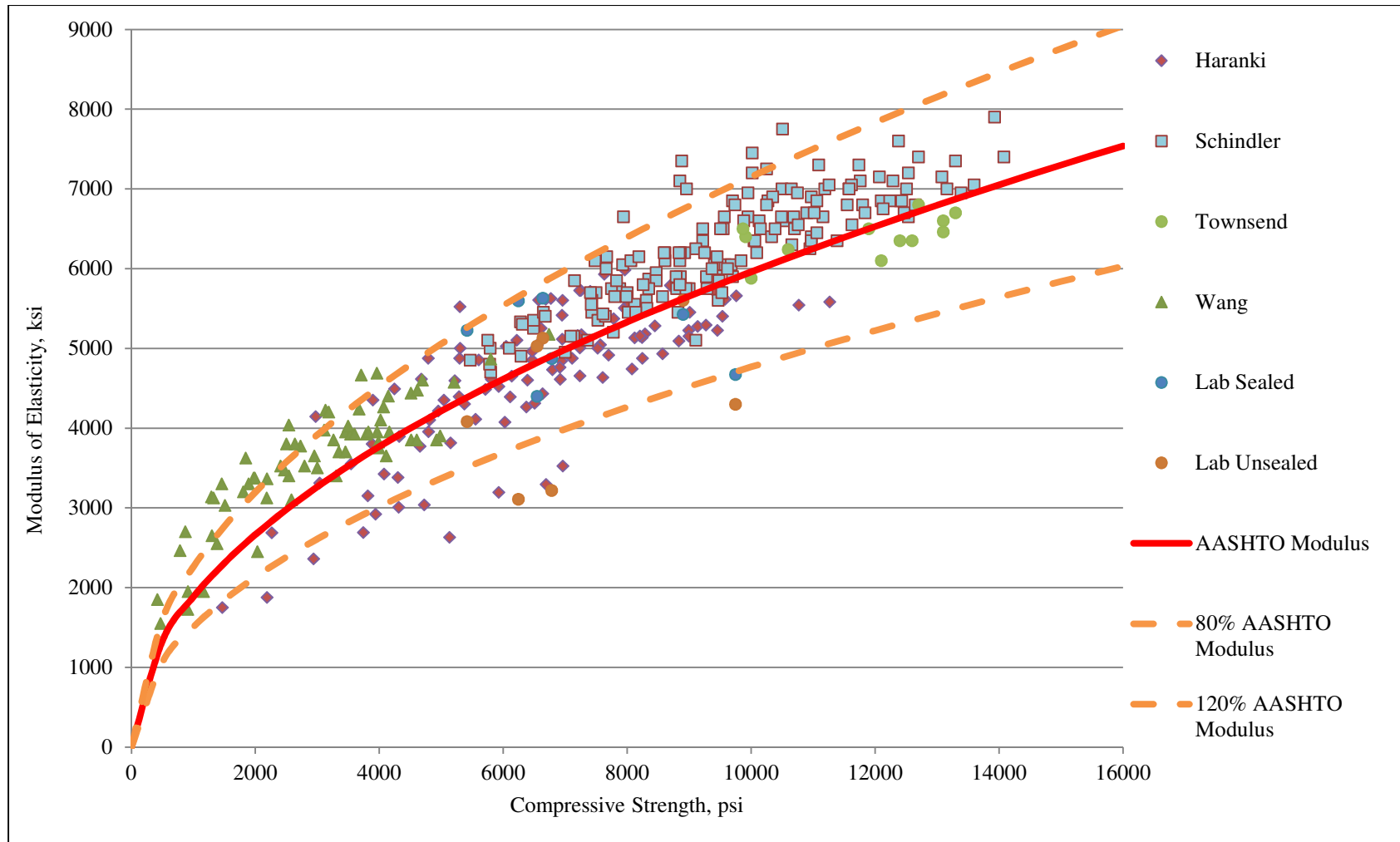
| Mix I.D. | Sealed | Unsealed | AASHTO | ACI 363R | CEB-FIP 90 | Tadros |
|----------|--------|----------|--------|----------|------------|--------|
| HPC 1    | 4870   | 3216     | 5114   | 4628     | 5215       | 4834   |
| HPC 2    | 5596   | 3105     | 4422   | 4041     | 5074       | 4613   |
| HPC 3    | 5226   | 4080     | 4334   | 4030     | 4838       | 4259   |
| HPC 4    | 5629   | 5129     | 4733   | 4293     | 5178       | 4775   |
| NC 1     | 5425   | 5602     | 5653   | 4964     | 5709       | 5657   |
| NC 2     | 4399   | 5027     | 4867   | 4423     | 5154       | 4737   |
| NC 3     | 4671   | 4297     | 5882   | 5118     | 5885       | 5971   |

**Table 5.3.** Difference in percent of modulus of elasticity between measured values and four models for sealed specimens

| Mix I.D. | Sealed elastic modulus | AASHTO | ACI 363R | CEB-FIP 90 | Tadros |
|----------|------------------------|--------|----------|------------|--------|
| HPC 1    | 0                      | 5      | -5       | 7          | -1     |
| HPC 2    | 0                      | -21    | -28      | -9         | -18    |
| HPC 3    | 0                      | -17    | -23      | -7         | -19    |
| HPC 4    | 0                      | -16    | -24      | -8         | -15    |
| NC 1     | 0                      | 4      | -8       | 5          | 4      |
| NC 2     | 0                      | 11     | 1        | 17         | 8      |
| NC 3     | 0                      | 26     | 10       | 26         | 28     |
| Average  | 0                      | -1     | -11      | 4          | -2     |

**Table 5.4.** Difference in percent of modulus of elasticity between measured values and four models for unsealed specimens

| Mix I.D. | Unsealed elastic modulus | AASHTO | ACI 363R | CEB-FIP 90 | Tadros |
|----------|--------------------------|--------|----------|------------|--------|
| HPC 1    | 0                        | 59     | 44       | 62         | 50     |
| HPC 2    | 0                        | 42     | 30       | 63         | 49     |
| HPC 3    | 0                        | 6      | -1       | 19         | 4      |
| HPC 4    | 0                        | -8     | -16      | 1          | -7     |
| NC 1     | 0                        | 1      | -11      | 2          | 1      |
| NC 2     | 0                        | -3     | -12      | 3          | -6     |
| NC 3     | 0                        | 37     | 19       | 37         | 39     |
| Average  | 0                        | 19     | 7        | 27         | 19     |



**Figure 5.1.** Comparison of modulus of elasticity between AASHTO model and measured values from five research projects



## 5.4 Summary of Creep and Shrinkage Tests

Three parts are presented in this section, including summary of seven mixes, relations between creep and shrinkage and material properties, and comparison of HPC and NC.

### 5.4.1 Summary of seven mixes

The properties of seven concrete mixes are summarized in Table 5.5, including w/c (water to cementitious) ratio, coarse aggregate content, a/c (aggregate to cementitious) ratio, slag replacement and fly ash replacement, and all values in this table are calculated by weight. It is observed that w/c ratio of seven mixes ranges from 0.300 to 0.380, and a/c ratio is in the range from 3.5 to 4.1, and slag replacement ranges from 0% to 25%, and fly ash replacement is in the range from 0% to 10%.

**Table 5.5.** Summary of seven concrete mixes

| Mix I.D. | w/c ratio | Coarse Aggregate Content | a/c ratio | Slag Replacement | Fly Ash Replacement |
|----------|-----------|--------------------------|-----------|------------------|---------------------|
| HPC 1    | 0.335     | 41%                      | 4.0       | 20%              | 0%                  |
| HPC 2    | 0.380     | 34%                      | 4.1       | 25%              | 10%                 |
| HPC 3    | 0.300     | 33%                      | 3.9       | 30%              | 0%                  |
| HPC 4    | 0.370     | 40%                      | 3.5       | 25%              | 10%                 |
| NC 1     | 0.334     | 41%                      | 3.9       | 0%               | 0%                  |
| NC 2     | 0.380     | 29%                      | 4.0       | 0%               | 0%                  |
| NC 3     | 0.360     | 41%                      | 4.0       | 0%               | 0%                  |

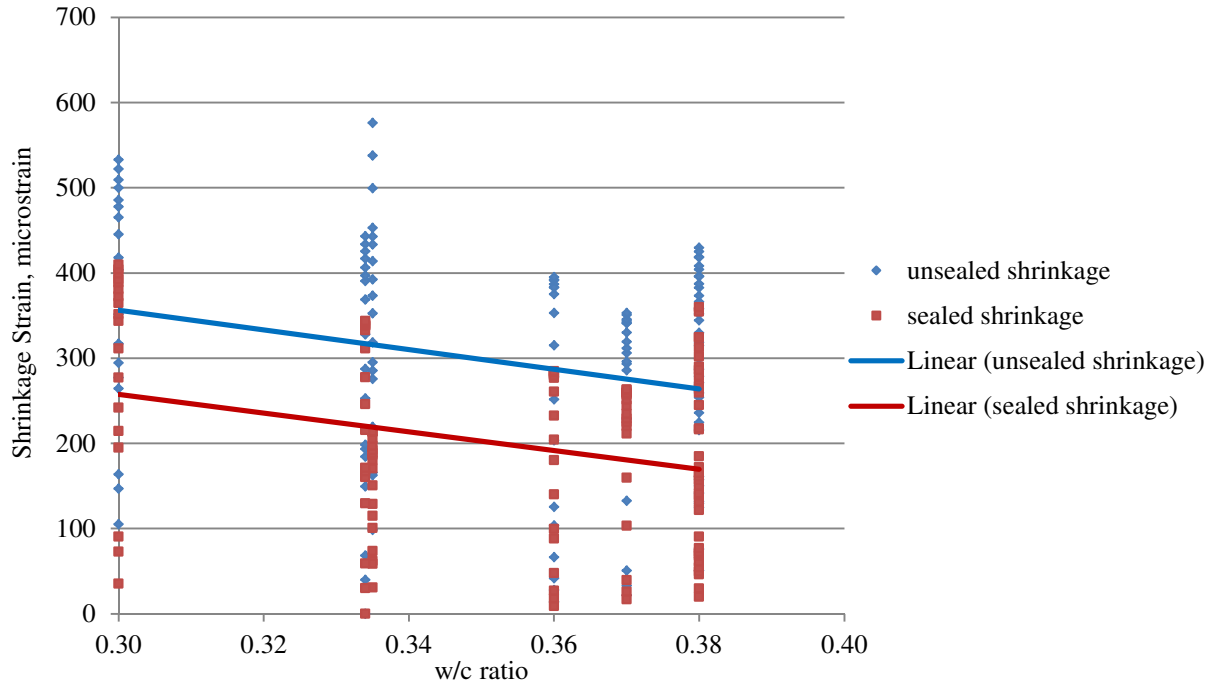
### 5.4.2 Relations between results of creep and shrinkage tests and material properties

Relations between shrinkage strain and creep coefficient during one year and material properties are shown from Figure 5.2 to Figure 5.11. According to the observation below, It is observed that results of sealed creep coefficient and sealed shrinkage agree with previous research projects mentioned in Chapter 2 very well except for w/c ratio effect, and for unsealed creep coefficient and unsealed shrinkage some opposite trends are observed. The detailed observations are shown below:

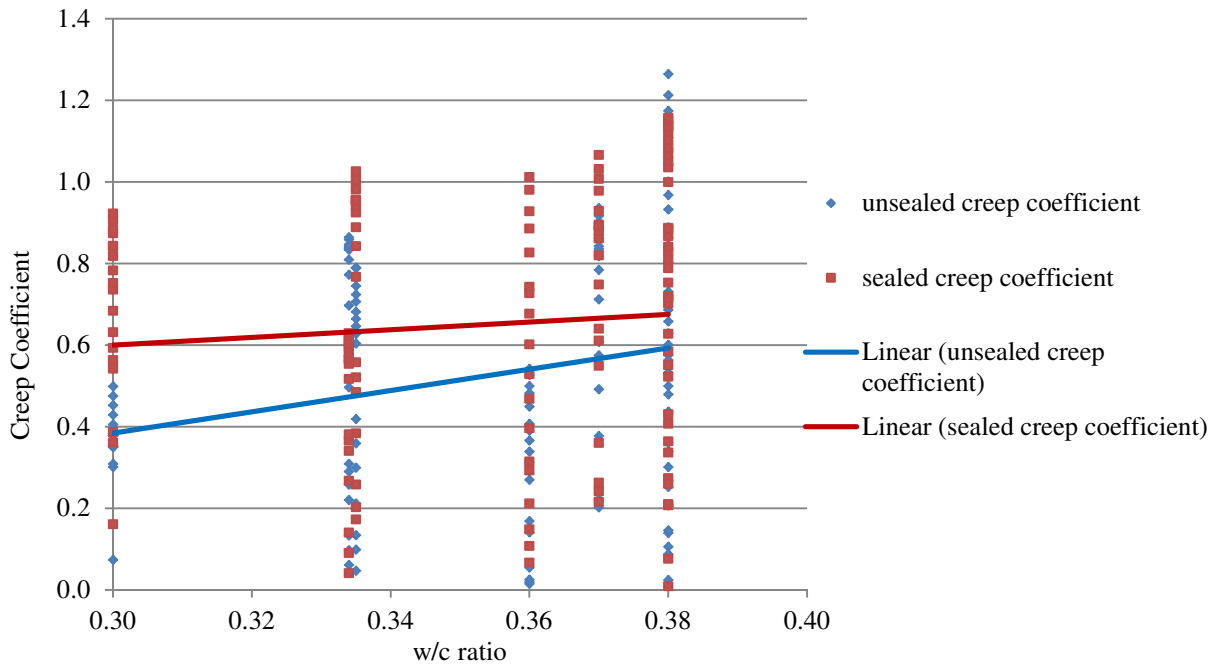
- Shrinkage strain for both unsealed and sealed specimens decreases with an increase of w/c ratio, which is an opposite trend comparing with results from previous researches mentioned Section 2.2.2.3. The possible reason is that the range of w/c ratio for seven mixes is narrow, and other factors may also cause this opposite trend, including coarse aggregate content, a/c ratio, slag replacement and fly ash replacement;
- Creep coefficient for both unsealed and sealed specimens increases with an increase of w/c ratio, which is the similar trend with other studies discussed in Section 2.1.2.3;
- Both unsealed and sealed shrinkage strain decrease with an increase of coarse aggregate content, which is consistent with previous studies mentioned in Section 2.2.2.1;
- Unsealed creep coefficient is not affected significantly by coarse aggregate content, and it increases slightly with an increase of coarse aggregate content, which is not consistent with previous researches mentioned in Section 2.1.2.1. Unsealed creep coefficient is also affected by other factors, including w/c ratio, a/c ratio, slag replacement and fly ash replacement. Sealed creep coefficient decreases with an increase of coarse aggregate content, which is consistent with previous studies mentioned in Section 2.1.2.1;
- Unsealed shrinkage increases with an increase of a/c ratio, which is the opposite trend discussed in Section 2.2.2.1. The possible reason is that other factors also have an influence on the unsealed shrinkage, including w/c ratio, slag replacement and fly ash replacement. Sealed shrinkage decreases with an increase of a/c ratio, and this observation is consistent with previous researches mentioned in Section 2.2.2.1;
- Unsealed creep coefficient decreases with an increase of a/c ratio, which is consistent with previous studies discussed in Section 2.1.2.1. The influence of a/c ratio on sealed creep coefficient is small, which is possibly caused by other factors, including w/c ratio, slag replacement and fly ash replacement;
- Both unsealed and sealed shrinkage increase with an increase of slag replacement of Portland cement from 0% to 30%, and the effect of slag replacement is similar for both unsealed and sealed specimens. The similar trend is observed by other researchers mentioned in Section 2.2.2.5 for early age loaded slag concrete;
- Both unsealed and sealed creep coefficient increase with an increase of slag replacement of Portland cement from 0% to 30%, and the extent of the effect of slag replacement for sealed specimens is higher than that for unsealed specimens. Those observations are

consistent with previous studies discussed in Section 2.1.2.2 for early age loaded slag concrete;

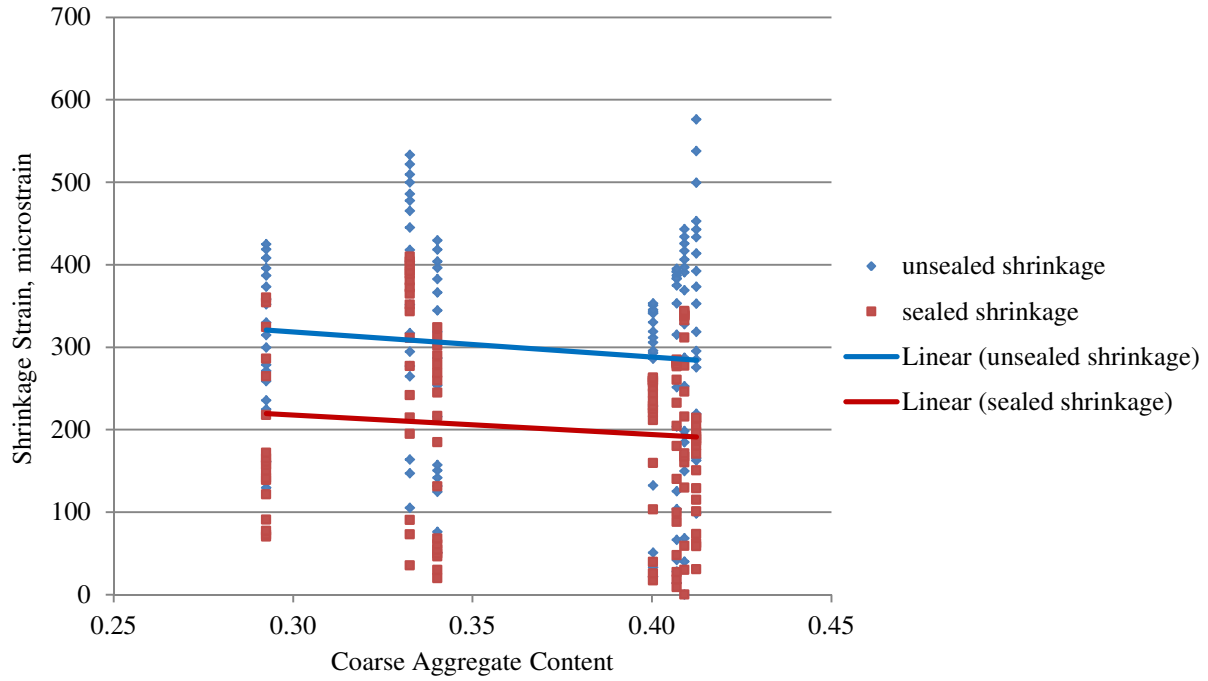
- Class C Fly ash decreases shrinkage for both unsealed and sealed specimens, and the extent of decrease effect for unsealed specimens is slightly higher than that for sealed specimens, which is consistent with previous researches discussed in Section 2.2.2.5;
- Class C Fly ash increases both unsealed and sealed creep coefficient, and the extent of effect for unsealed specimens is slightly higher than that for sealed specimens. Those observations are consistent with previous studies mentioned in Section 2.1.2.5.



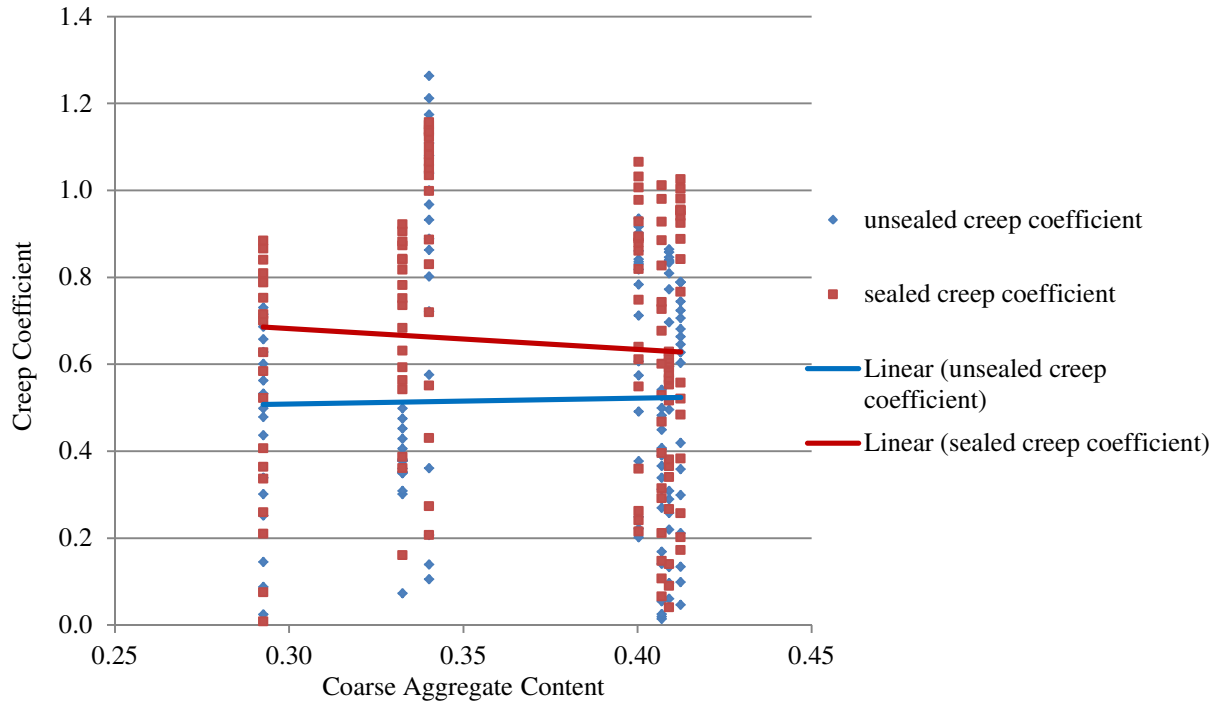
**Figure 5.2.** Relation between shrinkage and w/c ratio



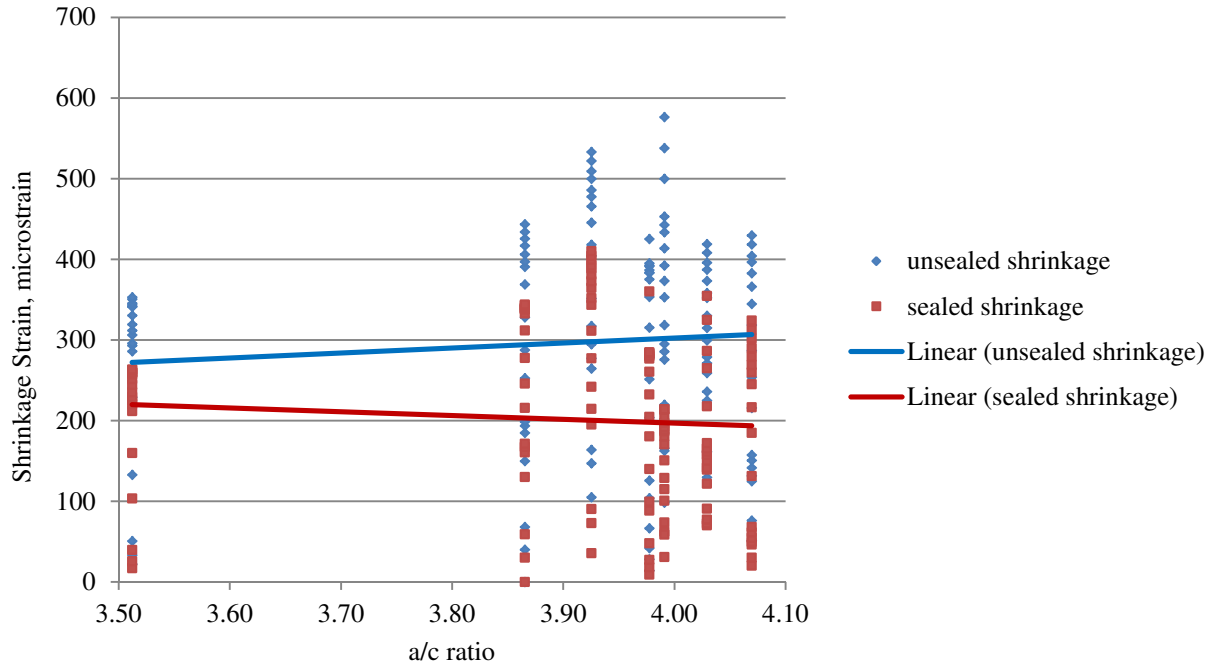
**Figure 5.3.** Relation between creep coefficient and w/c ratio



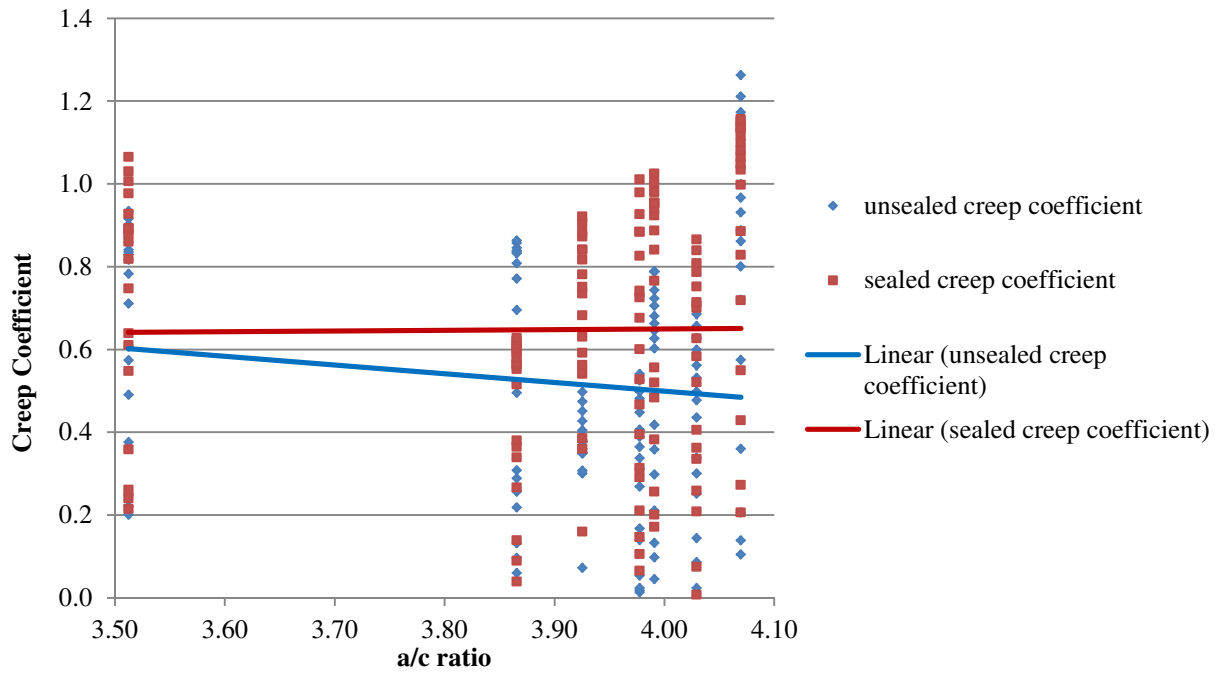
**Figure 5.4.** Relation between shrinkage and coarse aggregate content



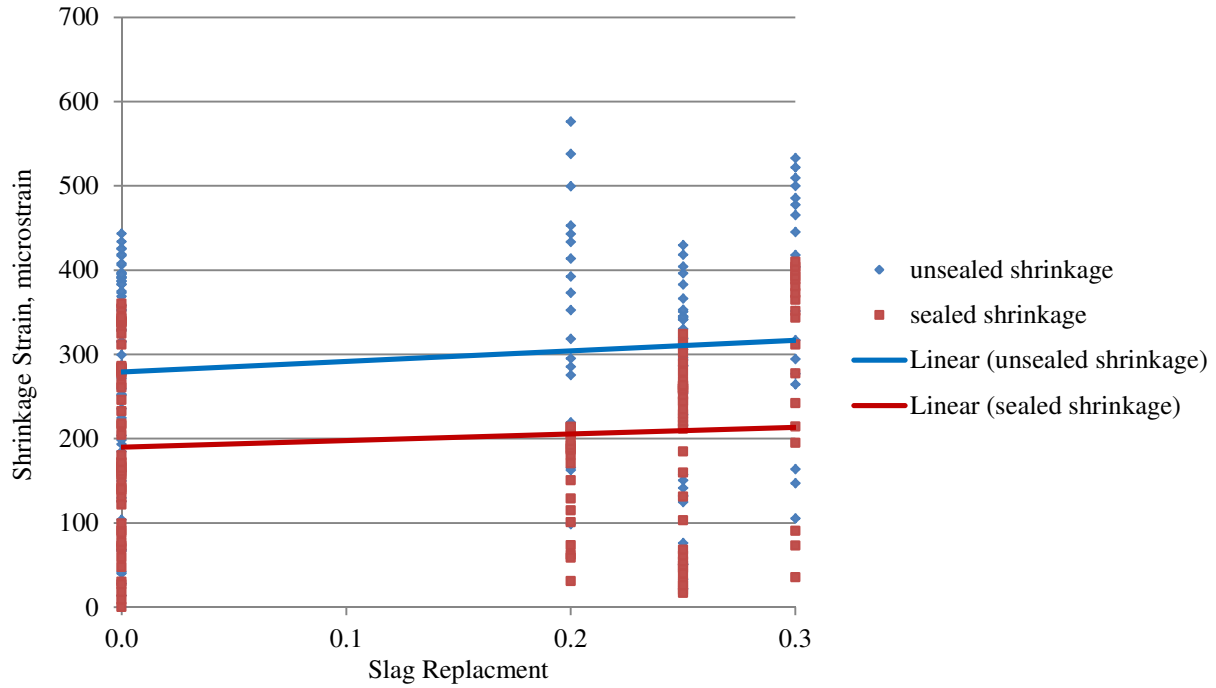
**Figure 5.5.** Relation between creep coefficient and coarse aggregate content



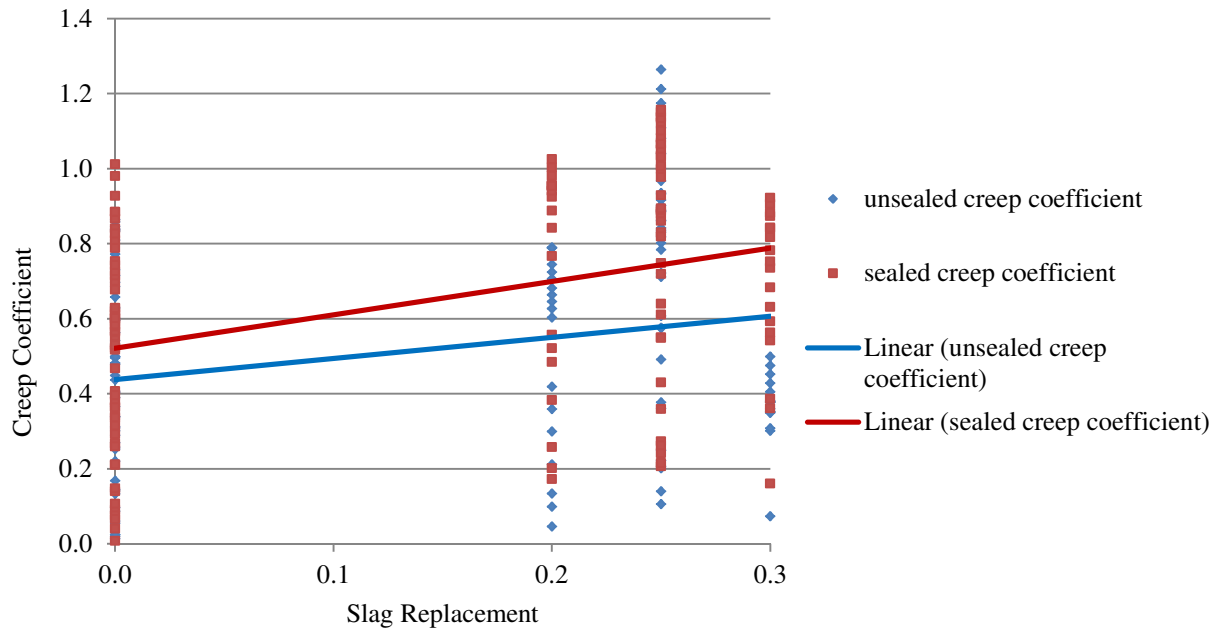
**Figure 5.6.** Relation between shrinkage and a/c ratio



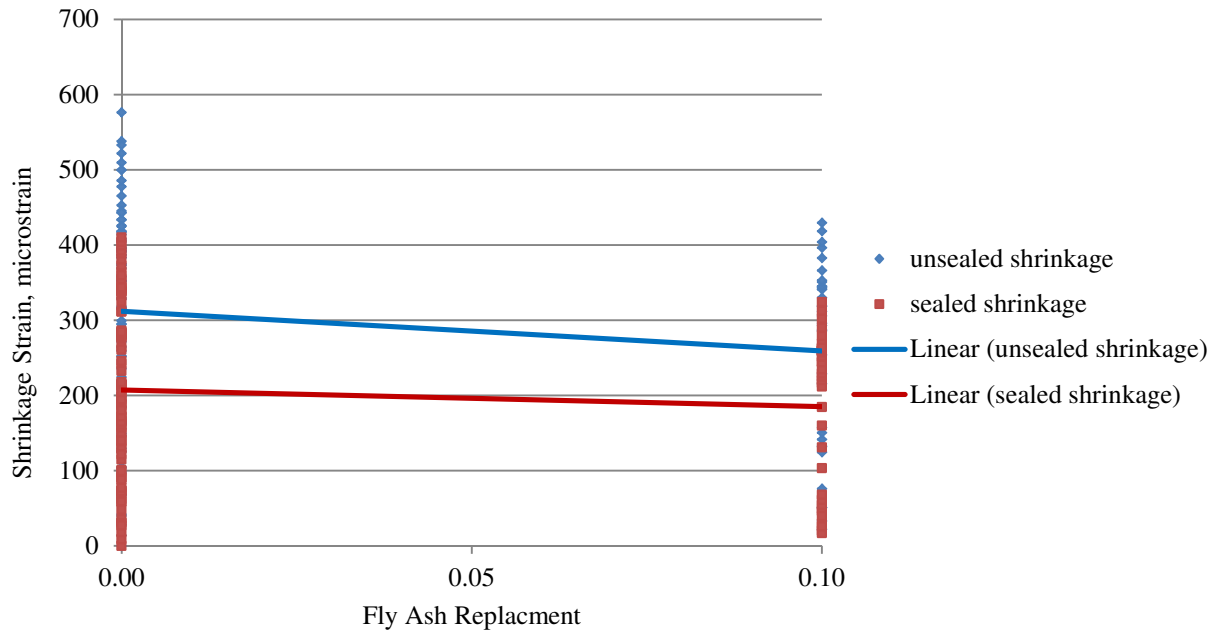
**Figure 5.7.** Relation between creep coefficient and a/c ratio



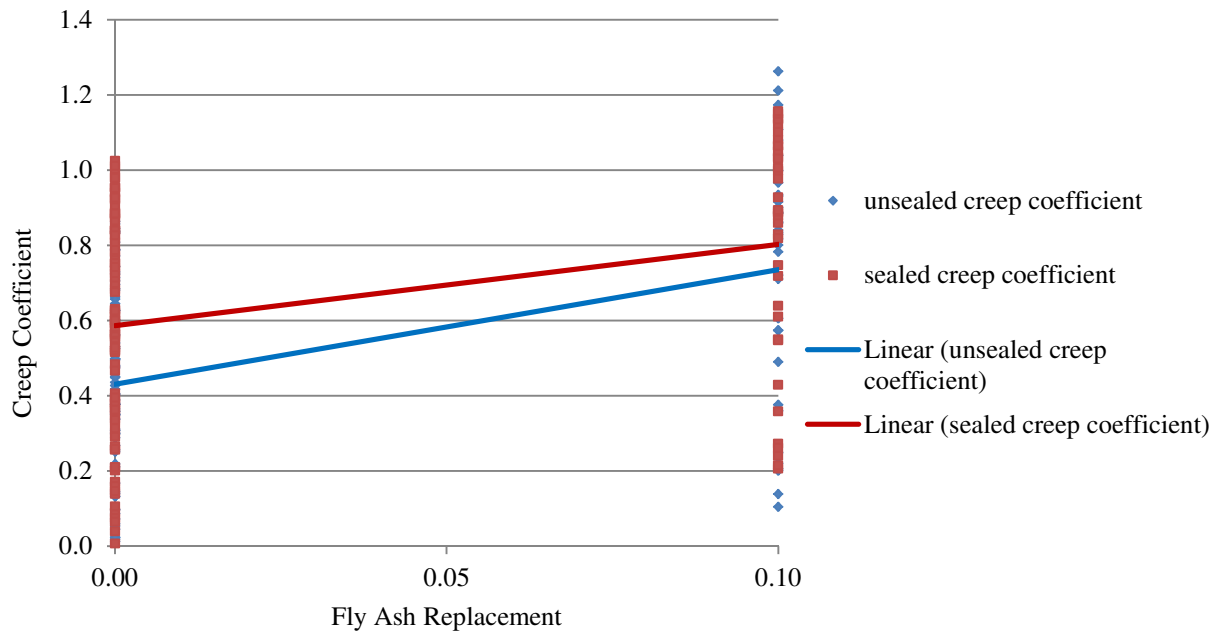
**Figure 5.8.** Relation between shrinkage and slag replacement



**Figure 5.9.** Relation between creep coefficient and slag replacement



**Figure 5.10.** Relation between shrinkage and fly ash replacement



**Figure 5.11.** Relation between creep coefficient and fly ash replacement



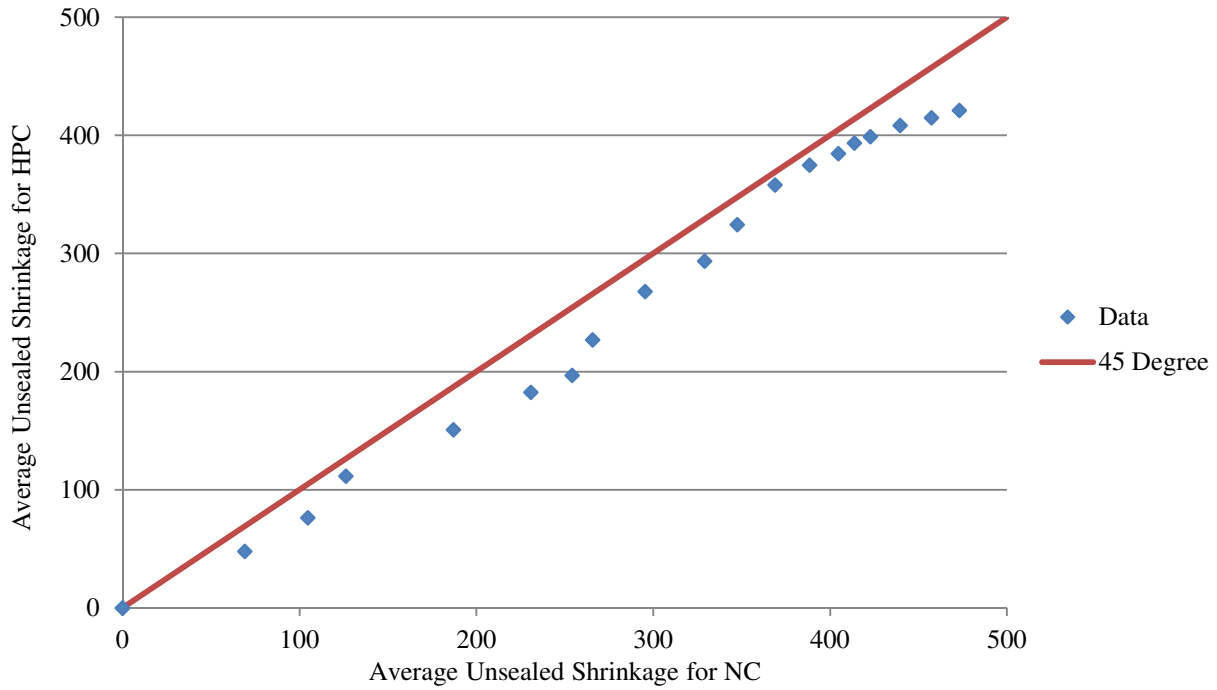
### 5.4.3 Comparison of HPC and NC

The comparison of average unsealed and sealed creep coefficient and shrinkage for HPC and NC at the same period during one year are shown from Figure 5.12 to Figure 5.15. The difference of shrinkage and creep coefficient between HPC and NC is summarized in Table 5.6

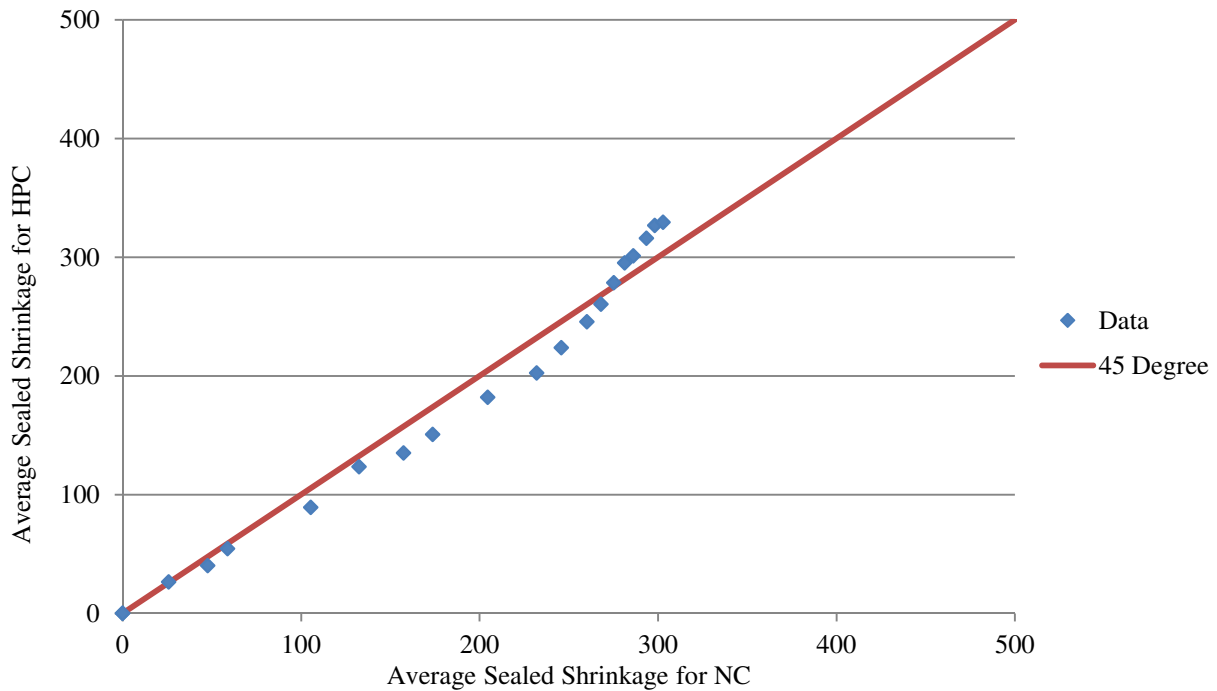
(difference in percent =  $\frac{\text{HPC value} - \text{NC value}}{\text{NC value}} * 100\%$ ). The following are the observations:

- Average unsealed shrinkage strain for HPC is higher than that for NC, and the average value is 15%. The difference of average unsealed shrinkage strain for HPC and NC becomes smaller with time;
- Average sealed shrinkage strain for HPC is higher than that for NC during 6-month, and is lower than that for NC between 6-month to 1-year, and the average difference is 5%;
- Average unsealed creep coefficient for HPC is higher than that for NC, and the average value is 88%. The difference decreases with time from 381% at 1-day to 22% at 1-year;
- Average sealed creep coefficient for HPC is higher than that for NC, and the average value is 79%. The difference decreases with time from 398% at 1-day to 24% at 1-year.

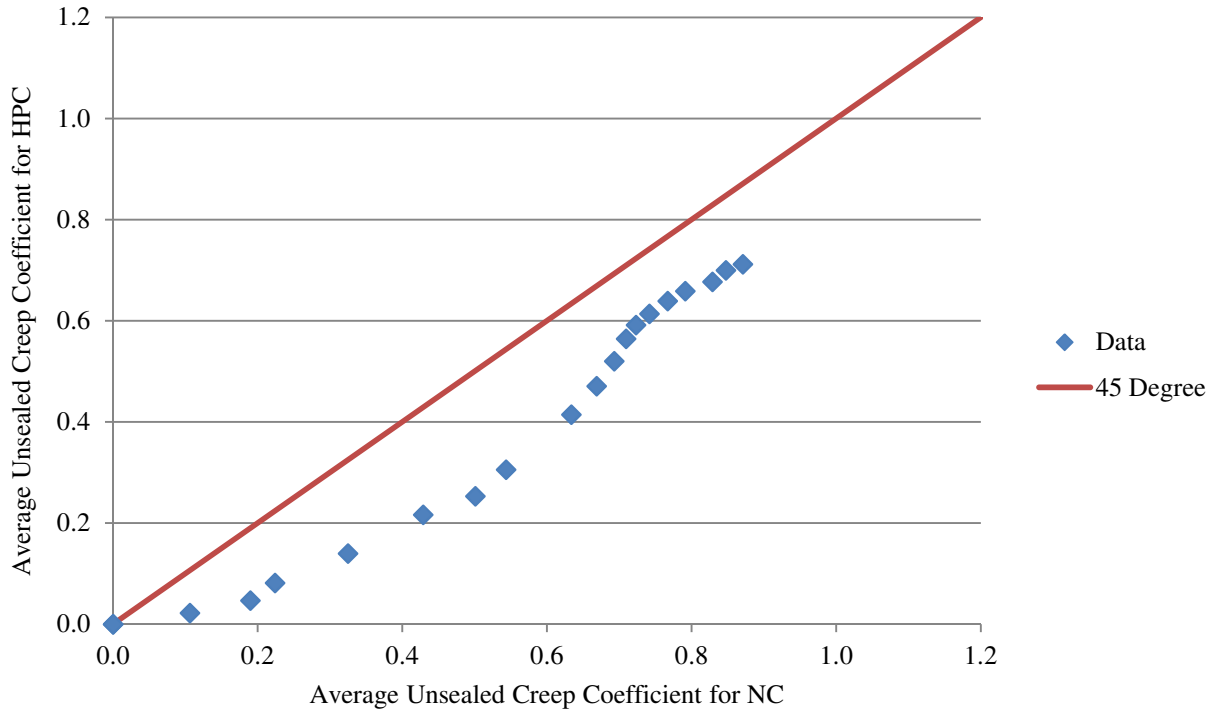
From the observation above, it is observed that HPC has higher shrinkage and creep coefficient for both unsealed and sealed specimens than NC at the early age after loading especially during the first month of loading, and after that the difference becomes smaller.



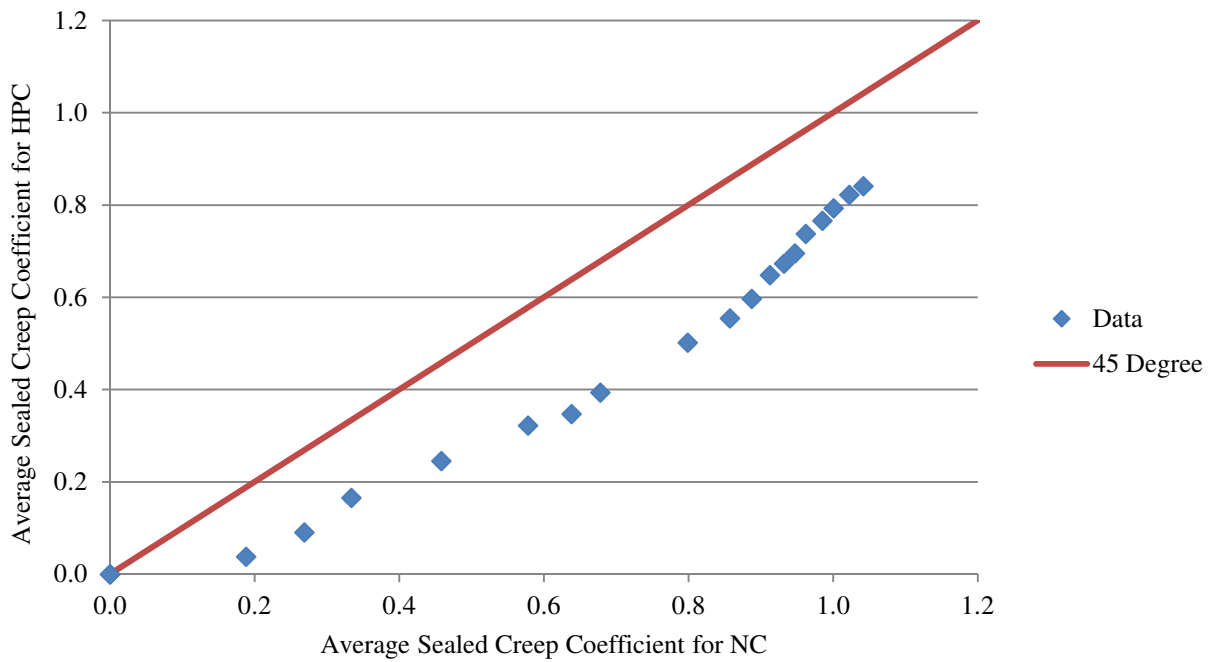
**Figure 5.12.** Comparison of average unsealed shrinkage for HPC and NC



**Figure 5.13.** Comparison of average sealed shrinkage for HPC and NC



**Figure 5.14.** Comparison of average unsealed creep coefficient for HPC and NC



**Figure 5.15.** Comparison of average sealed creep coefficient for HPC and NC

**Table 5.6.** Comparison of HPC and NC by using difference in percent

| Time after Loading, days | Unsealed Shrinkage | Sealed Shrinkage | Unsealed Creep Coefficient | Sealed Creep Coefficient |
|--------------------------|--------------------|------------------|----------------------------|--------------------------|
| 0                        | 0                  | 0                | 0                          | 0                        |
| 0                        | 0                  | 0                | 0                          | 0                        |
| 1                        | 44                 | -2               | 381                        | 398                      |
| 2                        | 37                 | 19               | 308                        | 197                      |
| 3                        | 13                 | 8                | 175                        | 102                      |
| 7                        | 24                 | 18               | 133                        | 87                       |
| 14                       | 26                 | 7                | 98                         | 79                       |
| 21                       | 29                 | 16               | 98                         | 84                       |
| 28                       | 17                 | 15               | 78                         | 72                       |
| 60                       | 10                 | 12               | 53                         | 59                       |
| 90                       | 12                 | 15               | 42                         | 55                       |
| 120                      | 7                  | 10               | 33                         | 49                       |
| 150                      | 3                  | 6                | 26                         | 41                       |
| 180                      | 4                  | 3                | 22                         | 38                       |
| 210                      | 5                  | -1               | 21                         | 36                       |
| 240                      | 5                  | -5               | 20                         | 30                       |
| 270                      | 6                  | -5               | 20                         | 29                       |
| 300                      | 8                  | -7               | 23                         | 26                       |
| 330                      | 10                 | -9               | 21                         | 24                       |
| 360                      | 12                 | -8               | 22                         | 24                       |
| Average                  | 15                 | 5                | 88                         | 79                       |

## 5.5 Comparison of Measured Data of Creep and Shrinkage Tests and Five Models

Comparison of measured creep and shrinkage data and five models in one year are shown in Table 5.5 and Table 5.6, where unsealed creep coefficient, sealed creep coefficient, unsealed shrinkage and sealed shrinkage are considered (difference in percent =  $\frac{\text{Model} - \text{Measured}}{\text{measured}} * 100\%$ ).

It is found that AASHTO LRFD 2010 model has the best prediction for both HPC and NC. It is also indicated that B3 model has the largest errors for both HPC and NC. Comparisons of measured and predicted results of creep and shrinkage in one year are shown in Appendix B.

**Table 5.7.** Average difference in percent between creep coefficient and shrinkage of 4 HPC mixes and five models in one year

| Models                   | Unsealed Creep Coefficient | Sealed Creep Coefficient | Unsealed Shrinkage | Sealed Shrinkage | Average Difference in Percent | Rank |
|--------------------------|----------------------------|--------------------------|--------------------|------------------|-------------------------------|------|
| AASHTO LRFD 2010         | 95                         | -32                      | -1                 | -44              | 4                             | 1    |
| ACI 209R-92              | 233                        | -30                      | -23                | \                | 60                            | 3    |
| ACI 209R-Modified by Huo | 203                        | -37                      | -21                | \                | 48                            | 2    |
| CEB-FIP 90               | 264                        | -14                      | 47                 | \                | 99                            | 4    |
| Bazant B3                | 335                        | 94                       | 57                 | -62              | 106                           | 5    |

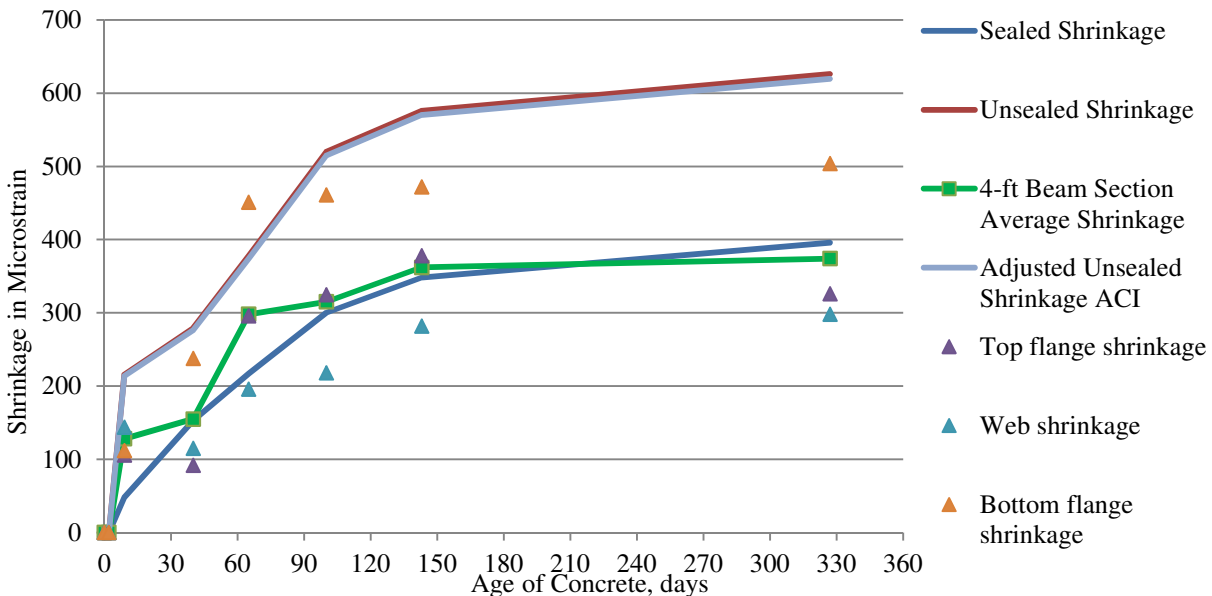
**Table 5.8.** Average difference in percent between creep coefficient and shrinkage of 3 NC mixes and five models in one year

| Models                   | Unsealed Creep Coefficient | Sealed Creep Coefficient | Unsealed Shrinkage | Sealed Shrinkage | Average Difference in Percent | Rank |
|--------------------------|----------------------------|--------------------------|--------------------|------------------|-------------------------------|------|
| AASHTO LRFD 2010         | 119                        | -6                       | 0                  | -49              | 16                            | 1    |
| ACI 209R-92              | 292                        | 31                       | -1                 | \                | 107                           | 3    |
| ACI 209R-Modified by Huo | 396                        | 21                       | 0                  | \                | 139                           | 4    |
| CEB-FIP 90               | 128                        | 95                       | 31                 | \                | 85                            | 2    |
| Bazant B3                | 291                        | 322                      | 91                 | -60              | 161                           | 5    |

## 5.6 Comparison of Shrinkage Behavior of 4-ft Beam Section and Laboratory Specimens

Figure 5.2 shows the comparison of shrinkage between 4-ft beam section and unsealed and sealed specimens stored in the environmentally controlled chamber. It is found that the 4-ft beam section has a similar shrinkage behavior with sealed specimens, which means the sealed specimens could represent the shrinkage behavior of beam very well. This observation is consistent with previous studies, including Hansen (1966) and Bryant (1987).

In Figure 5.2 shrinkage of the unsealed specimen is adjusted by using volume to surface ( $v/s$  ratio) according to Eq. 2-65 (ACI 209R 1990). It is observed that average shrinkage of the beam section is similar with that of sealed specimens. It is also found that bottom flange has higher shrinkage strain than top flange and web, which possibly results from the incomplete debonding between strands and concrete, and temperature gradient due to sunshine. After consideration of those two effects, the difference of shrinkage strain between bottom flange and top flange would be smaller. Extent of debonding between strand and concrete and temperature gradient has a smaller effect on the web of beam section, and it is observed that shrinkage of web of is lower than that of sealed specimens.



**Figure 5.16.** Comparison of shrinkage between 4-ft. beam section and laboratory specimens

## 5.7 Proposed Equations for Creep and Shrinkage of HPC

Measured average creep coefficient and shrinkage strain from sealed specimens of four HPC mixes are used to predict long-term camber of prestressed bridge girders within one year. Table 5.7 and Table 5.8 summarize the measured sealed creep coefficient and shrinkage strain and corresponding average values for four HPC mixes. If a prestressed bridge girder is stored in the yard of a precast plant more than one year, equations to present average sealed creep coefficient and sealed shrinkage strain are proposed according to one year's measured data for the tested four HPC mixes, which have the similar loading age and storage conditions. The format of AASHTO LRFD 2010 model of creep and shrinkage equations is followed. Least square method is used to obtain the appropriate parameters in the equations shown below.

**Table 5.9.** Measured sealed creep coefficient and average values for four HPC mixes

| Time after Loading, days | HPC 1   | HPC 2   | HPC 3   | HPC 4   | Average | Sta. Dev. |
|--------------------------|---------|---------|---------|---------|---------|-----------|
| 0                        | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000   |
| 0                        | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000   |
| 1                        | 0.17186 | 0.20649 | 0.15996 | 0.21487 | 0.18830 | 0.01149   |
| 2                        | 0.20138 | 0.27289 | 0.36042 | 0.24085 | 0.26888 | 0.02930   |
| 3                        | 0.25699 | 0.42961 | 0.38626 | 0.26184 | 0.33367 | 0.03792   |
| 7                        | 0.38265 | 0.55016 | 0.54134 | 0.35891 | 0.45827 | 0.04397   |
| 14                       | 0.48378 | 0.71894 | 0.56266 | 0.54802 | 0.57835 | 0.04321   |
| 21                       | 0.52042 | 0.82920 | 0.59250 | 0.61062 | 0.63819 | 0.05766   |
| 28                       | 0.55707 | 0.88609 | 0.63087 | 0.63966 | 0.67842 | 0.06206   |
| 60                       | 0.76635 | 0.99837 | 0.68287 | 0.74767 | 0.79882 | 0.05965   |
| 90                       | 0.84151 | 1.03454 | 0.73522 | 0.81871 | 0.85750 | 0.05480   |
| 120                      | 0.88788 | 1.05018 | 0.75161 | 0.86035 | 0.88751 | 0.05343   |
| 150                      | 0.92430 | 1.06514 | 0.78198 | 0.87970 | 0.91278 | 0.05096   |
| 180                      | 0.94038 | 1.08155 | 0.81697 | 0.88930 | 0.93205 | 0.04841   |
| 210                      | 0.95341 | 1.10117 | 0.84013 | 0.89390 | 0.94715 | 0.04877   |
| 240                      | 0.95564 | 1.12276 | 0.84229 | 0.92817 | 0.96221 | 0.05084   |
| 270                      | 0.95299 | 1.13770 | 0.87278 | 0.97726 | 0.98518 | 0.04808   |
| 300                      | 0.98059 | 1.13435 | 0.88203 | 1.00658 | 1.00089 | 0.04499   |
| 330                      | 1.00290 | 1.15021 | 0.90544 | 1.03095 | 1.02238 | 0.04364   |
| 360                      | 1.02522 | 1.15647 | 0.92176 | 1.06521 | 1.04217 | 0.04212   |

**Table 5.10.** Measured sealed shrinkage strain and average values for four HPC mixes (10<sup>-6</sup> in/in)

| Time after Loading, days | HPC 1 | HPC 2 | HPC 3 | HPC 4 | Average | Sta. Dev. |
|--------------------------|-------|-------|-------|-------|---------|-----------|
| 0                        | 0     | 0     | 0     | 0     | 0       | 0         |
| 0                        | 0     | 0     | 0     | 0     | 0       | 0         |
| 1                        | 31    | 20    | 36    | 17    | 26      | 4         |
| 2                        | 62    | 30    | 73    | 26    | 48      | 10        |
| 3                        | 59    | 46    | 90    | 40    | 59      | 10        |
| 7                        | 74    | 50    | 195   | 103   | 105     | 28        |
| 14                       | 101   | 54    | 214   | 160   | 132     | 30        |
| 21                       | 115   | 61    | 242   | 212   | 157     | 36        |
| 28                       | 129   | 68    | 277   | 220   | 174     | 40        |
| 60                       | 151   | 131   | 311   | 225   | 205     | 35        |
| 90                       | 171   | 185   | 344   | 229   | 232     | 34        |
| 120                      | 180   | 216   | 352   | 235   | 246     | 32        |
| 150                      | 187   | 245   | 365   | 244   | 260     | 32        |
| 180                      | 188   | 260   | 373   | 251   | 268     | 33        |
| 210                      | 192   | 269   | 381   | 259   | 275     | 34        |
| 240                      | 197   | 279   | 389   | 260   | 281     | 35        |
| 270                      | 205   | 290   | 392   | 257   | 286     | 34        |
| 300                      | 213   | 302   | 399   | 259   | 293     | 34        |
| 330                      | 214   | 313   | 404   | 262   | 298     | 35        |
| 360                      | 214   | 324   | 410   | 263   | 303     | 37        |

Proposed equation of average creep coefficient for sealed specimens of four HPC mixes is expressed as:

$$\varphi(t) = \frac{1.9t^{0.48}}{8 + t^{0.54}} \quad (\text{Eq 5-1})$$

where  $t$  = duration after loading for creep or duration after exposure to the air for shrinkage (days)

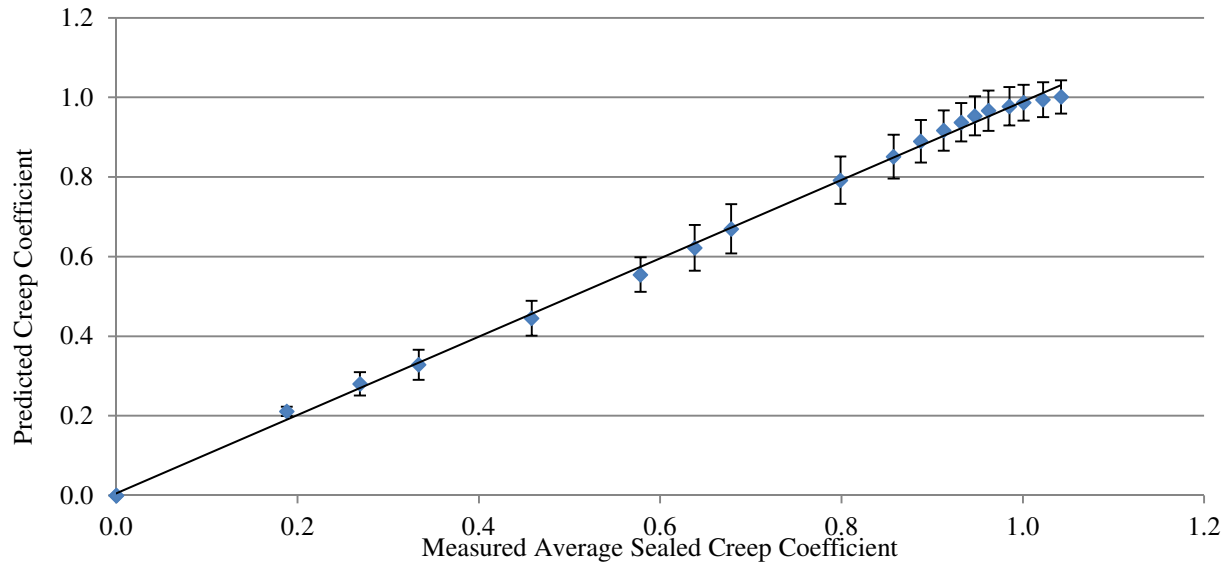
Proposed equation of average shrinkage strain in microstrain for sealed specimens of four HPC mixes is expressed as:

$$\varepsilon(t) = \frac{480t^{0.60}}{12 + t^{0.62}} \quad (\text{Eq 5-2})$$

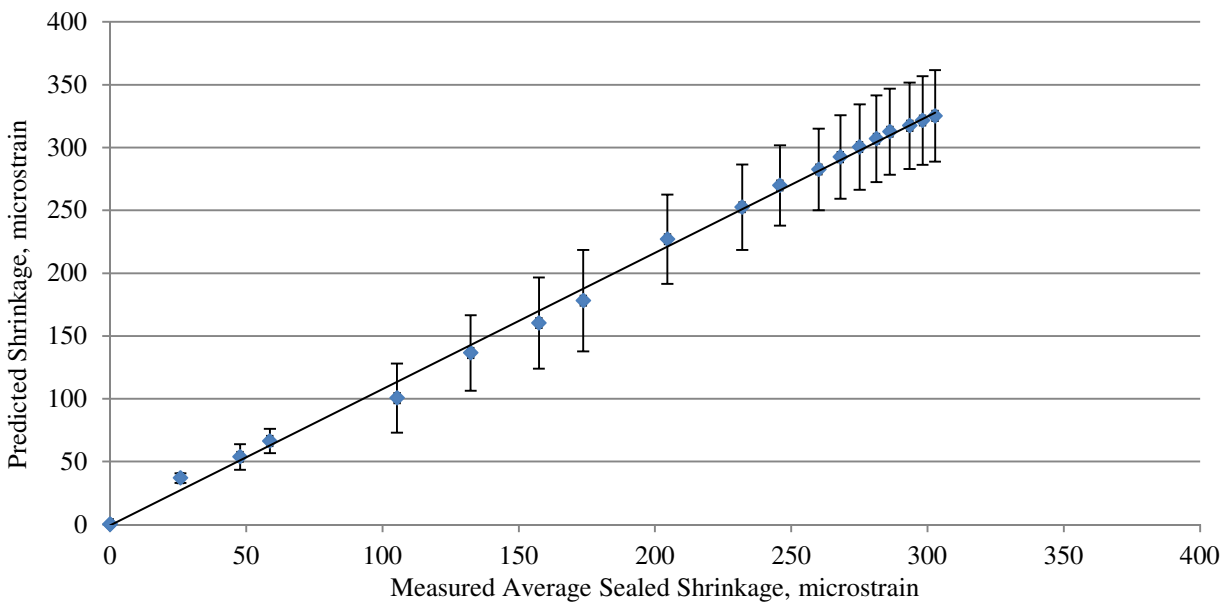
Figure 5.59 and Figure 5.60 show the comparison of predicted values from proposed equations and measured values. It is found that the standard deviation between predicted sealed



creep coefficient and the measured values is 0.00342. It is also indicated that the standard deviation between predicted sealed shrinkage strain and the measured values is 4.03215 microstrain. Vertical bars represent the standard deviation of measured values for four HPC mixes. According to the Eq 5-1 the ultimate sealed creep coefficient is 1.06.



**Figure 5.17.** Comparison of predicted sealed creep coefficient and measured average values



**Figure 5.18.** Comparison of predicted sealed shrinkage and measured values

## **5.8 Prediction of the Long-term Camber of Prestressed Bridge Girders**

Tadros's Method (2011), Naaman's Method (2004) and incremental method are used to predict long-term camber of a prestressed bridge girder. Average sealed creep coefficient and average sealed shrinkage values are applied. Transformed section properties are used to conduct related calculations. Twenty-six girders are analyzed, including three BTC 120 girders produced by plant A, nine BTE 110 girders and six BTE 145 girders cast by plant B, and eight BTD 135 girders made by plant C, and the analyzed results of camber are compared with measured values. It is observed that Naaman's Method and incremental method have the best prediction of camber of girders, and the results of those two methods are similar.

### **5.8.1 Tadros's Method**

Tadros's Method is highly dependent on the release camber, creep coefficient of HPC and prestress losses. Figure 5.5 and Figure 5.6 show the comparison of predicted camber and measured camber with and without overhang respectively. The release camber calculated by using incremental method is used for the prediction of long-term camber of girders. It is found that the average difference in percent between predicted camber by using Tadros's Method and the measured value is 12% for girders with overhang and 15% for girders without overhang, which means that Tadros's Method typically overestimates long-term camber.

### **5.8.2 Naaman's Method**

Naaman's Method is dependent on time-dependent prestress forces, time-dependent modulus of elasticity and creep. Figure 5.7 and Figure 5.8 show the comparison of predicted camber and measured camber with and without overhang respectively. It is observed that almost all data points are located within  $\pm 25\%$  lines. It is also found that the average difference in percent between predicted camber by using Naaman's Method and the measured value is -1% for girders with overhang and 0% for girders without overhang. Naaman's Method is a good method to predict long-term camber.

### 5.8.3 Incremental Method

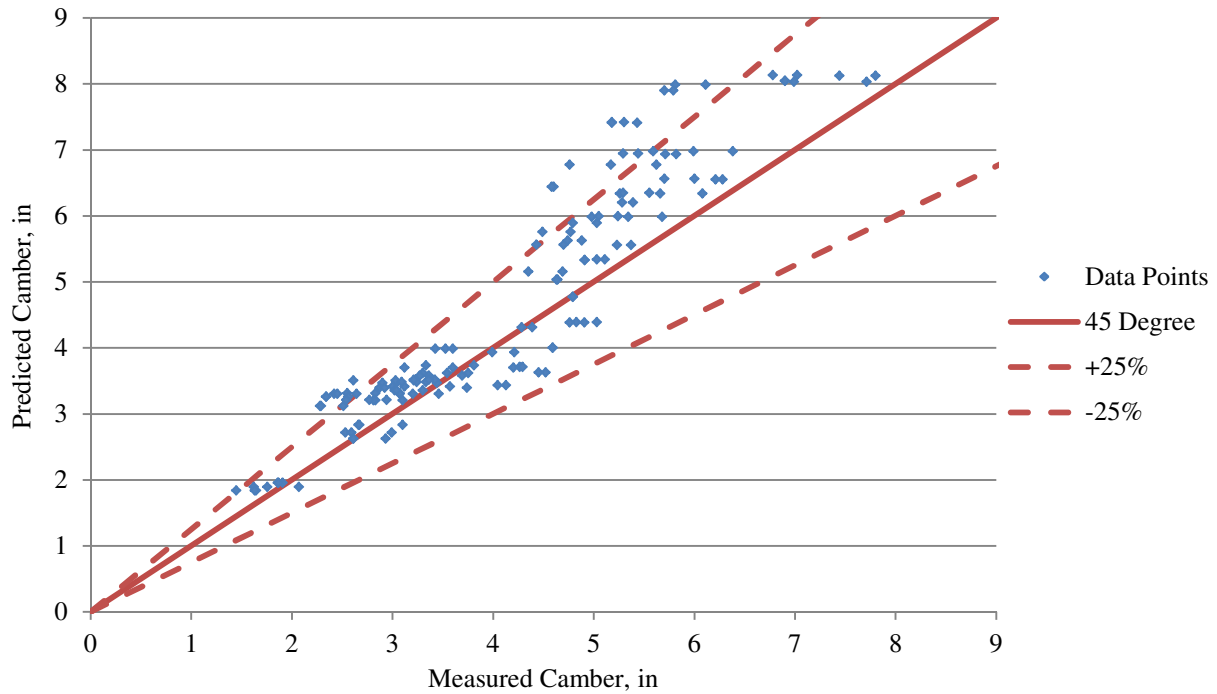
Incremental method is affected by the same factors with Naaman's method. Figure 5.9 and Figure 5.10 show the comparison of predicted camber and measured camber with and without overhang respectively. It is found that almost all data points are located within  $\pm 25\%$  lines. It is also observed that the average difference in percent between predicted camber using incremental method and the measured value is  $-1\%$  for girders with overhang and  $0\%$  for girders without overhang. Incremental method is also a good method to predict long-term camber.

### 5.8.4 Comparison of gross section and transformed section on camber of girders

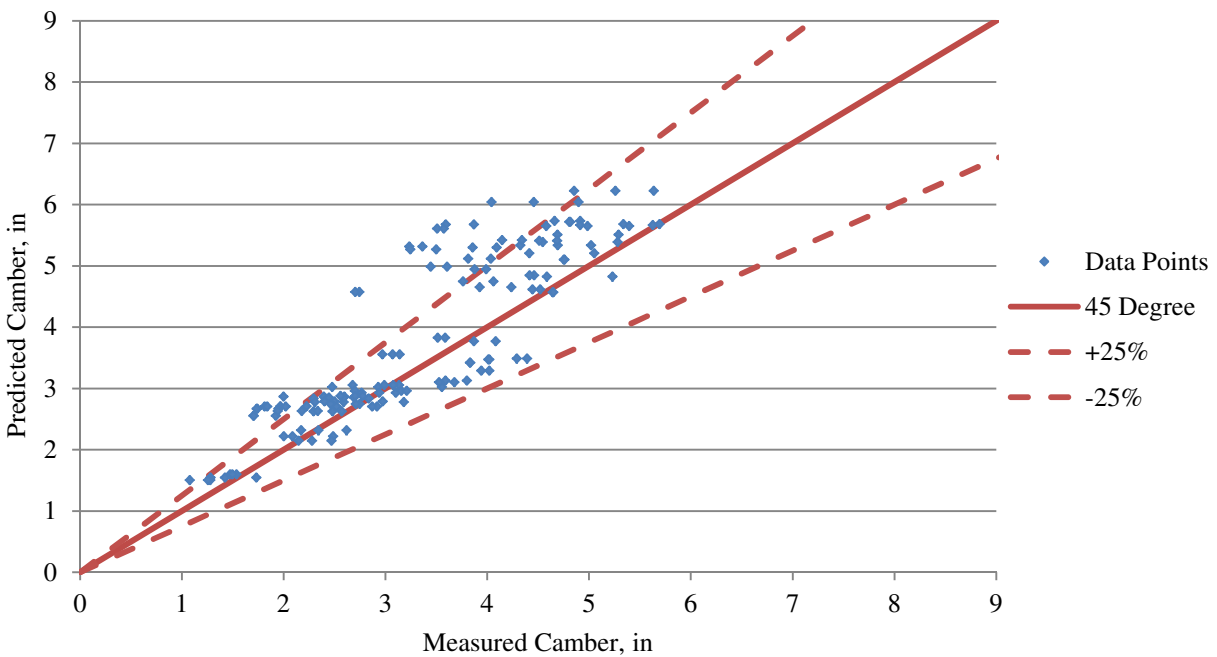
The comparison of predicted camber of girders by using three methods for gross section and transformed section is performed in Appendix C and Appendix D. It is found that predicted cambers of girders using gross section properties are always larger than those using transformed section properties, and the average value for all 26 girders is  $13\%$ .

### 5.8.5 Comparison of average creep and shrinkage and specified creep and shrinkage on the camber of girders

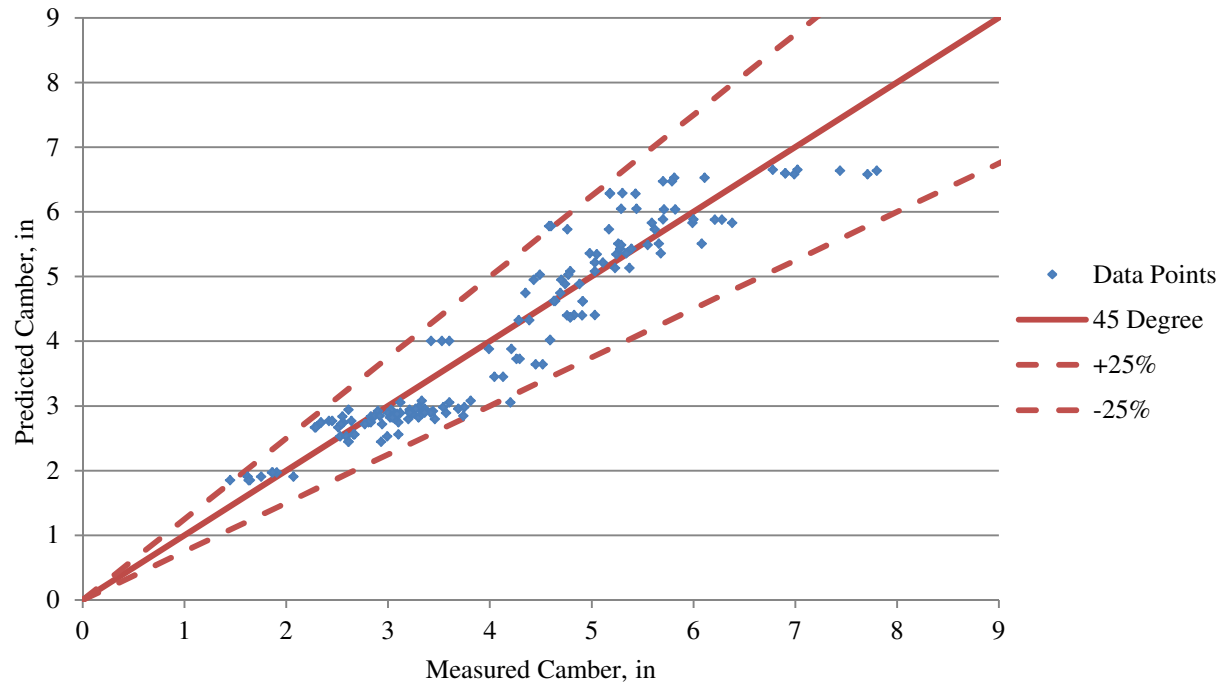
For the analysis above, the results of average sealed creep coefficient and average sealed shrinkage are used to predict long-term camber of girders. Predictions of cambers of girders by using average sealed creep and shrinkage data for four HPC mixes are summarized in Appendix C. Predictions of cambers of girders by using specified sealed creep and shrinkage data are shown in Appendix D, where due to the absence of specified mix of BTE 110 of plant B, the average sealed creep coefficient and sealed shrinkage of HPC 2 and HPC 4 of plant B are applied. It is found that the average difference of cambers of girders for those two types of creep and shrinkage data is on average within  $\pm 2\%$ . Therefore, it is acceptable to use the average values of sealed creep coefficient and sealed shrinkage for four HPC mixes to predict long-term camber of girders within one year. If the prestressed bridge girder is stored in the yard of a precast plant more than one year, the proposed equations of sealed creep coefficient and sealed shrinkage can be utilized to predict long-term camber.



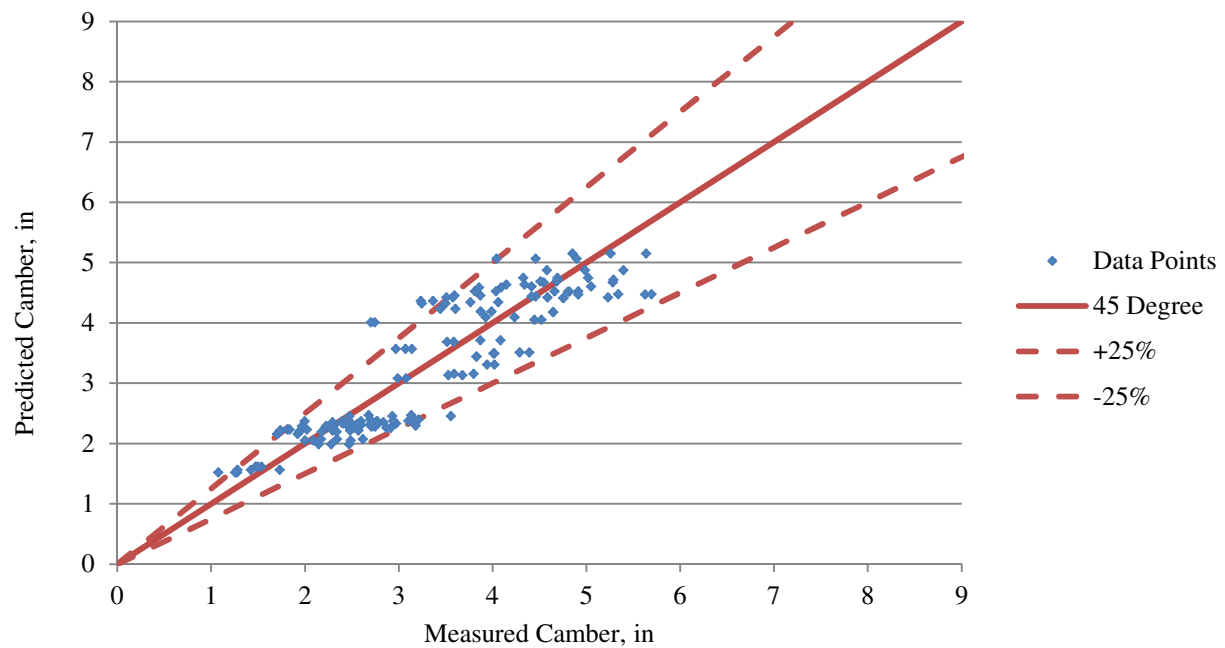
**Figure 5.19.** Comparison of predicted camber and measured camber with overhang by using Tadros's Method



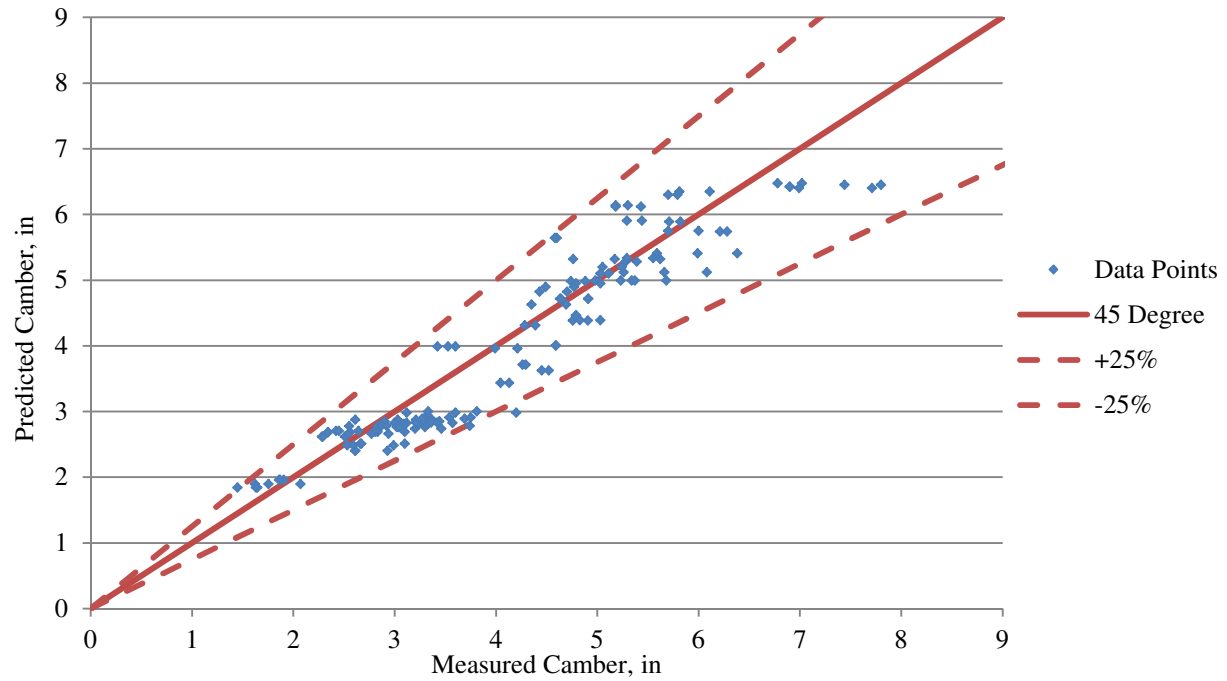
**Figure 5.20.** Comparison of predicted camber and measured camber without overhang by using Tadros's Method



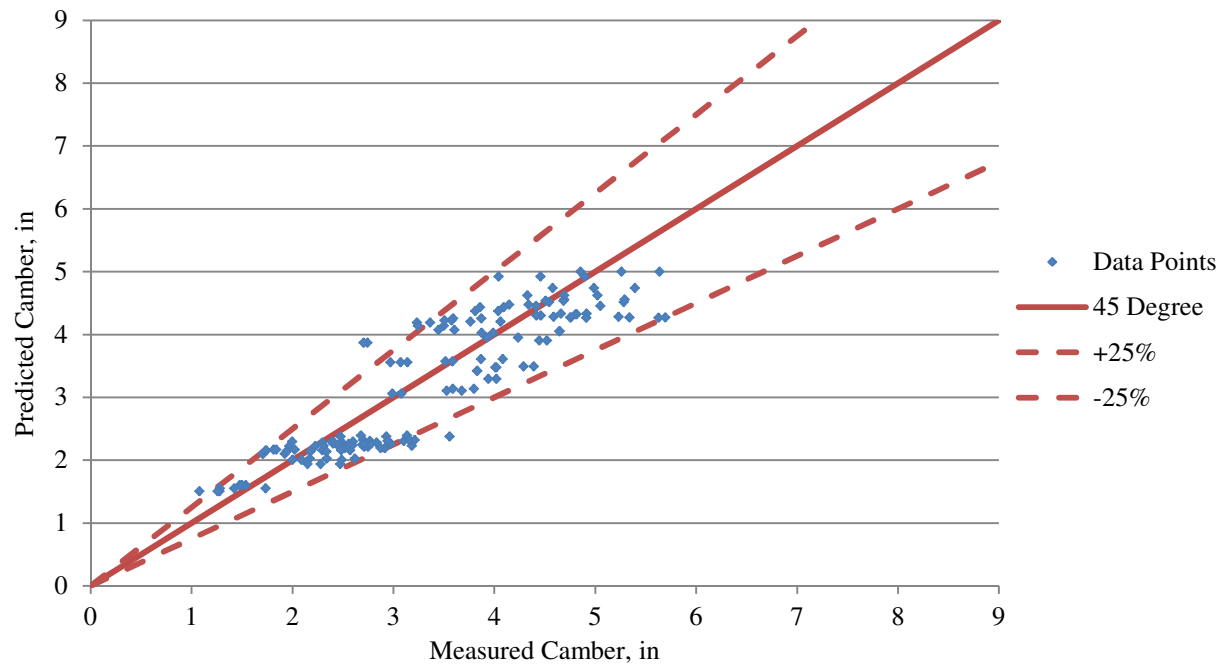
**Figure 5.21.** Comparison of predicted camber and measured camber with overhang by using Naaman's Method



**Figure 5.22.** Comparison of predicted camber and measured camber without overhang by using Naaman's Method



**Figure 5.23.** Comparison of predicted camber and measured camber with overhang by using Incremental method



**Figure 5.24.** Comparison of predicted camber and measured camber without overhang by using Incremental method

### 5.8.6 Comparison of AASHTO creep and shrinkage model and measured creep and shrinkage on the camber of girders

AASHTO unsealed creep and shrinkage values and gross section properties are typically used to calculate the long-term camber of prestressed bridge girders. If average AASHTO unsealed creep and shrinkage and gross section properties are used to calculate the long-term camber of girders during one year, it is found that the camber from AASHTO is higher on average 22% than the camber calculated by using measured sealed creep and shrinkage values and transformed section properties. That's one of reasons that the predicted camber at erection is typically higher than actual values for long-span bulb tee girders.

### 5.8.7 Calculated prestress losses and camber growth at 3-month and 1-year

Table 5.11 and Table 5.12 show the short-term and long-term prestress losses in percent and camber growth in percent at 3-month and 1-year. Transformed section properties are used to calculate the short-term and long-term losses. The camber calculated by using Naaman's

Method is used to compute camber growth (camber growth in percent =  $\frac{\Delta_{\text{long-term}} - \Delta_{\text{release}}}{\Delta_{\text{release}}} * 100\%$ ).

It is observed that for 26 girders average short-term prestress losses due to anchorage set, relaxation and elastic shortening is 7%, and average long-term prestress losses due to creep, shrinkage and relaxation is 10% at 3-month, and 12% at 1-year. It is also found that average camber growth for 26 girders is 42% at 3-month, and 50% at 1-year.

**Table 5.11.** Summary of prestress losses and camber growth at 3-month

| Girder Type | Plant | Girder I.D.                     | Prestress losses due to anchorage set, relaxation and elastic shortening | Prestress Losses due to creep, shrinkage and relaxation after 3-month | Camber Growth at 3-month |
|-------------|-------|---------------------------------|--|---|--------------------------|
| BTC 120     | A     | 103-09,<br>103-10,<br>103-11    | 6%   | 10%   | 44%                      |
| BTE 110     | B     | 144-270,<br>144-272,<br>144-268 | 6%   | 10%   | 45%                      |
|             |       | 144-274,<br>144-275,<br>144-278 | 6%   | 10%   | 44%                      |
|             |       | 144-284,<br>144-283,<br>144-280 | 6%   | 10%   | 45%                      |
| BTE 145     | B     | 144-311,<br>144-334             | 7%   | 10%   | 40%                      |
|             |       | 144-316,<br>144-317             | 7%   | 11%   | 40%                      |
|             |       | 144-366,<br>144-367             | 7%   | 10%   | 40%                      |
| BTD 135     | C     | 13501,<br>13502                 | 7%   | 10%   | 42%                      |
|             |       | 13503,<br>13504                 | 7%   | 10%   | 42%                      |
|             |       | 13507,<br>13508                 | 7%   | 10%   | 42%                      |
|             |       | 13511,<br>13512                 | 7%   | 10%   | 42%                      |
|             |       | Average                         | 7%   | 10%   | 42%                      |



**Table 5.12.** Summary of prestress losses and camber growth at 1-year

| Girder Type | Plant | Girder I.D.                     | Prestress losses due to anchorage set, relaxation and elastic shortening | Prestress Losses due to creep, shrinkage and relaxation after 1-year | Camber Growth at 1-year |
|-------------|-------|---------------------------------|--|--|-------------------------|
| BTC 120     | A     | 103-09,<br>103-10,<br>103-11    | 6%   | 12%  | 52%                     |
| BTE 110     | B     | 144-270,<br>144-272,<br>144-268 | 6%   | 12%  | 53%                     |
|             |       | 144-274,<br>144-275,<br>144-278 | 6%   | 12%  | 53%                     |
|             |       | 144-284,<br>144-283,<br>144-280 | 6%   | 12%  | 53%                     |
| BTE 145     | B     | 144-311,<br>144-334             | 7%   | 12%  | 44%                     |
|             |       | 144-316,<br>144-317             | 7%   | 12%  | 43%                     |
|             |       | 144-366,<br>144-367             | 7%   | 12%  | 47%                     |
| BTD 135     | C     | 13501,<br>13502                 | 7%   | 12%  | 49%                     |
|             |       | 13503,<br>13504                 | 7%   | 12%  | 50%                     |
|             |       | 13507,<br>13508                 | 7%   | 12%  | 50%                     |
|             |       | 13511,<br>13512                 | 7%   | 12%  | 49%                     |
|             |       | Average                         | 7%   | 12%  | 50%                     |

### 5.8.8 Effect of errors of three factors on the prediction of camber of prestressed bridge girders

Errors of three factors are considered, including modulus of elasticity, creep and shrinkage, and prestress forces. Table 5.9 shows the average effect of errors on the camber of prestressed bridge girders within one year when those factors are analyzed independently. It is found that  $\pm 20\%$  error of modulus can cause 13% error of the camber of girders, and  $\pm 20\%$  error of creep and shrinkage values can lead to 8% error of camber, and  $\pm 5\%$  error of prestress forces can result in 11% error of camber. ( $\pm 20\%$  is the error of elastic modulus of concrete discussed in Section 5.3,  $\pm 20\%$  is the typically error of creep and shrinkage tests observed from current and previous research projects, and  $\pm 5\%$  is the tolerance of error of prestress force approved by IA DOT.)

It is also found that the camber of a girder is very sensitive to the change of prestress forces, which means the inaccuracy of record of prestress forces by precast plants can lead to more error of camber. The error of modulus of elasticity of concrete has the moderate effect on the camber of girders. The error of creep and shrinkage of concrete has the least influence on the camber of a girder.

**Table 5.13.** Average effect of errors of three factors on camber of prestressed bridge girders within one year

| Sources of Errors                 | Error      | BTC 120    | BTE 110    | BTE 145    | BTD 135    | Average    |
|-----------------------------------|------------|------------|------------|------------|------------|------------|
| Modulus of Elasticity of Concrete | $\pm 20\%$ | $\pm 13\%$ | $\pm 13\%$ | $\pm 12\%$ | $\pm 12\%$ | $\pm 13\%$ |
| Creep and Shrinkage               | $\pm 20\%$ | $\pm 7\%$  | $\pm 8\%$  | $\pm 8\%$  | $\pm 8\%$  | $\pm 8\%$  |
| Prestress Forces                  | $\pm 5\%$  | $\pm 10\%$ | $\pm 10\%$ | $\pm 11\%$ | $\pm 11\%$ | $\pm 11\%$ |

### 5.8.9 Comparison of camber at erection between conspan and Naaman's Method

Table 5.14 and Table 5.15 summarize the comparison of camber at erection between Conspan and Naaman's Method for 26 prestressed bridge girders. The release camber is calculated by using Naaman's Method and transformed section properties in Table 5.14 and gross section properties in Table 5.15 respectively. Prestressed bridge girders are typically erected at the construction site at three month after transfer. Conspan uses multipliers to obtain the camber at erection, including 1.80 for camber due to prestress forces, and 1.85 for camber due to self-weight of the girder. Camber at erection by Naaman's Method utilizes transformed or gross section properties, average creep and shrinkage values at 3-month after transfer. In this section the overhang effect is not taken into account, and all corresponding cambers are calculated based on zero overhang. It is found that the camber at erection by Naaman's Method is on average 81% of camber by Consapn with transformed section properties, and 69% of camber by Conspan with gross section properties. It is also observed that the difference between the camber at erection by Naaman's Method and 80% of camber by Conspan with transformed section properties is within 3%, and the erection camber by Naaaman's Method and 70% of camber by Conspan with gross section propreties is within 5%.

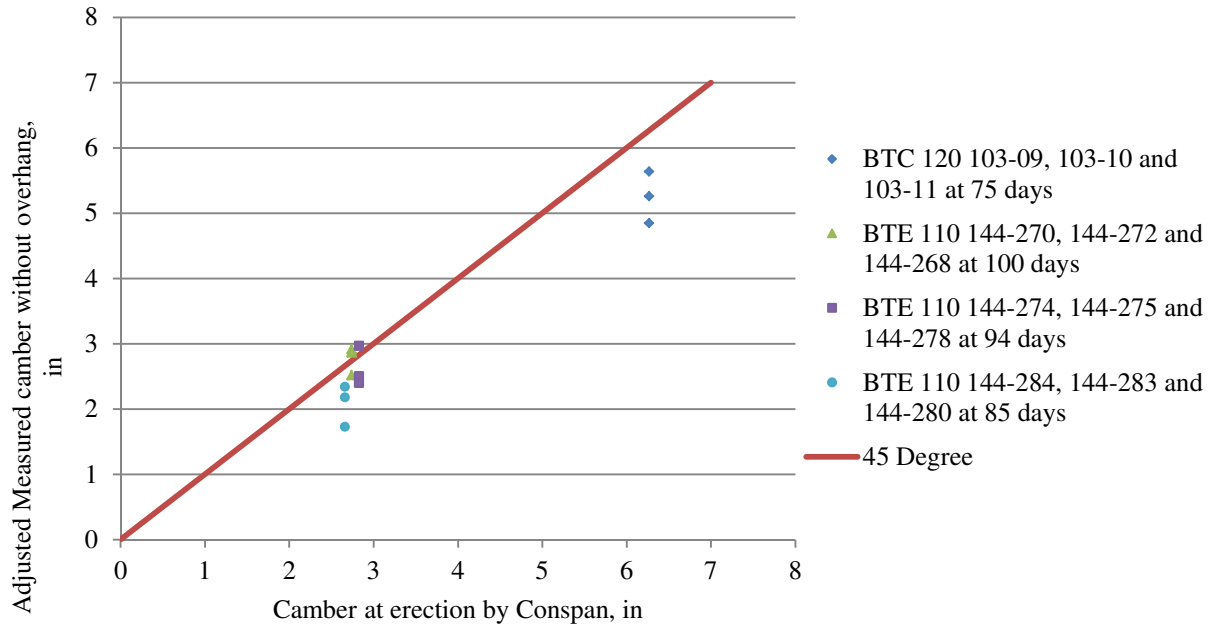
Figure 5.25 and Figure 5.26 show the comparison of adjusted measured camber without overhang in a range of 75 days to 100 days after transfer and the camber at erection by Conspan for 12 prestressed bridge girders for transformed section and gross section respectively. It is found that the camber by Conspan for transformed section is on average higher 14% than the adjusted measured camber about 3-month, and the camber by Conspan for gross section is on average higher 30% than the adjusted measured camber at erection. That's another reason why the prediction of camber at erection is typically higher than the actual value for long-span bulb tee girders.

**Table 5.14.** Comparison of camber at erection between Consplan (Itr) and Naaman's Method

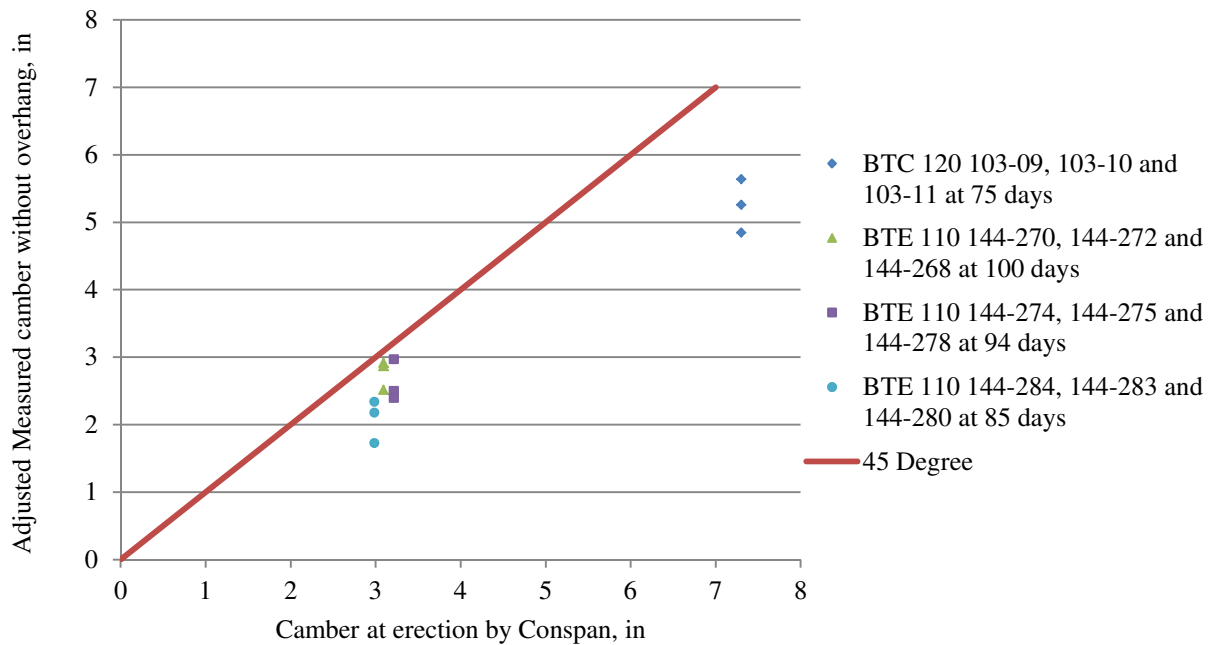
| Plant | Girder Type | Girder I.D.              | Release Camber Itr, in | Camber at Erection by Consplan Itr, in | Camber at erection by Naaman's Method Itr, in | 80% of Camber at Erection from Consplan Itr, in |
|-------|-------------|--------------------------|------------------------|--|---|---|
| A     | BTC 120     | 103-09, 103-10, 103-11   | 3.569                  | 6.265                                  | 5.147   | 5.012   |
| B     | BTE 110     | 144-270,144-272, 144-268 | 1.561                  | 2.737                                  | 2.256   | 2.190   |
| B     | BTE 110     | 144-274,144-275, 144-278 | 1.613                  | 2.828                                  | 2.329   | 2.262   |
| B     | BTE 110     | 144-284,144-283, 144-280 | 1.517                  | 2.660                                  | 2.193   | 2.128   |
| B     | BTE 145     | 144-311, 144-334         | 3.154                  | 5.491                                  | 4.421   | 4.393   |
| B     | BTE 145     | 144-316, 144-317         | 3.129                  | 5.442                                  | 4.375   | 4.354   |
| B     | BTE 145     | 144-366, 144-367         | 3.018                  | 5.252                                  | 4.227   | 4.201   |
| C     | BTD 135     | 13501, 13502             | 3.438                  | 6.002                                  | 4.880   | 4.802   |
| C     | BTD 135     | 13503, 13504             | 3.507                  | 6.126                                  | 4.988   | 4.901   |
| C     | BTD 135     | 13507, 13508             | 3.492                  | 6.100                                  | 4.968   | 4.880   |
| C     | BTD 135     | 13511, 13512             | 3.308                  | 5.777                                  | 4.694   | 4.621   |

**Table 5.15.** Comparison of camber at erection between Consplan (Ig) and Naaman's Method

| Plant | Girder Type | Girder I.D.              | Release Camber Ig, in | Camber at Erection from Consplan Ig, in | Camber at erection from Naaman' Method Itr, in | 70% of Camber at Erection from Consplan Ig, in |
|-------|-------------|--------------------------|-----------------------|---|--|--|
| A     | BTC 120     | 103-09, 103-10, 103-11   | 4.15                  | 7.300                                   | 5.147  | 5.110  |
| B     | BTE 110     | 144-270,144-272, 144-268 | 1.76                  | 3.091                                   | 2.256  | 2.163  |
| B     | BTE 110     | 144-274,144-275, 144-278 | 1.83                  | 3.214                                   | 2.329  | 2.249  |
| B     | BTE 110     | 144-284,144-283, 144-280 | 1.7                   | 2.986                                   | 2.193  | 2.090  |
| B     | BTE 145     | 144-311, 144-334         | 3.76                  | 6.568                                   | 4.421  | 4.597  |
| B     | BTE 145     | 144-316, 144-317         | 3.75                  | 6.546                                   | 4.375  | 4.582  |
| B     | BTE 145     | 144-366, 144-367         | 3.58                  | 6.251                                   | 4.227  | 4.375  |
| C     | BTD 135     | 13501, 13502             | 4.11                  | 7.198                                   | 4.880  | 5.039  |
| C     | BTD 135     | 13503, 13504             | 4.19                  | 7.342                                   | 4.988  | 5.139  |
| C     | BTD 135     | 13507, 13508             | 4.16                  | 7.289                                   | 4.968  | 5.102  |
| C     | BTD 135     | 13511, 13512             | 3.91                  | 6.848                                   | 4.694  | 4.794  |



**Figure 5.25.** Comparison of adjusted measured camber without overhang at erection with camber at erection by Conspan with Itr



**Figure 5.26.** Comparison of adjusted measured camber without overhang at erection with camber at erection by Conspan with Ig

#### **5.8.10 Comparison of current study with three previous studies**

It was observed that refined method of prestress losses from AASHTO LRFD 2010 had good prediction, which was consistent with four studies. Comparing with three previous studies discussed in Section 2.4.3, more things had been done and found beyond previous studies. In the current study, creep and shrinkage tests of four HPC mixes and three NC mixes during one year from three precast plants were taken, and decent data were collected. It was found that the HPC crept and shrink more than NC due to the use of slag and fly ash and the early age of loading application. Creep and shrinkage behavior between laboratory specimens and the full scale girder was correlated, and it was found that the sealed laboratory specimens could represent the creep and shrinkage behavior of the full scale girder. Additionally, a simplified time-dependent method (Naaman's Method) was recommended to predict long-term camber of a girder due to the uncertainty of erection time after production of a girder, which had the higher accuracy than the simply multipliers.

## CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

In this chapter, conclusions of this study are presented in Section 6.1, and recommendations of creep and shrinkage tests and prediction of long-term camber of prestressed bridge girders are discussed in Section 6.2.

### 6.1 Conclusions

In this study, objectives have been completed. It was found that the creep and shrinkage behavior between the measured and five models have large discrepancies. This is one source of error of camber prediction at erection. It was also observed that sealed specimens could represent the behavior of the full scale girders more effectively than unsealed specimens. It was observed that camber of 26 girders investigated in this study calculated by using AASHTO creep and shrinkage model is higher on average 22% than the camber computed by using measured creep and shrinkage values in the sealed specimens.

The IA DOT's current camber prediction method of simple multipliers for camber at release results in large differences with the actual camber at erection due to the uncertainty of time of erection after production, neglect of time-dependent material properties and environmental conditions, and the use of gross rather than transformed section properties. With this current method, camber of long span bulb tee girders is often over-predicted by more than 30%. Naaman's Method, which is relatively simple yet accounts for the factors listed above, yields a more accurate camber prediction with  $\pm 25\%$  errors with measured camber of girders.

In this study the following conclusions can also be made:

- The errors of modulus of elasticity of concrete are  $\pm 20\%$  between the predicted values by using AASHTO model and the measured values;
- AASHTO LRFD 2010 model is the most appropriate model to predict creep and shrinkage of seven groups of concretes for both HPC and NC relative to the rest of four

models investigated, including ACI 209R-90 model, ACI 209R-Modified by Huo model, CEB-FIP 90 model and the B3 model (Bazant). Although AASHTO LRFD 2010 model is better than the rest of four models, large errors exist between measured values and predicted values by using AASHTO model, i.e. under-prediction of sealed creep coefficient and sealed shrinkage on average by 32% and 44% respectively during one year;

- Sealed specimens of concrete represent the behavior of creep and shrinkage of the full scale prestressed bridge girder much better than unsealed specimens;
- Results of creep and shrinkage tests from sealed specimens have less standard deviation between four HPC mixes than unsealed specimens, which means the errors of results of creep and shrinkage of sealed specimens are smaller than those of unsealed specimens;
- The camber of 26 girders by gross section properties is on average 13% higher than the camber computed using transformed section properties during one year;
- Average error of the results of camber of girder is within 2% during one year between average creep coefficient and average shrinkage strain and specified sealed creep coefficient and specified shrinkage strain;
- For the prediction of long-term camber of prestressed bridge girders, Naaman's Method is recommended. Both Naaman's Method and the incremental method have the similar results, and the errors between the predicted and the measured values are within  $\pm 25\%$ . It is also easier for the calculations to use Naaman's Method than the the incremental method, and both of them yield the better predictions than Tadros's Method;
- The calculated average short-term prestress loss for 26 girders is 7%, and the average long-term prestress loss is 10% at 3-months and 12% at 1-year. Average camber growth for 26 girders is 42% at 3-months and 50% at 1-year;
- Camber of the prestressed girder is more sensitive to the error of prestress forces than modulus of elasticity and creep and shrinkage;
- Consplan typically overestimates camber at erection comparing with results by Naaman's Method. The difference between the camber at erection by Naaman's Method and 70% of camber by Consplan for gross section is within 5%.



## 6.2 Recommendations

Inaccuracy of prediction of creep and shrinkage by the current approach with no consideration of time-effects results in 31% average errors of camber at erection. This over-estimation of camber of the girder could lead to the increase of cost due to field modification of concrete haunches between the bridge girder and deck. In order to improve the accuracy of the prediction of the long-term camber of prestressed bridge girders, the following recommendations are provided:

- It is acceptable to use AASHTO model to predict modulus of elasticity of concrete according to the corresponding compressive strength and density of concrete;
- In order to obtain more accurate results, creep and shrinkage tests results of concrete using local materials in Iowa should be used;
- Sealed specimens should be used to obtain the similar behavior of creep and shrinkage of the full scale prestressed bridge girder;
- It is acceptable to use average sealed creep coefficient and average sealed shrinkage of four HPC mixes to predict the long-term camber of prestressed bridge girders within one year, and the proposed equations of sealed creep coefficient and sealed shrinkage can be applied to predict the long-term camber after one year;
- For the prediction of the long-term camber of 26 prestressed bridge girders, Naaman's Method is the recommended method comparing with Tadros's Method and the incremental method, and the errors of the prediction of camber are within  $\pm 25\%$ ;
- Transformed section properties should be utilized for the calculation of the camber of prestressed bridge girders;
- The measurement of prestress forces should be improved by precast plants due to the sensitivity of the camber of the girder to the error of prestress forces. Elongation of each strand should be recorded carefully before and after jacking;
- 70% of camber at erection (typically 3-month after transfer) by Conspan for gross section can be used to estimate the camber of 26 girders at erection.

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## **APPENDIX A**

### **Photographs**



**Figure A.1.** Sulfur-capped sealed and unsealed specimens



**Figure A.2.** Compressive strength test of a cylindrical specimen



**Figure A.3.** Loaded specimens for creep tests in the environmentally controlled chamber



**Figure A.4.** Unloaded specimens for shrinkage tests in the environmentally controlled chamber





**Figure A.5.** Device and Measurement of strain by using the DEMEC gage



**Figure A.6.** Debonded 4-ft BTB Beam section stored in precast plant A





**Figure A.7.** A Type D 60 prestressed bridge girder stored in precast plant C



**Figure A.8.** Support of a Type D 60 prestressed bridge girder stored in precast plant C

## **APPENDIX B**

### **Comparison of Measured Results of Creep and Shrinkage Tests and Five Models**

**Table B.1.** Comparison of measured unsealed creep coefficient with five models for HPC 1

| Time after Loading,<br>days | Measured Creep<br>Coefficient | AASHTO LRFD<br>2010 | ACI 209R-<br>1990 | ACI 209R-Modified by<br>Huo | CEB-FIP<br>90 | Bazant B3 |
|-----------------------------|-------------------------------|---------------------|-------------------|-----------------------------|---------------|-----------|
| 0                           | 0.00000                       | 0.00000             | 0.00000           | 0.00000                     | 0.00000       | 0.00000   |
| 0                           | 0.00000                       | 0.00000             | 0.00000           | 0.00000                     | 0.00000       | 0.00000   |
| 1                           | 0.04613                       | 0.05241             | 0.31131           | 0.31216                     | 0.80745       | 1.07852   |
| 2                           | 0.09829                       | 0.10190             | 0.45072           | 0.44646                     | 0.83970       | 1.11907   |
| 3                           | 0.13338                       | 0.14870             | 0.55475           | 0.54455                     | 0.86912       | 1.15609   |
| 7                           | 0.21138                       | 0.31300             | 0.83292           | 0.79838                     | 0.96702       | 1.27985   |
| 14                          | 0.29875                       | 0.53445             | 1.12176           | 1.04960                     | 1.09369       | 1.44298   |
| 21                          | 0.35857                       | 0.69938             | 1.31231           | 1.20889                     | 1.18953       | 1.57035   |
| 28                          | 0.41839                       | 0.82700             | 1.45454           | 1.32460                     | 1.26720       | 1.67688   |
| 60                          | 0.60306                       | 1.16798             | 1.84379           | 1.62816                     | 1.50709       | 2.02647   |
| 90                          | 0.62695                       | 1.32764             | 2.04791           | 1.78011                     | 1.64940       | 2.24439   |
| 120                         | 0.64573                       | 1.42504             | 2.18729           | 1.88116                     | 1.75302       | 2.40274   |
| 150                         | 0.66325                       | 1.49066             | 2.29101           | 1.95498                     | 1.83326       | 2.52214   |
| 180                         | 0.68093                       | 1.53787             | 2.37237           | 2.01208                     | 1.89783       | 2.61470   |
| 210                         | 0.70615                       | 1.57346             | 2.43855           | 2.05802                     | 1.95122       | 2.68818   |
| 240                         | 0.72343                       | 1.60125             | 2.49383           | 2.09605                     | 1.99627       | 2.74774   |
| 270                         | 0.74416                       | 1.62356             | 2.54094           | 2.12821                     | 2.03488       | 2.79696   |
| 300                         | 0.78917                       | 1.64186             | 2.58174           | 2.15589                     | 2.06841       | 2.83834   |
| 330                         | 0.78859                       | 1.65714             | 2.61754           | 2.18003                     | 2.09783       | 2.87366   |
| 360                         | 0.78800                       | 1.67009             | 2.64929           | 2.20134                     | 2.12388       | 2.90425   |

**Table B.2.** Comparison of measured sealed creep coefficient with five models for HPC 1

| Time after Loading,<br>days | Measured Creep<br>Coefficient | AASHTO LRFD<br>2010 | ACI 209R-<br>1990 | ACI 209R-Modified by<br>Huo | CEB-FIP<br>90 | Bazant B3 |
|-----------------------------|-------------------------------|---------------------|-------------------|-----------------------------|---------------|-----------|
| 0                           | 0.00000                       | 0.00000             | 0.00000           | 0.00000                     | 0.00000       | 0.00000   |
| 0                           | 0.00000                       | 0.00000             | 0.00000           | 0.00000                     | 0.00000       | 0.00000   |
| 1                           | 0.17186                       | 0.02601             | 0.09485           | 0.09511                     | 0.27535       | 0.85135   |
| 2                           | 0.20138                       | 0.05058             | 0.13733           | 0.13603                     | 0.28654       | 0.87873   |
| 3                           | 0.25699                       | 0.07380             | 0.16902           | 0.16591                     | 0.29679       | 0.90322   |
| 7                           | 0.38265                       | 0.15535             | 0.25377           | 0.24325                     | 0.33114       | 0.98144   |
| 14                          | 0.48378                       | 0.26527             | 0.34178           | 0.31979                     | 0.37630       | 1.07570   |
| 21                          | 0.52042                       | 0.34713             | 0.39984           | 0.36832                     | 0.41119       | 1.14258   |
| 28                          | 0.55707                       | 0.41047             | 0.44317           | 0.40358                     | 0.44003       | 1.19446   |
| 60                          | 0.76635                       | 0.57972             | 0.56176           | 0.49607                     | 0.53359       | 1.34541   |
| 90                          | 0.84151                       | 0.65897             | 0.62396           | 0.54236                     | 0.59368       | 1.43143   |
| 120                         | 0.88788                       | 0.70731             | 0.66642           | 0.57315                     | 0.64056       | 1.49408   |
| 150                         | 0.92430                       | 0.73988             | 0.69802           | 0.59564                     | 0.67921       | 1.54338   |
| 180                         | 0.94038                       | 0.76331             | 0.72281           | 0.61304                     | 0.71216       | 1.58403   |
| 210                         | 0.95341                       | 0.78098             | 0.74298           | 0.62704                     | 0.74091       | 1.61862   |
| 240                         | 0.95564                       | 0.79477             | 0.75982           | 0.63862                     | 0.76639       | 1.64872   |
| 270                         | 0.95299                       | 0.80584             | 0.77417           | 0.64842                     | 0.78926       | 1.67537   |
| 300                         | 0.98059                       | 0.81492             | 0.78660           | 0.65685                     | 0.81000       | 1.69927   |
| 330                         | 1.00290                       | 0.82251             | 0.79751           | 0.66421                     | 0.82894       | 1.72095   |
| 360                         | 1.02522                       | 0.82894             | 0.80718           | 0.67070                     | 0.84636       | 1.74077   |



**Table B.3.** Comparison of measured unsealed shrinkage with five models for HPC 1

| Time after Loading, days | Measured Shrinkage | AASHTO LRFD<br>2010 | ACI 209R-<br>1990 | ACI 209R-Modified by<br>Huo | CEB-FIP<br>90 | Bazant B3 |
|--------------------------|--------------------|---------------------|-------------------|-----------------------------|---------------|-----------|
| 0                        | 0                  | 0                   | 0                 | 0                           | 0             | 0         |
| 0                        | 0                  | 0                   | 0                 | 0                           | 0             | 0         |
| 1                        | 98                 | 15                  | 8                 | 15                          | 147           | 152       |
| 2                        | 163                | 30                  | 17                | 29                          | 156           | 162       |
| 3                        | 166                | 43                  | 24                | 41                          | 165           | 172       |
| 7                        | 219                | 91                  | 53                | 84                          | 194           | 207       |
| 14                       | 276                | 155                 | 96                | 136                         | 232           | 255       |
| 21                       | 285                | 203                 | 131               | 171                         | 262           | 292       |
| 28                       | 295                | 239                 | 159               | 197                         | 285           | 322       |
| 60                       | 319                | 338                 | 247               | 260                         | 353           | 414       |
| 90                       | 353                | 384                 | 293               | 287                         | 390           | 462       |
| 120                      | 373                | 413                 | 324               | 302                         | 414           | 493       |
| 150                      | 392                | 432                 | 346               | 312                         | 431           | 513       |
| 180                      | 414                | 445                 | 362               | 319                         | 444           | 528       |
| 210                      | 433                | 456                 | 374               | 325                         | 455           | 538       |
| 240                      | 443                | 464                 | 384               | 329                         | 463           | 546       |
| 270                      | 453                | 470                 | 393               | 332                         | 469           | 551       |
| 300                      | 500                | 475                 | 399               | 335                         | 475           | 556       |
| 330                      | 538                | 480                 | 405               | 337                         | 480           | 559       |
| 360                      | 576                | 484                 | 410               | 339                         | 484           | 562       |

**Table B.4.** Comparison of measured sealed shrinkage with five models for HPC 1

| Time after Loading, days | Measured Shrinkage | AASHTO LRFD<br>2010 | ACI 209R-<br>1990 | ACI 209R-Modified by<br>Huo | CEB-FIP<br>90 | Bazant B3 |
|--------------------------|--------------------|---------------------|-------------------|-----------------------------|---------------|-----------|
| 0                        | 0                  | 0                   | \                 | \                           | \             | 0         |
| 0                        | 0                  | 0                   | \                 | \                           | \             | 0         |
| 1                        | 31                 | 5                   | \                 | \                           | \             | 23        |
| 2                        | 62                 | 10                  | \                 | \                           | \             | 24        |
| 3                        | 59                 | 15                  | \                 | \                           | \             | 26        |
| 7                        | 74                 | 32                  | \                 | \                           | \             | 31        |
| 14                       | 101                | 54                  | \                 | \                           | \             | 38        |
| 21                       | 115                | 71                  | \                 | \                           | \             | 43        |
| 28                       | 129                | 84                  | \                 | \                           | \             | 47        |
| 60                       | 151                | 118                 | \                 | \                           | \             | 59        |
| 90                       | 171                | 134                 | \                 | \                           | \             | 65        |
| 120                      | 180                | 144                 | \                 | \                           | \             | 68        |
| 150                      | 187                | 151                 | \                 | \                           | \             | 70        |
| 180                      | 188                | 156                 | \                 | \                           | \             | 72        |
| 210                      | 192                | 159                 | \                 | \                           | \             | 73        |
| 240                      | 197                | 162                 | \                 | \                           | \             | 73        |
| 270                      | 205                | 164                 | \                 | \                           | \             | 74        |
| 300                      | 213                | 166                 | \                 | \                           | \             | 74        |
| 330                      | 214                | 168                 | \                 | \                           | \             | 75        |
| 360                      | 214                | 169                 | \                 | \                           | \             | 75        |

**Table B.5.** Comparison of measured unsealed creep coefficient with five models for HPC 2

| Time after Loading,<br>days | Measured Creep<br>Coefficient | AASHTO LRFD<br>2010 | ACI 209R-<br>1990 | ACI 209R-Modified by<br>Huo | CEB-FIP<br>90 | Bazant B3 |
|-----------------------------|-------------------------------|---------------------|-------------------|-----------------------------|---------------|-----------|
| 0                           | 0.00000                       | 0.00000             | 0.00000           | 0.00000                     | 0.00000       | 0.00000   |
| 0                           | 0.00000                       | 0.00000             | 0.00000           | 0.00000                     | 0.00000       | 0.00000   |
| 1                           | 0.10519                       | 0.05303             | 0.31131           | 0.31199                     | 0.84775       | 0.86016   |
| 2                           | 0.13924                       | 0.10326             | 0.45072           | 0.44734                     | 0.88160       | 0.89415   |
| 3                           | 0.20651                       | 0.15092             | 0.55475           | 0.54664                     | 0.91249       | 0.92510   |
| 7                           | 0.36018                       | 0.31940             | 0.83292           | 0.80532                     | 1.01528       | 1.02785   |
| 14                          | 0.57533                       | 0.54939             | 1.12176           | 1.06382                     | 1.14826       | 1.16162   |
| 21                          | 0.72104                       | 0.72291             | 1.31231           | 1.22901                     | 1.24889       | 1.26481   |
| 28                          | 0.80130                       | 0.85847             | 1.45454           | 1.34965                     | 1.33043       | 1.35035   |
| 60                          | 0.86230                       | 1.22646             | 1.84379           | 1.66871                     | 1.58230       | 1.62743   |
| 90                          | 0.88825                       | 1.40171             | 2.04791           | 1.82982                     | 1.73171       | 1.79863   |
| 120                         | 0.93161                       | 1.50957             | 2.18729           | 1.93750                     | 1.84050       | 1.92306   |
| 150                         | 0.96715                       | 1.58263             | 2.29101           | 2.01642                     | 1.92474       | 2.01727   |
| 180                         | 0.99976                       | 1.63540             | 2.37237           | 2.07764                     | 1.99253       | 2.09076   |
| 210                         | 1.03922                       | 1.67530             | 2.43855           | 2.12698                     | 2.04859       | 2.14953   |
| 240                         | 1.07995                       | 1.70652             | 2.49383           | 2.16789                     | 2.09588       | 2.19757   |
| 270                         | 1.10826                       | 1.73163             | 2.54094           | 2.20254                     | 2.13643       | 2.23759   |
| 300                         | 1.17376                       | 1.75225             | 2.58174           | 2.23239                     | 2.17163       | 2.27152   |
| 330                         | 1.21172                       | 1.76949             | 2.61754           | 2.25846                     | 2.20252       | 2.30073   |
| 360                         | 1.26346                       | 1.78411             | 2.64929           | 2.28149                     | 2.22986       | 2.32622   |

**Table B.6.** Comparison of measured sealed creep coefficient with five models for HPC 2

| Time after Loading,<br>days | Measured Creep<br>Coefficient | AASHTO LRFD<br>2010 | ACI 209R-<br>1990 | ACI 209R-Modified by<br>Huo | CEB-FIP<br>90 | Bazant B3 |
|-----------------------------|-------------------------------|---------------------|-------------------|-----------------------------|---------------|-----------|
| 0                           | 0.00000                       | 0.00000             | 0.00000           | 0.00000                     | 0.00000       | 0.00000   |
| 0                           | 0.00000                       | 0.00000             | 0.00000           | 0.00000                     | 0.00000       | 0.00000   |
| 1                           | 0.20649                       | 0.02632             | 0.09485           | 0.09506                     | 0.28909       | 0.69856   |
| 2                           | 0.27289                       | 0.05125             | 0.13733           | 0.13629                     | 0.30084       | 0.72319   |
| 3                           | 0.42961                       | 0.07491             | 0.16902           | 0.16655                     | 0.31160       | 0.74522   |
| 7                           | 0.55016                       | 0.15853             | 0.25377           | 0.24536                     | 0.34767       | 0.81558   |
| 14                          | 0.71894                       | 0.27269             | 0.34178           | 0.32412                     | 0.39508       | 0.90036   |
| 21                          | 0.82920                       | 0.35881             | 0.39984           | 0.37446                     | 0.43171       | 0.96052   |
| 28                          | 0.88609                       | 0.42610             | 0.44317           | 0.41121                     | 0.46198       | 1.00718   |
| 60                          | 0.99837                       | 0.60875             | 0.56176           | 0.50842                     | 0.56022       | 1.14296   |
| 90                          | 1.03454                       | 0.69573             | 0.62396           | 0.55751                     | 0.62331       | 1.22033   |
| 120                         | 1.05018                       | 0.74926             | 0.66642           | 0.59032                     | 0.67252       | 1.27668   |
| 150                         | 1.06514                       | 0.78553             | 0.69802           | 0.61436                     | 0.71310       | 1.32102   |
| 180                         | 1.08155                       | 0.81172             | 0.72281           | 0.63301                     | 0.74770       | 1.35759   |
| 210                         | 1.10117                       | 0.83152             | 0.74298           | 0.64805                     | 0.77788       | 1.38870   |
| 240                         | 1.12276                       | 0.84702             | 0.75982           | 0.66051                     | 0.80463       | 1.41578   |
| 270                         | 1.13770                       | 0.85948             | 0.77417           | 0.67107                     | 0.82865       | 1.43974   |
| 300                         | 1.13435                       | 0.86971             | 0.78660           | 0.68016                     | 0.85042       | 1.46125   |
| 330                         | 1.15021                       | 0.87827             | 0.79751           | 0.68811                     | 0.87030       | 1.48074   |
| 360                         | 1.15647                       | 0.88553             | 0.80718           | 0.69512                     | 0.88859       | 1.49857   |

**Table B.7.** Comparison of measured unsealed shrinkage with five models for HPC 2

| Time after Loading, days | Measured Shrinkage | AASHTO LRFD<br>2010 | ACI 209R-<br>1990 | ACI 209R-Modified by<br>Huo | CEB-FIP<br>90 | Bazant B3 |
|--------------------------|--------------------|---------------------|-------------------|-----------------------------|---------------|-----------|
| 0                        | 0                  | 0                   | 0                 | 0                           | 0             | 0         |
| 0                        | 0                  | 0                   | 0                 | 0                           | 0             | 0         |
| 1                        | 51                 | 15                  | 10                | 17                          | 163           | 162       |
| 2                        | 76                 | 30                  | 19                | 32                          | 174           | 174       |
| 3                        | 125                | 44                  | 28                | 47                          | 183           | 185       |
| 7                        | 132                | 92                  | 61                | 95                          | 216           | 222       |
| 14                       | 142                | 159                 | 110               | 156                         | 259           | 273       |
| 21                       | 150                | 209                 | 150               | 199                         | 291           | 312       |
| 28                       | 157                | 249                 | 183               | 230                         | 317           | 345       |
| 60                       | 216                | 355                 | 284               | 308                         | 393           | 442       |
| 90                       | 254                | 406                 | 338               | 341                         | 434           | 494       |
| 120                      | 287                | 437                 | 373               | 361                         | 461           | 527       |
| 150                      | 319                | 458                 | 398               | 374                         | 480           | 549       |
| 180                      | 344                | 474                 | 417               | 383                         | 494           | 564       |
| 210                      | 366                | 485                 | 431               | 390                         | 506           | 576       |
| 240                      | 383                | 494                 | 442               | 395                         | 515           | 584       |
| 270                      | 396                | 501                 | 452               | 400                         | 522           | 590       |
| 300                      | 404                | 507                 | 460               | 403                         | 529           | 594       |
| 330                      | 418                | 512                 | 466               | 406                         | 534           | 598       |
| 360                      | 429                | 517                 | 472               | 408                         | 539           | 601       |

**Table B.8.** Comparison of measured sealed shrinkage with five models for HPC 2

| Time after Loading, days | Measured Shrinkage | AASHTO LRFD<br>2010 | ACI 209R-<br>1990 | ACI 209R-Modified by<br>Huo | CEB-FIP<br>90 | Bazant B3 |
|--------------------------|--------------------|---------------------|-------------------|-----------------------------|---------------|-----------|
| 0                        | 0                  | 0                   | \                 | \                           | \             | 0         |
| 0                        | 0                  | 0                   | \                 | \                           | \             | 0         |
| 1                        | 20                 | 5                   | \                 | \                           | \             | 24        |
| 2                        | 30                 | 10                  | \                 | \                           | \             | 26        |
| 3                        | 46                 | 15                  | \                 | \                           | \             | 28        |
| 7                        | 50                 | 32                  | \                 | \                           | \             | 33        |
| 14                       | 54                 | 56                  | \                 | \                           | \             | 40        |
| 21                       | 61                 | 73                  | \                 | \                           | \             | 46        |
| 28                       | 68                 | 87                  | \                 | \                           | \             | 50        |
| 60                       | 131                | 124                 | \                 | \                           | \             | 63        |
| 90                       | 185                | 142                 | \                 | \                           | \             | 69        |
| 120                      | 216                | 153                 | \                 | \                           | \             | 73        |
| 150                      | 245                | 160                 | \                 | \                           | \             | 75        |
| 180                      | 260                | 166                 | \                 | \                           | \             | 77        |
| 210                      | 269                | 170                 | \                 | \                           | \             | 78        |
| 240                      | 279                | 173                 | \                 | \                           | \             | 79        |
| 270                      | 290                | 175                 | \                 | \                           | \             | 79        |
| 300                      | 302                | 177                 | \                 | \                           | \             | 79        |
| 330                      | 313                | 179                 | \                 | \                           | \             | 80        |
| 360                      | 324                | 181                 | \                 | \                           | \             | 80        |

**Table B.9.** Comparison of measured unsealed creep coefficient with five models for HPC 3

| Time after Loading,<br>days | Measured Creep<br>Coefficient | AASHTO LRFD<br>2010 | ACI 209R-<br>1990 | ACI 209R-Modified by<br>Huo | CEB-FIP<br>90 | Bazant B3 |
|-----------------------------|-------------------------------|---------------------|-------------------|-----------------------------|---------------|-----------|
| 0                           | 0.00000                       | 0.00000             | 0.00000           | 0.00000                     | 0.00000       | 0.00000   |
| 0                           | 0.00000                       | 0.00000             | 0.00000           | 0.00000                     | 0.00000       | 0.00000   |
| 1                           | 0.07272                       | 0.05495             | 0.31131           | 0.31177                     | 0.91166       | 0.99677   |
| 2                           | 0.30072                       | 0.10725             | 0.45072           | 0.44839                     | 0.94807       | 1.03315   |
| 3                           | 0.30802                       | 0.15708             | 0.55475           | 0.54915                     | 0.98128       | 1.06643   |
| 7                           | 0.35181                       | 0.33487             | 0.83292           | 0.81376                     | 1.09182       | 1.17809   |
| 14                          | 0.35113                       | 0.58183             | 1.12176           | 1.08130                     | 1.23483       | 1.32623   |
| 21                          | 0.35019                       | 0.77148             | 1.31231           | 1.25393                     | 1.34305       | 1.44255   |
| 28                          | 0.34897                       | 0.92170             | 1.45454           | 1.38082                     | 1.43074       | 1.54016   |
| 60                          | 0.35959                       | 1.33880             | 1.84379           | 1.71983                     | 1.70159       | 1.86109   |
| 90                          | 0.37776                       | 1.54238             | 2.04791           | 1.89293                     | 1.86226       | 2.06017   |
| 120                         | 0.37773                       | 1.66929             | 2.18729           | 2.00934                     | 1.97926       | 2.20363   |
| 150                         | 0.37764                       | 1.75599             | 2.29101           | 2.09504                     | 2.06985       | 2.31088   |
| 180                         | 0.37749                       | 1.81897             | 2.37237           | 2.16172                     | 2.14275       | 2.39337   |
| 210                         | 0.38106                       | 1.86679             | 2.43855           | 2.21561                     | 2.20304       | 2.45840   |
| 240                         | 0.40511                       | 1.90434             | 2.49383           | 2.26038                     | 2.25390       | 2.51080   |
| 270                         | 0.42800                       | 1.93461             | 2.54094           | 2.29837                     | 2.29750       | 2.55388   |
| 300                         | 0.45176                       | 1.95953             | 2.58174           | 2.33115                     | 2.33535       | 2.58995   |
| 330                         | 0.47493                       | 1.98039             | 2.61754           | 2.35981                     | 2.36857       | 2.62064   |
| 360                         | 0.49840                       | 1.99813             | 2.64929           | 2.38516                     | 2.39798       | 2.64715   |

**Table B.10.** Comparison of measured sealed creep coefficient with five models for HPC 3

| Time after Loading,<br>days | Measured Creep<br>Coefficient | AASHTO LRFD<br>2010 | ACI 209R-<br>1990 | ACI 209R-Modified by<br>Huo | CEB-FIP<br>90 | Bazant B3 |
|-----------------------------|-------------------------------|---------------------|-------------------|-----------------------------|---------------|-----------|
| 0                           | 0.00000                       | 0.00000             | 0.00000           | 0.00000                     | 0.00000       | 0.00000   |
| 0                           | 0.00000                       | 0.00000             | 0.00000           | 0.00000                     | 0.00000       | 0.00000   |
| 1                           | 0.15996                       | 0.02728             | 0.09485           | 0.09499                     | 0.31088       | 0.77902   |
| 2                           | 0.36042                       | 0.05323             | 0.13733           | 0.13662                     | 0.32352       | 0.80268   |
| 3                           | 0.38626                       | 0.07796             | 0.16902           | 0.16732                     | 0.33509       | 0.82385   |
| 7                           | 0.54134                       | 0.16621             | 0.25377           | 0.24794                     | 0.37388       | 0.89146   |
| 14                          | 0.56266                       | 0.28879             | 0.34178           | 0.32945                     | 0.42487       | 0.97292   |
| 21                          | 0.59250                       | 0.38292             | 0.39984           | 0.38205                     | 0.46425       | 1.03072   |
| 28                          | 0.63087                       | 0.45748             | 0.44317           | 0.42071                     | 0.49681       | 1.07556   |
| 60                          | 0.68287                       | 0.66451             | 0.56176           | 0.52400                     | 0.60245       | 1.20603   |
| 90                          | 0.73522                       | 0.76555             | 0.62396           | 0.57674                     | 0.67030       | 1.28037   |
| 120                         | 0.75161                       | 0.82854             | 0.66642           | 0.61221                     | 0.72322       | 1.33451   |
| 150                         | 0.78198                       | 0.87157             | 0.69802           | 0.63831                     | 0.76686       | 1.37712   |
| 180                         | 0.81697                       | 0.90283             | 0.72281           | 0.65863                     | 0.80407       | 1.41225   |
| 210                         | 0.84013                       | 0.92657             | 0.74298           | 0.67505                     | 0.83652       | 1.44215   |
| 240                         | 0.84229                       | 0.94521             | 0.75982           | 0.68869                     | 0.86530       | 1.46817   |
| 270                         | 0.87278                       | 0.96023             | 0.77417           | 0.70027                     | 0.89112       | 1.49120   |
| 300                         | 0.88203                       | 0.97260             | 0.78660           | 0.71025                     | 0.91453       | 1.51186   |
| 330                         | 0.90544                       | 0.98295             | 0.79751           | 0.71899                     | 0.93592       | 1.53059   |
| 360                         | 0.92176                       | 0.99176             | 0.80718           | 0.72671                     | 0.95558       | 1.54772   |



**Table B.11.** Comparison of measured unsealed shrinkage with five models for HPC 3

| Time after Loading, days | Measured Shrinkage | AASHTO LRFD<br>2010 | ACI 209R-<br>1990 | ACI 209R-Modified by<br>Huo | CEB-FIP<br>90 | Bazant B3 |
|--------------------------|--------------------|---------------------|-------------------|-----------------------------|---------------|-----------|
| 0                        | 0                  | 0                   | 0                 | 0                           | 0             | 0         |
| 0                        | 0                  | 0                   | 0                 | 0                           | 0             | 0         |
| 1                        | 105                | 16                  | 8                 | 14                          | 185           | 172       |
| 2                        | 147                | 31                  | 17                | 27                          | 197           | 184       |
| 3                        | 164                | 45                  | 24                | 39                          | 208           | 195       |
| 7                        | 265                | 97                  | 53                | 81                          | 245           | 234       |
| 14                       | 277                | 168                 | 96                | 135                         | 293           | 288       |
| 21                       | 295                | 223                 | 130               | 174                         | 330           | 329       |
| 28                       | 317                | 267                 | 159               | 202                         | 360           | 363       |
| 60                       | 351                | 388                 | 246               | 276                         | 446           | 464       |
| 90                       | 404                | 447                 | 293               | 308                         | 492           | 517       |
| 120                      | 418                | 483                 | 323               | 328                         | 522           | 550       |
| 150                      | 445                | 508                 | 345               | 341                         | 544           | 572       |
| 180                      | 465                | 527                 | 361               | 350                         | 561           | 587       |
| 210                      | 478                | 541                 | 373               | 357                         | 574           | 598       |
| 240                      | 486                | 551                 | 383               | 362                         | 584           | 606       |
| 270                      | 500                | 560                 | 392               | 366                         | 592           | 612       |
| 300                      | 509                | 567                 | 398               | 369                         | 600           | 617       |
| 330                      | 522                | 573                 | 404               | 372                         | 606           | 620       |
| 360                      | 533                | 579                 | 409               | 375                         | 611           | 623       |

**Table B.12.** Comparison of measured sealed shrinkage with five models for HPC 3

| Time after Loading, days | Measured Shrinkage | AASHTO LRFD<br>2010 | ACI 209R-<br>1990 | ACI 209R-Modified by<br>Huo | CEB-FIP<br>90 | Bazant B3 |
|--------------------------|--------------------|---------------------|-------------------|-----------------------------|---------------|-----------|
| 0                        | 0                  | 0                   | \                 | \                           | \             | 0         |
| 0                        | 0                  | 0                   | \                 | \                           | \             | 0         |
| 1                        | 36                 | 6                   | \                 | \                           | \             | 26        |
| 2                        | 73                 | 11                  | \                 | \                           | \             | 28        |
| 3                        | 90                 | 16                  | \                 | \                           | \             | 29        |
| 7                        | 195                | 34                  | \                 | \                           | \             | 35        |
| 14                       | 214                | 59                  | \                 | \                           | \             | 43        |
| 21                       | 242                | 78                  | \                 | \                           | \             | 48        |
| 28                       | 277                | 93                  | \                 | \                           | \             | 53        |
| 60                       | 311                | 136                 | \                 | \                           | \             | 66        |
| 90                       | 344                | 156                 | \                 | \                           | \             | 72        |
| 120                      | 352                | 169                 | \                 | \                           | \             | 76        |
| 150                      | 365                | 178                 | \                 | \                           | \             | 78        |
| 180                      | 373                | 184                 | \                 | \                           | \             | 80        |
| 210                      | 381                | 189                 | \                 | \                           | \             | 81        |
| 240                      | 389                | 193                 | \                 | \                           | \             | 81        |
| 270                      | 392                | 196                 | \                 | \                           | \             | 82        |
| 300                      | 399                | 198                 | \                 | \                           | \             | 82        |
| 330                      | 404                | 201                 | \                 | \                           | \             | 83        |
| 360                      | 410                | 202                 | \                 | \                           | \             | 83        |

**Table B.13.** Comparison of measured unsealed creep coefficient with five models for HPC 4

| Time after Loading,<br>days | Measured Creep<br>Coefficient | AASHTO LRFD<br>2010 | ACI 209R-<br>1990 | ACI 209R-Modified by<br>Huo | CEB-FIP<br>90 | Bazant B3 |
|-----------------------------|-------------------------------|---------------------|-------------------|-----------------------------|---------------|-----------|
| 0                           | 0.00000                       | 0.00000             | 0.00000           | 0.00000                     | 0.00000       | 0.00000   |
| 0                           | 0.00019                       | 0.00000             | 0.00000           | 0.00000                     | 0.00000       | 0.00000   |
| 1                           | 0.20137                       | 0.05253             | 0.31131           | 0.31209                     | 0.82307       | 1.05867   |
| 2                           | 0.22125                       | 0.10218             | 0.45072           | 0.44682                     | 0.85594       | 1.09912   |
| 3                           | 0.24892                       | 0.14917             | 0.55475           | 0.54542                     | 0.88593       | 1.13611   |
| 7                           | 0.37690                       | 0.31446             | 0.83292           | 0.80125                     | 0.98573       | 1.26014   |
| 14                          | 0.49110                       | 0.53804             | 1.12176           | 1.05547                     | 1.11485       | 1.42453   |
| 21                          | 0.57438                       | 0.70516             | 1.31231           | 1.21718                     | 1.21254       | 1.55357   |
| 28                          | 0.60676                       | 0.83481             | 1.45454           | 1.33491                     | 1.29171       | 1.66190   |
| 60                          | 0.71138                       | 1.18274             | 1.84379           | 1.64479                     | 1.53625       | 2.01925   |
| 90                          | 0.78334                       | 1.34641             | 2.04791           | 1.80047                     | 1.68131       | 2.24267   |
| 120                         | 0.81742                       | 1.44649             | 2.18729           | 1.90421                     | 1.78694       | 2.40491   |
| 150                         | 0.83024                       | 1.51401             | 2.29101           | 1.98009                     | 1.86872       | 2.52697   |
| 180                         | 0.83552                       | 1.56264             | 2.37237           | 2.03885                     | 1.93455       | 2.62131   |
| 210                         | 0.84156                       | 1.59934             | 2.43855           | 2.08617                     | 1.98897       | 2.69594   |
| 240                         | 0.86018                       | 1.62801             | 2.49383           | 2.12536                     | 2.03489       | 2.75622   |
| 270                         | 0.88508                       | 1.65103             | 2.54094           | 2.15853                     | 2.07425       | 2.80584   |
| 300                         | 0.90160                       | 1.66992             | 2.58174           | 2.18708                     | 2.10843       | 2.84741   |
| 330                         | 0.91603                       | 1.68570             | 2.61754           | 2.21200                     | 2.13842       | 2.88277   |
| 360                         | 0.93464                       | 1.69908             | 2.64929           | 2.23400                     | 2.16497       | 2.91329   |

**Table B.14.** Comparison of measured sealed creep coefficient with five models for HPC 4

| Time after Loading,<br>days | Measured Creep<br>Coefficient | AASHTO LRFD<br>2010 | ACI 209R-<br>1990 | ACI 209R-Modified by<br>Huo | CEB-FIP<br>90 | Bazant B3 |
|-----------------------------|-------------------------------|---------------------|-------------------|-----------------------------|---------------|-----------|
| 0                           | 0.00000                       | 0.00000             | 0.00000           | 0.00000                     | 0.00000       | 0.00000   |
| 0                           | 0.00038                       | 0.00000             | 0.00000           | 0.00000                     | 0.00000       | 0.00000   |
| 1                           | 0.21487                       | 0.02607             | 0.09485           | 0.09509                     | 0.28067       | 0.81653   |
| 2                           | 0.24085                       | 0.05071             | 0.13733           | 0.13614                     | 0.29209       | 0.84295   |
| 3                           | 0.26184                       | 0.07404             | 0.16902           | 0.16618                     | 0.30253       | 0.86658   |
| 7                           | 0.35891                       | 0.15608             | 0.25377           | 0.24412                     | 0.33755       | 0.94203   |
| 14                          | 0.54802                       | 0.26705             | 0.34178           | 0.32158                     | 0.38358       | 1.03297   |
| 21                          | 0.61062                       | 0.35000             | 0.39984           | 0.37085                     | 0.41914       | 1.09748   |
| 28                          | 0.63966                       | 0.41435             | 0.44317           | 0.40672                     | 0.44854       | 1.14752   |
| 60                          | 0.74767                       | 0.58704             | 0.56176           | 0.50113                     | 0.54391       | 1.29315   |
| 90                          | 0.81871                       | 0.66828             | 0.62396           | 0.54856                     | 0.60517       | 1.37613   |
| 120                         | 0.86035                       | 0.71795             | 0.66642           | 0.58017                     | 0.65295       | 1.43656   |
| 150                         | 0.87970                       | 0.75147             | 0.69802           | 0.60329                     | 0.69235       | 1.48412   |
| 180                         | 0.88930                       | 0.77561             | 0.72281           | 0.62120                     | 0.72594       | 1.52333   |
| 210                         | 0.89390                       | 0.79382             | 0.74298           | 0.63561                     | 0.75524       | 1.55670   |
| 240                         | 0.92817                       | 0.80805             | 0.75982           | 0.64755                     | 0.78122       | 1.58574   |
| 270                         | 0.97726                       | 0.81948             | 0.77417           | 0.65766                     | 0.80453       | 1.61145   |
| 300                         | 1.00658                       | 0.82885             | 0.78660           | 0.66636                     | 0.82567       | 1.63451   |
| 330                         | 1.03095                       | 0.83669             | 0.79751           | 0.67395                     | 0.84498       | 1.65542   |
| 360                         | 1.06521                       | 0.84333             | 0.80718           | 0.68065                     | 0.86273       | 1.67454   |

**Table B.15.** Comparison of measured unsealed shrinkage with five models for HPC 4

| Time after Loading, days | Measured Shrinkage | AASHTO LRFD<br>2010 | ACI 209R-<br>1990 | ACI 209R-Modified by<br>Huo | CEB-FIP<br>90 | Bazant B3 |
|--------------------------|--------------------|---------------------|-------------------|-----------------------------|---------------|-----------|
| 0                        | 0                  | 0                   | 0                 | 0                           | 0             | 0         |
| 0                        | 0                  | 0                   | 0                 | 0                           | 0             | 0         |
| 1                        | 22                 | 15                  | 10                | 17                          | 153           | 152       |
| 2                        | 33                 | 30                  | 19                | 32                          | 163           | 162       |
| 3                        | 51                 | 43                  | 28                | 46                          | 172           | 172       |
| 7                        | 133                | 91                  | 60                | 94                          | 203           | 207       |
| 14                       | 229                | 156                 | 108               | 153                         | 243           | 255       |
| 21                       | 286                | 204                 | 147               | 194                         | 274           | 292       |
| 28                       | 293                | 242                 | 180               | 223                         | 298           | 322       |
| 60                       | 296                | 342                 | 278               | 296                         | 369           | 413       |
| 90                       | 306                | 390                 | 330               | 327                         | 407           | 461       |
| 120                      | 312                | 419                 | 365               | 346                         | 433           | 492       |
| 150                      | 319                | 438                 | 389               | 357                         | 451           | 512       |
| 180                      | 330                | 452                 | 408               | 366                         | 465           | 526       |
| 210                      | 341                | 463                 | 422               | 372                         | 475           | 537       |
| 240                      | 344                | 471                 | 433               | 377                         | 484           | 544       |
| 270                      | 342                | 478                 | 442               | 381                         | 491           | 550       |
| 300                      | 345                | 484                 | 450               | 384                         | 497           | 554       |
| 330                      | 351                | 488                 | 456               | 386                         | 502           | 558       |
| 360                      | 353                | 492                 | 462               | 389                         | 506           | 560       |

**Table B.16.** Comparison of measured sealed shrinkage with five models for HPC 4

| Time after Loading, days | Measured Shrinkage | AASHTO LRFD<br>2010 | ACI 209R-<br>1990 | ACI 209R-Modified by<br>Huo | CEB-FIP<br>90 | Bazant B3 |
|--------------------------|--------------------|---------------------|-------------------|-----------------------------|---------------|-----------|
| 0                        | 0                  | 0                   | \                 | \                           | \             | 0         |
| 0                        | 0                  | 0                   | \                 | \                           | \             | 0         |
| 1                        | 17                 | 5                   | \                 | \                           | \             | 23        |
| 2                        | 26                 | 10                  | \                 | \                           | \             | 24        |
| 3                        | 40                 | 15                  | \                 | \                           | \             | 26        |
| 7                        | 103                | 32                  | \                 | \                           | \             | 31        |
| 14                       | 160                | 54                  | \                 | \                           | \             | 38        |
| 21                       | 212                | 71                  | \                 | \                           | \             | 43        |
| 28                       | 220                | 85                  | \                 | \                           | \             | 47        |
| 60                       | 225                | 120                 | \                 | \                           | \             | 59        |
| 90                       | 229                | 136                 | \                 | \                           | \             | 65        |
| 120                      | 235                | 146                 | \                 | \                           | \             | 68        |
| 150                      | 244                | 153                 | \                 | \                           | \             | 70        |
| 180                      | 251                | 158                 | \                 | \                           | \             | 72        |
| 210                      | 259                | 162                 | \                 | \                           | \             | 73        |
| 240                      | 260                | 165                 | \                 | \                           | \             | 73        |
| 270                      | 257                | 167                 | \                 | \                           | \             | 74        |
| 300                      | 259                | 169                 | \                 | \                           | \             | 74        |
| 330                      | 262                | 171                 | \                 | \                           | \             | 74        |
| 360                      | 263                | 172                 | \                 | \                           | \             | 75        |

**Table B.17.** Comparison of measured unsealed creep coefficient with five models for NC 1

| Time after Loading,<br>days | Measured Creep<br>Coefficient | AASHTO LRFD<br>2010 | ACI 209R-<br>1990 | ACI 209R-Modified by<br>Huo | CEB-FIP<br>90 | Bazant B3 |
|-----------------------------|-------------------------------|---------------------|-------------------|-----------------------------|---------------|-----------|
| 0                           | 0.00000                       | 0.00000             | 0.00000           | 0.00000                     | 0.00000       | 0.00000   |
| 0                           | 0.00000                       | 0.00000             | 0.00000           | 0.00000                     | 0.00000       | 0.00000   |
| 1                           | 0.06025                       | 0.05442             | 0.34279           | 0.31492                     | 0.80745       | 1.18566   |
| 2                           | 0.09649                       | 0.10487             | 0.49631           | 0.45039                     | 0.83970       | 1.23657   |
| 3                           | 0.13272                       | 0.15177             | 0.61086           | 0.54935                     | 0.86912       | 1.28289   |
| 7                           | 0.21936                       | 0.31040             | 0.91717           | 0.80542                     | 0.96702       | 1.43652   |
| 14                          | 0.25714                       | 0.51049             | 1.23522           | 1.05886                     | 1.09369       | 1.63600   |
| 21                          | 0.28914                       | 0.65019             | 1.44505           | 1.21955                     | 1.18953       | 1.78938   |
| 28                          | 0.30834                       | 0.75326             | 1.60166           | 1.33628                     | 1.26720       | 1.91609   |
| 60                          | 0.49544                       | 1.00925             | 2.03028           | 1.64252                     | 1.50709       | 2.32313   |
| 90                          | 0.59498                       | 1.12029             | 2.25505           | 1.79580                     | 1.64940       | 2.57133   |
| 120                         | 0.69625                       | 1.18551             | 2.40853           | 1.89775                     | 1.75302       | 2.74997   |
| 150                         | 0.77192                       | 1.22842             | 2.52273           | 1.97221                     | 1.83326       | 2.88433   |
| 180                         | 0.80871                       | 1.25879             | 2.61232           | 2.02982                     | 1.89783       | 2.98874   |
| 210                         | 0.83287                       | 1.28142             | 2.68520           | 2.07617                     | 1.95122       | 3.07211   |
| 240                         | 0.83909                       | 1.29893             | 2.74607           | 2.11453                     | 1.99627       | 3.14028   |
| 270                         | 0.83635                       | 1.31289             | 2.79794           | 2.14698                     | 2.03488       | 3.19717   |
| 300                         | 0.84556                       | 1.32428             | 2.84287           | 2.17490                     | 2.06841       | 3.24554   |
| 330                         | 0.85776                       | 1.33374             | 2.88229           | 2.19926                     | 2.09783       | 3.28731   |
| 360                         | 0.86399                       | 1.34173             | 2.91726           | 2.22075                     | 2.12388       | 3.32391   |

**Table B.18.** Comparison of measured sealed creep coefficient with five models for NC 1

| Time after Loading,<br>days | Measured Creep<br>Coefficient | AASHTO LRFD<br>2010 | ACI 209R-<br>1990 | ACI 209R-Modified by<br>Huo | CEB-FIP<br>90 | Bazant B3 |
|-----------------------------|-------------------------------|---------------------|-------------------|-----------------------------|---------------|-----------|
| 0                           | 0.00000                       | 0.00000             | 0.00000           | 0.00000                     | 0.00000       | 0.00000   |
| 0                           | 0.00000                       | 0.00000             | 0.00000           | 0.00000                     | 0.00000       | 0.00000   |
| 1                           | 0.03997                       | 0.02701             | 0.10444           | 0.09595                     | 0.27535       | 0.95653   |
| 2                           | 0.08978                       | 0.05205             | 0.15122           | 0.13723                     | 0.28654       | 0.99401   |
| 3                           | 0.13959                       | 0.07533             | 0.18612           | 0.16738                     | 0.29679       | 1.02755   |
| 7                           | 0.26657                       | 0.15407             | 0.27944           | 0.24539                     | 0.33114       | 1.13463   |
| 14                          | 0.33955                       | 0.25338             | 0.37635           | 0.32261                     | 0.37630       | 1.26367   |
| 21                          | 0.36494                       | 0.32272             | 0.44028           | 0.37157                     | 0.41119       | 1.35523   |
| 28                          | 0.38016                       | 0.37388             | 0.48799           | 0.40714                     | 0.44003       | 1.42625   |
| 60                          | 0.51619                       | 0.50093             | 0.61858           | 0.50044                     | 0.53359       | 1.63291   |
| 90                          | 0.55266                       | 0.55605             | 0.68707           | 0.54714                     | 0.59368       | 1.75067   |
| 120                         | 0.56393                       | 0.58842             | 0.73383           | 0.57820                     | 0.64056       | 1.83643   |
| 150                         | 0.56711                       | 0.60972             | 0.76862           | 0.60089                     | 0.67921       | 1.90392   |
| 180                         | 0.57925                       | 0.62479             | 0.79592           | 0.61845                     | 0.71216       | 1.95957   |
| 210                         | 0.59197                       | 0.63602             | 0.81812           | 0.63257                     | 0.74091       | 2.00693   |
| 240                         | 0.59922                       | 0.64472             | 0.83667           | 0.64425                     | 0.76639       | 2.04814   |
| 270                         | 0.60374                       | 0.65164             | 0.85248           | 0.65414                     | 0.78926       | 2.08462   |
| 300                         | 0.61190                       | 0.65729             | 0.86616           | 0.66265                     | 0.81000       | 2.11735   |
| 330                         | 0.62097                       | 0.66199             | 0.87818           | 0.67007                     | 0.82894       | 2.14702   |
| 360                         | 0.62822                       | 0.66596             | 0.88883           | 0.67662                     | 0.84636       | 2.17416   |



**Table B.19.** Comparison of measured unsealed shrinkage with five models for NC 1

| Time after Loading,<br>days | Measured Shrinkage | AASHTO LRFD<br>2010 | ACI 209R-<br>1990 | ACI 209R-Modified by<br>Huo | CEB-FIP<br>90 | Bazant B3 |
|-----------------------------|--------------------|---------------------|-------------------|-----------------------------|---------------|-----------|
| 0                           | 0                  | 0                   | 0                 | 0                           | 0             | 0         |
| 0                           | 0                  | 0                   | 0                 | 0                           | 0             | 0         |
| 1                           | 0                  | 16                  | 8                 | 14                          | 117           | 156       |
| 2                           | 40                 | 30                  | 17                | 26                          | 124           | 167       |
| 3                           | 68                 | 44                  | 25                | 38                          | 131           | 178       |
| 7                           | 150                | 90                  | 53                | 76                          | 154           | 213       |
| 14                          | 185                | 148                 | 96                | 123                         | 185           | 262       |
| 21                          | 193                | 188                 | 131               | 155                         | 208           | 300       |
| 28                          | 199                | 218                 | 160               | 179                         | 227           | 330       |
| 60                          | 253                | 292                 | 247               | 236                         | 281           | 421       |
| 90                          | 287                | 324                 | 294               | 260                         | 310           | 468       |
| 120                         | 328                | 343                 | 325               | 274                         | 330           | 498       |
| 150                         | 369                | 356                 | 347               | 283                         | 343           | 518       |
| 180                         | 391                | 364                 | 363               | 289                         | 354           | 531       |
| 210                         | 397                | 371                 | 375               | 294                         | 362           | 541       |
| 240                         | 406                | 376                 | 385               | 298                         | 369           | 548       |
| 270                         | 417                | 380                 | 394               | 301                         | 374           | 553       |
| 300                         | 426                | 383                 | 400               | 303                         | 378           | 557       |
| 330                         | 434                | 386                 | 406               | 305                         | 382           | 560       |
| 360                         | 443                | 389                 | 411               | 307                         | 386           | 562       |

**Table B.20.** Comparison of measured sealed shrinkage with five models for NC 1

| Time after Loading,<br>days | Measured Shrinkage | AASHTO LRFD<br>2010 | ACI 209R-<br>1990 | ACI 209R-Modified by<br>Huo | CEB-FIP<br>90 | Bazant B3 |
|-----------------------------|--------------------|---------------------|-------------------|-----------------------------|---------------|-----------|
| 0                           | 0                  | 0                   | \                 | \                           | \             | 0         |
| 0                           | 0                  | 0                   | \                 | \                           | \             | 0         |
| 1                           | 0                  | 6                   | \                 | \                           | \             | 24        |
| 2                           | 30                 | 11                  | \                 | \                           | \             | 25        |
| 3                           | 59                 | 15                  | \                 | \                           | \             | 27        |
| 7                           | 130                | 31                  | \                 | \                           | \             | 32        |
| 14                          | 161                | 52                  | \                 | \                           | \             | 39        |
| 21                          | 167                | 66                  | \                 | \                           | \             | 44        |
| 28                          | 171                | 76                  | \                 | \                           | \             | 48        |
| 60                          | 216                | 102                 | \                 | \                           | \             | 60        |
| 90                          | 246                | 113                 | \                 | \                           | \             | 65        |
| 120                         | 278                | 120                 | \                 | \                           | \             | 69        |
| 150                         | 312                | 124                 | \                 | \                           | \             | 71        |
| 180                         | 333                | 127                 | \                 | \                           | \             | 72        |
| 210                         | 338                | 130                 | \                 | \                           | \             | 73        |
| 240                         | 339                | 132                 | \                 | \                           | \             | 74        |
| 270                         | 338                | 133                 | \                 | \                           | \             | 74        |
| 300                         | 340                | 134                 | \                 | \                           | \             | 74        |
| 330                         | 343                | 135                 | \                 | \                           | \             | 75        |
| 360                         | 344                | 136                 | \                 | \                           | \             | 75        |

**Table B.21.** Comparison of measured unsealed creep coefficient with five models for NC 2

| Time after Loading,<br>days | Measured Creep<br>Coefficient | AASHTO LRFD<br>2010 | ACI 209R-<br>1990 | ACI 209R-Modified by<br>Huo | CEB-FIP<br>90 | Bazant B3 |
|-----------------------------|-------------------------------|---------------------|-------------------|-----------------------------|---------------|-----------|
| 0                           | 0.00000                       | 0.00000             | 0.00000           | 0.00000                     | 0.00000       | 0.00000   |
| 0                           | 0.00000                       | 0.00000             | 0.00000           | 0.00000                     | 0.00000       | 0.00000   |
| 1                           | -0.00768                      | 0.05262             | 0.31131           | 0.31190                     | 0.86954       | 1.25687   |
| 2                           | 0.02393                       | 0.10239             | 0.45072           | 0.44774                     | 0.90427       | 1.30066   |
| 3                           | 0.08715                       | 0.14952             | 0.55475           | 0.54759                     | 0.93595       | 1.34061   |
| 7                           | 0.14514                       | 0.31551             | 0.83292           | 0.80850                     | 1.04139       | 1.47389   |
| 14                          | 0.25188                       | 0.54052             | 1.12176           | 1.07038                     | 1.17779       | 1.64892   |
| 21                          | 0.30063                       | 0.70909             | 1.31231           | 1.23835                     | 1.28100       | 1.78505   |
| 28                          | 0.33857                       | 0.84009             | 1.45454           | 1.36130                     | 1.36464       | 1.89854   |
| 60                          | 0.43608                       | 1.19262             | 1.84379           | 1.68773                     | 1.62298       | 2.26868   |
| 90                          | 0.47820                       | 1.35893             | 2.04791           | 1.85326                     | 1.77623       | 2.49773   |
| 120                         | 0.49850                       | 1.46079             | 2.18729           | 1.96414                     | 1.88782       | 2.66347   |
| 150                         | 0.53189                       | 1.52958             | 2.29101           | 2.04553                     | 1.97423       | 2.78818   |
| 180                         | 0.56235                       | 1.57916             | 2.37237           | 2.10874                     | 2.04377       | 2.88480   |
| 210                         | 0.60038                       | 1.61659             | 2.43855           | 2.15975                     | 2.10126       | 2.96154   |
| 240                         | 0.62798                       | 1.64584             | 2.49383           | 2.20206                     | 2.14978       | 3.02385   |
| 270                         | 0.65742                       | 1.66934             | 2.54094           | 2.23793                     | 2.19136       | 3.07544   |
| 300                         | 0.68564                       | 1.68862             | 2.58174           | 2.26885                     | 2.22747       | 3.11893   |
| 330                         | 0.71447                       | 1.70474             | 2.61754           | 2.29586                     | 2.25915       | 3.15618   |
| 360                         | 0.73004                       | 1.71840             | 2.64929           | 2.31973                     | 2.28720       | 3.18853   |

**Table B.22.** Comparison of measured sealed creep coefficient with five models for NC 2

| Time after Loading,<br>days | Measured Creep<br>Coefficient | AASHTO LRFD<br>2010 | ACI 209R-<br>1990 | ACI 209R-Modified by<br>Huo | CEB-FIP<br>90 | Bazant B3 |
|-----------------------------|-------------------------------|---------------------|-------------------|-----------------------------|---------------|-----------|
| 0                           | 0.00000                       | 0.00000             | 0.00000           | 0.00000                     | 0.00000       | 0.00000   |
| 0                           | 0.00000                       | 0.00000             | 0.00000           | 0.00000                     | 0.00000       | 0.00000   |
| 1                           | 0.00779                       | 0.02612             | 0.09485           | 0.09503                     | 0.29652       | 1.02440   |
| 2                           | 0.07495                       | 0.05082             | 0.13733           | 0.13642                     | 0.30858       | 1.05466   |
| 3                           | 0.20926                       | 0.07421             | 0.16902           | 0.16684                     | 0.31961       | 1.08173   |
| 7                           | 0.25892                       | 0.15660             | 0.25377           | 0.24633                     | 0.35661       | 1.16817   |
| 14                          | 0.33585                       | 0.26828             | 0.34178           | 0.32612                     | 0.40524       | 1.27233   |
| 21                          | 0.36312                       | 0.35195             | 0.39984           | 0.37730                     | 0.44281       | 1.34624   |
| 28                          | 0.40630                       | 0.41697             | 0.44317           | 0.41476                     | 0.47386       | 1.40357   |
| 60                          | 0.52148                       | 0.59195             | 0.56176           | 0.51422                     | 0.57462       | 1.57038   |
| 90                          | 0.58374                       | 0.67450             | 0.62396           | 0.56465                     | 0.63933       | 1.66544   |
| 120                         | 0.62707                       | 0.72505             | 0.66642           | 0.59843                     | 0.68981       | 1.73467   |
| 150                         | 0.70029                       | 0.75920             | 0.69802           | 0.62323                     | 0.73143       | 1.78915   |
| 180                         | 0.71463                       | 0.78381             | 0.72281           | 0.64249                     | 0.76693       | 1.83407   |
| 210                         | 0.75244                       | 0.80238             | 0.74298           | 0.65803                     | 0.79788       | 1.87229   |
| 240                         | 0.78744                       | 0.81690             | 0.75982           | 0.67092                     | 0.82532       | 1.90556   |
| 270                         | 0.80916                       | 0.82856             | 0.77417           | 0.68185                     | 0.84996       | 1.93501   |
| 300                         | 0.83973                       | 0.83814             | 0.78660           | 0.69127                     | 0.87228       | 1.96143   |
| 330                         | 0.86587                       | 0.84613             | 0.79751           | 0.69950                     | 0.89268       | 1.98538   |
| 360                         | 0.88432                       | 0.85292             | 0.80718           | 0.70677                     | 0.91144       | 2.00729   |

**Table B.23.** Comparison of measured unsealed shrinkage with five models for NC 2

| Time after Loading, days | Measured Shrinkage | AASHTO LRFD<br>2010 | ACI 209R-<br>1990 | ACI 209R-Modified by<br>Huo | CEB-FIP<br>90 | Bazant B3 |
|--------------------------|--------------------|---------------------|-------------------|-----------------------------|---------------|-----------|
| 0                        | 0                  | 0                   | 0                 | 0                           | 0             | 0         |
| 0                        | 0                  | 0                   | 0                 | 0                           | 0             | 0         |
| 1                        | 130                | 21                  | 13                | 21                          | 171           | 177       |
| 2                        | 161                | 40                  | 25                | 41                          | 182           | 190       |
| 3                        | 225                | 58                  | 36                | 59                          | 192           | 202       |
| 7                        | 236                | 118                 | 79                | 122                         | 226           | 242       |
| 14                       | 259                | 194                 | 142               | 201                         | 271           | 298       |
| 21                       | 271                | 247                 | 193               | 257                         | 305           | 341       |
| 28                       | 279                | 286                 | 236               | 298                         | 333           | 376       |
| 60                       | 299                | 383                 | 365               | 401                         | 412           | 481       |
| 90                       | 315                | 426                 | 435               | 446                         | 455           | 536       |
| 120                      | 330                | 450                 | 480               | 473                         | 483           | 571       |
| 150                      | 352                | 467                 | 512               | 491                         | 503           | 595       |
| 180                      | 358                | 478                 | 536               | 503                         | 519           | 611       |
| 210                      | 373                | 487                 | 555               | 512                         | 531           | 623       |
| 240                      | 387                | 493                 | 570               | 519                         | 540           | 631       |
| 270                      | 396                | 499                 | 582               | 525                         | 548           | 638       |
| 300                      | 408                | 503                 | 592               | 530                         | 555           | 642       |
| 330                      | 419                | 507                 | 600               | 534                         | 560           | 646       |
| 360                      | 425                | 510                 | 607               | 537                         | 565           | 649       |

**Table B.24.** Comparison of measured sealed shrinkage with five models for NC 2

| Time after Loading, days | Measured Shrinkage | AASHTO LRFD<br>2010 | ACI 209R-<br>1990 | ACI 209R-Modified by<br>Huo | CEB-FIP<br>90 | Bazant B3 |
|--------------------------|--------------------|---------------------|-------------------|-----------------------------|---------------|-----------|
| 0                        | 0                  | 0                   | \                 | \                           | \             | 0         |
| 0                        | 0                  | 0                   | \                 | \                           | \             | 0         |
| 1                        | 70                 | 7                   | \                 | \                           | \             | 27        |
| 2                        | 73                 | 14                  | \                 | \                           | \             | 29        |
| 3                        | 77                 | 20                  | \                 | \                           | \             | 30        |
| 7                        | 91                 | 41                  | \                 | \                           | \             | 36        |
| 14                       | 122                | 68                  | \                 | \                           | \             | 44        |
| 21                       | 139                | 86                  | \                 | \                           | \             | 50        |
| 28                       | 141                | 100                 | \                 | \                           | \             | 55        |
| 60                       | 150                | 134                 | \                 | \                           | \             | 69        |
| 90                       | 157                | 149                 | \                 | \                           | \             | 75        |
| 120                      | 161                | 157                 | \                 | \                           | \             | 79        |
| 150                      | 165                | 163                 | \                 | \                           | \             | 81        |
| 180                      | 172                | 167                 | \                 | \                           | \             | 83        |
| 210                      | 218                | 170                 | \                 | \                           | \             | 84        |
| 240                      | 265                | 173                 | \                 | \                           | \             | 85        |
| 270                      | 286                | 174                 | \                 | \                           | \             | 85        |
| 300                      | 325                | 176                 | \                 | \                           | \             | 86        |
| 330                      | 354                | 177                 | \                 | \                           | \             | 86        |
| 360                      | 360                | 178                 | \                 | \                           | \             | 86        |

**Table B.25.** Comparison of measured unsealed creep coefficient with five models for NC 3

| Time after Loading,<br>days | Measured Creep<br>Coefficient | AASHTO LRFD<br>2010 | ACI 209R-<br>1990 | ACI 209R-Modified by<br>Huo | CEB-FIP<br>90 | Bazant B3 |
|-----------------------------|-------------------------------|---------------------|-------------------|-----------------------------|---------------|-----------|
| 0                           | 0.00000                       | 0.00000             | 0.00000           | 0.00000                     | 0.00000       | 0.00000   |
| 0                           | 0.00000                       | 0.00000             | 0.00000           | 0.00000                     | 0.00000       | 0.00000   |
| 1                           | 0.01379                       | 0.05752             | 0.31131           | 0.36248                     | 0.71950       | 1.44676   |
| 2                           | 0.01916                       | 0.11025             | 0.45072           | 0.51591                     | 0.74823       | 1.49629   |
| 3                           | 0.02452                       | 0.15877             | 0.55475           | 0.62705                     | 0.77445       | 1.54133   |
| 7                           | 0.05440                       | 0.31936             | 0.83292           | 0.91101                     | 0.86169       | 1.69059   |
| 14                          | 0.14018                       | 0.51452             | 1.12176           | 1.18706                     | 0.97455       | 1.88401   |
| 21                          | 0.16816                       | 0.64614             | 1.31231           | 1.35956                     | 1.05996       | 2.03233   |
| 28                          | 0.26889                       | 0.74091             | 1.45454           | 1.48366                     | 1.12917       | 2.15455   |
| 60                          | 0.31187                       | 0.96809             | 1.84379           | 1.80453                     | 1.34293       | 2.54453   |
| 90                          | 0.33835                       | 1.06317             | 2.04791           | 1.96262                     | 1.46974       | 2.77988   |
| 120                         | 0.36531                       | 1.11808             | 2.18729           | 2.06685                     | 1.56207       | 2.94803   |
| 150                         | 0.38972                       | 1.15383             | 2.29101           | 2.14252                     | 1.63356       | 3.07392   |
| 180                         | 0.40353                       | 1.17896             | 2.37237           | 2.20081                     | 1.69110       | 3.17153   |
| 210                         | 0.40667                       | 1.19759             | 2.43855           | 2.24753                     | 1.73868       | 3.24942   |
| 240                         | 0.44864                       | 1.21196             | 2.49383           | 2.28610                     | 1.77882       | 3.31317   |
| 270                         | 0.48179                       | 1.22337             | 2.54094           | 2.31864                     | 1.81323       | 3.36647   |
| 300                         | 0.49901                       | 1.23266             | 2.58174           | 2.34658                     | 1.84310       | 3.41190   |
| 330                         | 0.52618                       | 1.24037             | 2.61754           | 2.37092                     | 1.86932       | 3.45126   |
| 360                         | 0.54098                       | 1.24686             | 2.64929           | 2.39236                     | 1.89253       | 3.48586   |

**Table B.26.** Comparison of measured sealed creep coefficient with five models for NC 3

| Time after Loading,<br>days | Measured Creep<br>Coefficient | AASHTO LRFD<br>2010 | ACI 209R-<br>1990 | ACI 209R-Modified by<br>Huo | CEB-FIP<br>90 | Bazant B3 |
|-----------------------------|-------------------------------|---------------------|-------------------|-----------------------------|---------------|-----------|
| 0                           | 0.00000                       | 0.00000             | 0.00000           | 0.00000                     | 0.00000       | 0.00000   |
| 0                           | 0.00000                       | 0.00000             | 0.00000           | 0.00000                     | 0.00000       | 0.00000   |
| 1                           | 0.06562                       | 0.02855             | 0.09485           | 0.11044                     | 0.24535       | 1.23318   |
| 2                           | 0.10648                       | 0.05472             | 0.13733           | 0.15719                     | 0.25533       | 1.27008   |
| 3                           | 0.14733                       | 0.07880             | 0.16902           | 0.19105                     | 0.26446       | 1.30309   |
| 7                           | 0.21115                       | 0.15851             | 0.25377           | 0.27757                     | 0.29507       | 1.40852   |
| 14                          | 0.29153                       | 0.25538             | 0.34178           | 0.36167                     | 0.33531       | 1.53556   |
| 21                          | 0.31410                       | 0.32071             | 0.39984           | 0.41423                     | 0.36640       | 1.62569   |
| 28                          | 0.39536                       | 0.36775             | 0.44317           | 0.45204                     | 0.39210       | 1.69561   |
| 60                          | 0.46723                       | 0.48050             | 0.56176           | 0.54980                     | 0.47547       | 1.89906   |
| 90                          | 0.52824                       | 0.52770             | 0.62396           | 0.59797                     | 0.52901       | 2.01500   |
| 120                         | 0.60072                       | 0.55495             | 0.66642           | 0.62973                     | 0.57078       | 2.09943   |
| 150                         | 0.67654                       | 0.57269             | 0.69802           | 0.65278                     | 0.60522       | 2.16588   |
| 180                         | 0.72637                       | 0.58517             | 0.72281           | 0.67054                     | 0.63459       | 2.22066   |
| 210                         | 0.74236                       | 0.59442             | 0.74298           | 0.68478                     | 0.66020       | 2.26728   |
| 240                         | 0.82635                       | 0.60155             | 0.75982           | 0.69653                     | 0.68291       | 2.30786   |
| 270                         | 0.88451                       | 0.60721             | 0.77417           | 0.70644                     | 0.70329       | 2.34377   |
| 300                         | 0.92715                       | 0.61182             | 0.78660           | 0.71495                     | 0.72177       | 2.37599   |
| 330                         | 0.97949                       | 0.61565             | 0.79751           | 0.72237                     | 0.73864       | 2.40520   |
| 360                         | 1.01115                       | 0.61887             | 0.80718           | 0.72890                     | 0.75416       | 2.43192   |



**Table B.27.** Comparison of measured unsealed shrinkage with five models for NC 3

| Time after Loading, days | Measured Shrinkage | AASHTO LRFD<br>2010 | ACI 209R-<br>1990 | ACI 209R-Modified by<br>Huo | CEB-FIP<br>90 | Bazant B3 |
|--------------------------|--------------------|---------------------|-------------------|-----------------------------|---------------|-----------|
| 0                        | 0                  | 0                   | 0                 | 0                           | 0             | 0         |
| 0                        | 0                  | 0                   | 0                 | 0                           | 0             | 0         |
| 1                        | 14                 | 17                  | 10                | 17                          | 100           | 166       |
| 2                        | 28                 | 32                  | 20                | 32                          | 107           | 177       |
| 3                        | 42                 | 46                  | 29                | 47                          | 113           | 188       |
| 7                        | 67                 | 92                  | 64                | 96                          | 133           | 226       |
| 14                       | 104                | 149                 | 116               | 158                         | 159           | 277       |
| 21                       | 126                | 187                 | 157               | 202                         | 179           | 316       |
| 28                       | 204                | 215                 | 192               | 235                         | 195           | 348       |
| 60                       | 252                | 280                 | 297               | 317                         | 242           | 442       |
| 90                       | 278                | 308                 | 353               | 352                         | 267           | 490       |
| 120                      | 315                | 324                 | 390               | 373                         | 283           | 520       |
| 150                      | 353                | 334                 | 417               | 387                         | 295           | 539       |
| 180                      | 375                | 341                 | 436               | 397                         | 304           | 552       |
| 210                      | 383                | 347                 | 451               | 404                         | 311           | 562       |
| 240                      | 387                | 351                 | 463               | 410                         | 317           | 568       |
| 270                      | 383                | 354                 | 473               | 414                         | 321           | 573       |
| 300                      | 391                | 357                 | 481               | 418                         | 325           | 577       |
| 330                      | 392                | 359                 | 488               | 421                         | 329           | 580       |
| 360                      | 395                | 361                 | 494               | 424                         | 331           | 582       |

**Table B.28.** Comparison of measured sealed shrinkage with five models for NC 3

| Time after Loading, days | Measured Shrinkage | AASHTO LRFD<br>2010 | ACI 209R-<br>1990 | ACI 209R-Modified by<br>Huo | CEB-FIP<br>90 | Bazant B3 |
|--------------------------|--------------------|---------------------|-------------------|-----------------------------|---------------|-----------|
| 0                        | 0                  | 0                   | \                 | \                           | \             | 0         |
| 0                        | 0                  | 0                   | \                 | \                           | \             | 0         |
| 1                        | 9                  | 6                   | \                 | \                           | \             | 25        |
| 2                        | 18                 | 11                  | \                 | \                           | \             | 27        |
| 3                        | 27                 | 16                  | \                 | \                           | \             | 28        |
| 7                        | 48                 | 32                  | \                 | \                           | \             | 34        |
| 14                       | 88                 | 52                  | \                 | \                           | \             | 41        |
| 21                       | 99                 | 65                  | \                 | \                           | \             | 46        |
| 28                       | 140                | 75                  | \                 | \                           | \             | 51        |
| 60                       | 180                | 98                  | \                 | \                           | \             | 63        |
| 90                       | 204                | 108                 | \                 | \                           | \             | 68        |
| 120                      | 233                | 113                 | \                 | \                           | \             | 71        |
| 150                      | 261                | 117                 | \                 | \                           | \             | 73        |
| 180                      | 277                | 119                 | \                 | \                           | \             | 75        |
| 210                      | 281                | 121                 | \                 | \                           | \             | 76        |
| 240                      | 282                | 123                 | \                 | \                           | \             | 76        |
| 270                      | 280                | 124                 | \                 | \                           | \             | 77        |
| 300                      | 283                | 125                 | \                 | \                           | \             | 77        |
| 330                      | 283                | 126                 | \                 | \                           | \             | 77        |
| 360                      | 285                | 126                 | \                 | \                           | \             | 77        |

## **APPENDIX C**

**Comparison of Cambers for Different Types of Girders by Using Three Methods,  
and Gross Section Properties and Transformed Section Properties, and Average  
Sealed Creep Coefficient and Sealed Shrinkage Data**

**Table C.1.** Camber prediction of 3 BTC 120 prestressed girders with overhang by using three methods and two types of section properties at plant A

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 4.562                   | 4.614                | 4.562                | 3.991                    | 4.003                 | 3.991                 |
| 0                         | 4.430                   | 4.476                | 4.444                | 3.701                    | 3.949                 | 3.885                 |
| 1                         | 5.065                   | 5.128                | 5.232                | 4.245                    | 4.540                 | 4.579                 |
| 2                         | 5.276                   | 5.347                | 5.563                | 4.433                    | 4.745                 | 4.870                 |
| 3                         | 5.441                   | 5.518                | 5.833                | 4.581                    | 4.906                 | 5.107                 |
| 7                         | 5.662                   | 5.751                | 6.336                | 4.792                    | 5.137                 | 5.550                 |
| 14                        | 5.874                   | 5.975                | 6.833                | 4.993                    | 5.359                 | 5.987                 |
| 21                        | 5.953                   | 6.060                | 7.073                | 5.072                    | 5.447                 | 6.198                 |
| 28                        | 6.007                   | 6.118                | 7.235                | 5.125                    | 5.506                 | 6.341                 |
| 60                        | 6.222                   | 6.347                | 7.730                | 5.324                    | 5.730                 | 6.777                 |
| 90                        | 6.319                   | 6.451                | 7.964                | 5.411                    | 5.831                 | 6.982                 |
| 120                       | 6.365                   | 6.502                | 8.083                | 5.454                    | 5.881                 | 7.088                 |
| 150                       | 6.405                   | 6.545                | 8.182                | 5.489                    | 5.922                 | 7.175                 |
| 180                       | 6.438                   | 6.581                | 8.260                | 5.519                    | 5.957                 | 7.243                 |
| 210                       | 6.464                   | 6.608                | 8.320                | 5.542                    | 5.984                 | 7.296                 |
| 240                       | 6.491                   | 6.638                | 8.380                | 5.566                    | 6.012                 | 7.349                 |
| 270                       | 6.542                   | 6.692                | 8.475                | 5.610                    | 6.062                 | 7.433                 |
| 300                       | 6.571                   | 6.723                | 8.538                | 5.635                    | 6.092                 | 7.488                 |
| 330                       | 6.618                   | 6.773                | 8.627                | 5.676                    | 6.139                 | 7.566                 |
| 360                       | 6.660                   | 6.819                | 8.709                | 5.713                    | 6.181                 | 7.638                 |

**Table C.2.** Camber prediction of 3 BTC 120 prestressed girders without overhang by using three methods and two types of section properties at plant A

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 4.103                   | 4.153                | 4.103                | 3.558                    | 3.569                 | 3.558                 |
| 0                         | 3.967                   | 4.012                | 3.995                | 3.434                    | 3.512                 | 3.463                 |
| 1                         | 4.529                   | 4.589                | 4.706                | 3.937                    | 4.033                 | 4.082                 |
| 2                         | 4.713                   | 4.782                | 5.004                | 4.110                    | 4.212                 | 4.342                 |
| 3                         | 4.858                   | 4.932                | 5.247                | 4.246                    | 4.353                 | 4.554                 |
| 7                         | 5.046                   | 5.132                | 5.700                | 4.438                    | 4.553                 | 4.950                 |
| 14                        | 5.227                   | 5.324                | 6.147                | 4.623                    | 4.745                 | 5.340                 |
| 21                        | 5.292                   | 5.395                | 6.363                | 4.693                    | 4.820                 | 5.528                 |
| 28                        | 5.337                   | 5.444                | 6.509                | 4.741                    | 4.870                 | 5.655                 |
| 60                        | 5.519                   | 5.640                | 6.955                | 4.922                    | 5.062                 | 6.045                 |
| 90                        | 5.599                   | 5.726                | 7.166                | 5.000                    | 5.147                 | 6.228                 |
| 120                       | 5.637                   | 5.768                | 7.273                | 5.038                    | 5.188                 | 6.322                 |
| 150                       | 5.668                   | 5.803                | 7.363                | 5.069                    | 5.222                 | 6.400                 |
| 180                       | 5.696                   | 5.833                | 7.432                | 5.096                    | 5.251                 | 6.461                 |
| 210                       | 5.717                   | 5.856                | 7.486                | 5.116                    | 5.273                 | 6.508                 |
| 240                       | 5.740                   | 5.881                | 7.541                | 5.138                    | 5.297                 | 6.556                 |
| 270                       | 5.783                   | 5.927                | 7.627                | 5.177                    | 5.340                 | 6.630                 |
| 300                       | 5.806                   | 5.953                | 7.683                | 5.200                    | 5.365                 | 6.679                 |
| 330                       | 5.846                   | 5.995                | 7.763                | 5.237                    | 5.405                 | 6.749                 |
| 360                       | 5.882                   | 6.034                | 7.837                | 5.270                    | 5.441                 | 6.813                 |

**Table C.3.** Camber prediction of 3 BTE 110 prestressed girders with overhang by using three methods and two types of section properties at plant B, including 144-270, 144-272 and 144-268

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 2.105                   | 2.126                | 2.105                | 1.896                    | 1.906                 | 1.896                 |
| 0                         | 2.048                   | 2.067                | 2.042                | 1.843                    | 1.869                 | 1.838                 |
| 1                         | 2.350                   | 2.376                | 2.407                | 2.122                    | 2.154                 | 2.168                 |
| 2                         | 2.452                   | 2.482                | 2.560                | 2.219                    | 2.254                 | 2.306                 |
| 3                         | 2.532                   | 2.564                | 2.684                | 2.295                    | 2.333                 | 2.419                 |
| 7                         | 2.642                   | 2.680                | 2.916                | 2.406                    | 2.448                 | 2.629                 |
| 14                        | 2.748                   | 2.791                | 3.146                | 2.512                    | 2.558                 | 2.837                 |
| 21                        | 2.789                   | 2.834                | 3.256                | 2.554                    | 2.603                 | 2.937                 |
| 28                        | 2.818                   | 2.865                | 3.331                | 2.584                    | 2.633                 | 3.004                 |
| 60                        | 2.927                   | 2.980                | 3.559                | 2.691                    | 2.746                 | 3.211                 |
| 90                        | 2.977                   | 3.033                | 3.667                | 2.740                    | 2.799                 | 3.308                 |
| 120                       | 3.002                   | 3.060                | 3.722                | 2.765                    | 2.824                 | 3.358                 |
| 150                       | 3.023                   | 3.082                | 3.767                | 2.785                    | 2.846                 | 3.399                 |
| 180                       | 3.040                   | 3.101                | 3.803                | 2.802                    | 2.864                 | 3.431                 |
| 210                       | 3.054                   | 3.115                | 3.830                | 2.815                    | 2.878                 | 3.456                 |
| 240                       | 3.068                   | 3.130                | 3.858                | 2.829                    | 2.892                 | 3.482                 |
| 270                       | 3.094                   | 3.157                | 3.902                | 2.853                    | 2.918                 | 3.521                 |
| 300                       | 3.109                   | 3.173                | 3.931                | 2.867                    | 2.933                 | 3.547                 |
| 330                       | 3.133                   | 3.198                | 3.972                | 2.890                    | 2.957                 | 3.585                 |
| 360                       | 3.154                   | 3.221                | 4.010                | 2.911                    | 2.979                 | 3.619                 |

**Table C.4.** Camber prediction of 3 BTE 110 prestressed girders without overhang by using three methods and two types of section properties at plant B, including 144-270, 144-272 and 144-268

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 1.739                   | 1.761                | 1.739                | 1.551                    | 1.561                 | 1.551                 |
| 0                         | 1.680                   | 1.699                | 1.687                | 1.496                    | 1.521                 | 1.503                 |
| 1                         | 1.923                   | 1.949                | 1.989                | 1.718                    | 1.751                 | 1.774                 |
| 2                         | 2.004                   | 2.033                | 2.115                | 1.795                    | 1.830                 | 1.887                 |
| 3                         | 2.067                   | 2.099                | 2.219                | 1.855                    | 1.893                 | 1.979                 |
| 7                         | 2.152                   | 2.189                | 2.411                | 1.940                    | 1.983                 | 2.151                 |
| 14                        | 2.233                   | 2.276                | 2.600                | 2.022                    | 2.071                 | 2.321                 |
| 21                        | 2.263                   | 2.308                | 2.692                | 2.054                    | 2.105                 | 2.403                 |
| 28                        | 2.284                   | 2.331                | 2.754                | 2.076                    | 2.128                 | 2.459                 |
| 60                        | 2.367                   | 2.420                | 2.943                | 2.157                    | 2.216                 | 2.628                 |
| 90                        | 2.404                   | 2.460                | 3.032                | 2.193                    | 2.256                 | 2.708                 |
| 120                       | 2.422                   | 2.479                | 3.078                | 2.211                    | 2.275                 | 2.749                 |
| 150                       | 2.437                   | 2.496                | 3.115                | 2.226                    | 2.291                 | 2.783                 |
| 180                       | 2.450                   | 2.510                | 3.145                | 2.238                    | 2.304                 | 2.809                 |
| 210                       | 2.460                   | 2.520                | 3.168                | 2.247                    | 2.315                 | 2.830                 |
| 240                       | 2.470                   | 2.532                | 3.191                | 2.258                    | 2.326                 | 2.850                 |
| 270                       | 2.490                   | 2.553                | 3.227                | 2.276                    | 2.346                 | 2.883                 |
| 300                       | 2.501                   | 2.565                | 3.251                | 2.286                    | 2.357                 | 2.904                 |
| 330                       | 2.519                   | 2.584                | 3.285                | 2.303                    | 2.375                 | 2.935                 |
| 360                       | 2.535                   | 2.602                | 3.316                | 2.319                    | 2.392                 | 2.963                 |

**Table C.5.** Camber prediction of 3 BTE 110 prestressed girders with overhang by using three methods and two types of section properties at plant B, including 144-274, 144-275 and 144-278

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 2.187                   | 2.209                | 2.187                | 1.960                    | 1.971                 | 1.960                 |
| 0                         | 2.128                   | 2.149                | 2.122                | 1.906                    | 1.934                 | 1.901                 |
| 1                         | 2.440                   | 2.469                | 2.500                | 2.193                    | 2.229                 | 2.241                 |
| 2                         | 2.546                   | 2.578                | 2.658                | 2.293                    | 2.332                 | 2.384                 |
| 3                         | 2.628                   | 2.664                | 2.788                | 2.372                    | 2.413                 | 2.501                 |
| 7                         | 2.742                   | 2.783                | 3.028                | 2.486                    | 2.531                 | 2.717                 |
| 14                        | 2.851                   | 2.897                | 3.265                | 2.595                    | 2.645                 | 2.931                 |
| 21                        | 2.893                   | 2.942                | 3.380                | 2.639                    | 2.691                 | 3.034                 |
| 28                        | 2.922                   | 2.973                | 3.457                | 2.669                    | 2.723                 | 3.104                 |
| 60                        | 3.034                   | 3.091                | 3.694                | 2.779                    | 2.839                 | 3.317                 |
| 90                        | 3.085                   | 3.146                | 3.805                | 2.830                    | 2.892                 | 3.418                 |
| 120                       | 3.111                   | 3.173                | 3.862                | 2.854                    | 2.919                 | 3.469                 |
| 150                       | 3.132                   | 3.196                | 3.909                | 2.875                    | 2.941                 | 3.511                 |
| 180                       | 3.150                   | 3.215                | 3.946                | 2.893                    | 2.960                 | 3.545                 |
| 210                       | 3.164                   | 3.230                | 3.975                | 2.906                    | 2.974                 | 3.571                 |
| 240                       | 3.178                   | 3.246                | 4.004                | 2.920                    | 2.989                 | 3.597                 |
| 270                       | 3.205                   | 3.273                | 4.049                | 2.945                    | 3.015                 | 3.638                 |
| 300                       | 3.220                   | 3.290                | 4.079                | 2.959                    | 3.031                 | 3.664                 |
| 330                       | 3.244                   | 3.316                | 4.122                | 2.983                    | 3.055                 | 3.703                 |
| 360                       | 3.267                   | 3.339                | 4.161                | 3.004                    | 3.078                 | 3.738                 |



**Table C.6.** Camber prediction of 3 BTE 110 prestressed girders without overhang by using three methods and two types of section properties at plant B, including 144-274, 144-275 and 144-278

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 1.806                   | 1.829                | 1.806                | 1.602                    | 1.613                 | 1.602                 |
| 0                         | 1.745                   | 1.766                | 1.752                | 1.546                    | 1.573                 | 1.553                 |
| 1                         | 1.996                   | 2.025                | 2.065                | 1.775                    | 1.810                 | 1.832                 |
| 2                         | 2.080                   | 2.112                | 2.196                | 1.853                    | 1.892                 | 1.948                 |
| 3                         | 2.145                   | 2.180                | 2.303                | 1.915                    | 1.957                 | 2.044                 |
| 7                         | 2.232                   | 2.272                | 2.502                | 2.003                    | 2.050                 | 2.221                 |
| 14                        | 2.315                   | 2.361                | 2.698                | 2.087                    | 2.139                 | 2.397                 |
| 21                        | 2.346                   | 2.395                | 2.793                | 2.119                    | 2.175                 | 2.481                 |
| 28                        | 2.367                   | 2.418                | 2.857                | 2.142                    | 2.199                 | 2.538                 |
| 60                        | 2.452                   | 2.509                | 3.053                | 2.225                    | 2.289                 | 2.713                 |
| 90                        | 2.490                   | 2.550                | 3.146                | 2.262                    | 2.329                 | 2.795                 |
| 120                       | 2.508                   | 2.570                | 3.193                | 2.280                    | 2.349                 | 2.837                 |
| 150                       | 2.523                   | 2.587                | 3.232                | 2.295                    | 2.366                 | 2.872                 |
| 180                       | 2.536                   | 2.601                | 3.262                | 2.308                    | 2.379                 | 2.899                 |
| 210                       | 2.546                   | 2.612                | 3.286                | 2.317                    | 2.390                 | 2.920                 |
| 240                       | 2.557                   | 2.624                | 3.310                | 2.328                    | 2.401                 | 2.942                 |
| 270                       | 2.577                   | 2.645                | 3.348                | 2.346                    | 2.422                 | 2.975                 |
| 300                       | 2.588                   | 2.657                | 3.372                | 2.357                    | 2.433                 | 2.997                 |
| 330                       | 2.607                   | 2.677                | 3.408                | 2.374                    | 2.452                 | 3.029                 |
| 360                       | 2.623                   | 2.696                | 3.440                | 2.390                    | 2.469                 | 3.058                 |

**Table C.7.** Camber prediction of 3 BTE 110 prestressed girders with overhang by using three methods and two types of section properties at plant B, including 144-284, 144-283 and 144-280

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 2.037                   | 2.056                | 2.037                | 1.842                    | 1.851                 | 1.842                 |
| 0                         | 1.981                   | 1.999                | 1.975                | 1.790                    | 1.814                 | 1.785                 |
| 1                         | 2.274                   | 2.298                | 2.329                | 2.061                    | 2.091                 | 2.106                 |
| 2                         | 2.373                   | 2.401                | 2.477                | 2.156                    | 2.189                 | 2.241                 |
| 3                         | 2.451                   | 2.481                | 2.598                | 2.230                    | 2.265                 | 2.351                 |
| 7                         | 2.559                   | 2.594                | 2.823                | 2.338                    | 2.377                 | 2.555                 |
| 14                        | 2.662                   | 2.702                | 3.045                | 2.441                    | 2.484                 | 2.757                 |
| 21                        | 2.702                   | 2.744                | 3.152                | 2.483                    | 2.528                 | 2.854                 |
| 28                        | 2.730                   | 2.774                | 3.224                | 2.511                    | 2.558                 | 2.920                 |
| 60                        | 2.837                   | 2.886                | 3.446                | 2.617                    | 2.668                 | 3.121                 |
| 90                        | 2.886                   | 2.938                | 3.550                | 2.665                    | 2.719                 | 3.216                 |
| 120                       | 2.910                   | 2.964                | 3.604                | 2.688                    | 2.744                 | 3.264                 |
| 150                       | 2.931                   | 2.986                | 3.648                | 2.708                    | 2.765                 | 3.304                 |
| 180                       | 2.948                   | 3.004                | 3.682                | 2.725                    | 2.783                 | 3.336                 |
| 210                       | 2.961                   | 3.018                | 3.709                | 2.738                    | 2.797                 | 3.360                 |
| 240                       | 2.975                   | 3.033                | 3.736                | 2.751                    | 2.811                 | 3.384                 |
| 270                       | 3.000                   | 3.059                | 3.779                | 2.775                    | 2.836                 | 3.423                 |
| 300                       | 3.015                   | 3.075                | 3.807                | 2.789                    | 2.851                 | 3.448                 |
| 330                       | 3.038                   | 3.100                | 3.846                | 2.811                    | 2.874                 | 3.485                 |
| 360                       | 3.060                   | 3.122                | 3.883                | 2.831                    | 2.896                 | 3.518                 |

**Table C.8.** Camber prediction of 3 BTE 110 prestressed girders without overhang by using three methods and two types of section properties at plant B, including 144-284, 144-283 and 144-280

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 1.683                   | 1.703                | 1.683                | 1.507                    | 1.517                 | 1.507                 |
| 0                         | 1.625                   | 1.643                | 1.632                | 1.454                    | 1.477                 | 1.461                 |
| 1                         | 1.861                   | 1.886                | 1.925                | 1.671                    | 1.701                 | 1.724                 |
| 2                         | 1.940                   | 1.968                | 2.048                | 1.745                    | 1.778                 | 1.834                 |
| 3                         | 2.002                   | 2.032                | 2.148                | 1.804                    | 1.840                 | 1.925                 |
| 7                         | 2.085                   | 2.119                | 2.334                | 1.887                    | 1.927                 | 2.092                 |
| 14                        | 2.164                   | 2.204                | 2.518                | 1.967                    | 2.012                 | 2.258                 |
| 21                        | 2.194                   | 2.236                | 2.607                | 1.998                    | 2.046                 | 2.338                 |
| 28                        | 2.214                   | 2.258                | 2.667                | 2.019                    | 2.069                 | 2.391                 |
| 60                        | 2.296                   | 2.345                | 2.850                | 2.100                    | 2.155                 | 2.557                 |
| 90                        | 2.332                   | 2.384                | 2.937                | 2.135                    | 2.193                 | 2.634                 |
| 120                       | 2.350                   | 2.403                | 2.981                | 2.152                    | 2.212                 | 2.674                 |
| 150                       | 2.364                   | 2.419                | 3.018                | 2.167                    | 2.228                 | 2.707                 |
| 180                       | 2.377                   | 2.433                | 3.046                | 2.179                    | 2.241                 | 2.733                 |
| 210                       | 2.387                   | 2.443                | 3.068                | 2.188                    | 2.251                 | 2.753                 |
| 240                       | 2.397                   | 2.454                | 3.091                | 2.198                    | 2.262                 | 2.773                 |
| 270                       | 2.416                   | 2.475                | 3.126                | 2.216                    | 2.281                 | 2.804                 |
| 300                       | 2.427                   | 2.487                | 3.149                | 2.226                    | 2.292                 | 2.825                 |
| 330                       | 2.445                   | 2.506                | 3.182                | 2.243                    | 2.310                 | 2.855                 |
| 360                       | 2.461                   | 2.523                | 3.212                | 2.258                    | 2.327                 | 2.882                 |

**Table C.9.** Camber prediction of 2 BTE 145 prestressed girders with overhang by using three methods and two types of section properties at plant B, including 144-311 and 144-334

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 5.037                   | 5.094                | 5.037                | 4.390                    | 4.405                 | 4.390                 |
| 0                         | 4.893                   | 4.942                | 4.903                | 4.258                    | 4.344                 | 4.270                 |
| 1                         | 5.590                   | 5.658                | 5.766                | 4.886                    | 4.992                 | 5.027                 |
| 2                         | 5.821                   | 5.899                | 6.127                | 5.104                    | 5.216                 | 5.344                 |
| 3                         | 6.001                   | 6.086                | 6.423                | 5.274                    | 5.392                 | 5.603                 |
| 7                         | 6.242                   | 6.340                | 6.972                | 5.519                    | 5.644                 | 6.086                 |
| 14                        | 6.471                   | 6.583                | 7.515                | 5.753                    | 5.886                 | 6.562                 |
| 21                        | 6.556                   | 6.675                | 7.777                | 5.844                    | 5.982                 | 6.792                 |
| 28                        | 6.614                   | 6.739                | 7.954                | 5.907                    | 6.047                 | 6.948                 |
| 60                        | 6.846                   | 6.988                | 8.495                | 6.138                    | 6.291                 | 7.423                 |
| 90                        | 6.951                   | 7.101                | 8.750                | 6.241                    | 6.401                 | 7.647                 |
| 120                       | 7.001                   | 7.156                | 8.880                | 6.291                    | 6.455                 | 7.761                 |
| 150                       | 7.043                   | 7.202                | 8.988                | 6.333                    | 6.500                 | 7.856                 |
| 180                       | 7.079                   | 7.241                | 9.073                | 6.368                    | 6.538                 | 7.930                 |
| 210                       | 7.107                   | 7.271                | 9.138                | 6.395                    | 6.567                 | 7.988                 |
| 240                       | 7.137                   | 7.303                | 9.204                | 6.423                    | 6.598                 | 8.046                 |
| 270                       | 7.191                   | 7.361                | 9.308                | 6.475                    | 6.653                 | 8.137                 |
| 300                       | 7.222                   | 7.395                | 9.377                | 6.504                    | 6.685                 | 8.197                 |
| 330                       | 7.273                   | 7.450                | 9.474                | 6.552                    | 6.736                 | 8.283                 |
| 360                       | 7.319                   | 7.499                | 9.563                | 6.595                    | 6.783                 | 8.361                 |

**Table C.10.** Camber prediction of 2 BTE 145 prestressed girders without overhang by using three methods and two types of section properties at plant B, including 144-311 and 144-334

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 3.695                   | 3.760                | 3.695                | 3.132                    | 3.154                 | 3.132                 |
| 0                         | 3.542                   | 3.599                | 3.595                | 2.992                    | 3.077                 | 3.045                 |
| 1                         | 4.055                   | 4.135                | 4.274                | 3.443                    | 3.551                 | 3.624                 |
| 2                         | 4.191                   | 4.278                | 4.517                | 3.570                    | 3.685                 | 3.832                 |
| 3                         | 4.272                   | 4.365                | 4.687                | 3.649                    | 3.769                 | 3.977                 |
| 7                         | 4.435                   | 4.542                | 5.103                | 3.815                    | 3.947                 | 4.332                 |
| 14                        | 4.559                   | 4.681                | 5.487                | 3.947                    | 4.090                 | 4.659                 |
| 21                        | 4.630                   | 4.761                | 5.716                | 4.021                    | 4.172                 | 4.855                 |
| 28                        | 4.678                   | 4.815                | 5.875                | 4.071                    | 4.228                 | 4.991                 |
| 60                        | 4.794                   | 4.949                | 6.262                | 4.191                    | 4.362                 | 5.321                 |
| 90                        | 4.845                   | 5.008                | 6.435                | 4.242                    | 4.421                 | 5.469                 |
| 120                       | 4.875                   | 5.043                | 6.540                | 4.272                    | 4.456                 | 5.558                 |
| 150                       | 4.895                   | 5.066                | 6.611                | 4.292                    | 4.479                 | 5.619                 |
| 180                       | 4.909                   | 5.082                | 6.662                | 4.306                    | 4.496                 | 5.662                 |
| 210                       | 4.919                   | 5.094                | 6.700                | 4.316                    | 4.507                 | 5.694                 |
| 240                       | 4.926                   | 5.103                | 6.729                | 4.323                    | 4.516                 | 5.719                 |
| 270                       | 4.932                   | 5.110                | 6.752                | 4.329                    | 4.523                 | 5.739                 |
| 300                       | 4.936                   | 5.115                | 6.770                | 4.333                    | 4.528                 | 5.754                 |
| 330                       | 4.939                   | 5.119                | 6.785                | 4.336                    | 4.532                 | 5.767                 |
| 360                       | 4.942                   | 5.122                | 6.797                | 4.339                    | 4.536                 | 5.777                 |

**Table C.11.** Camber prediction of 2 BTE 145 prestressed girders with overhang by using three methods and two types of section properties at plant B, including 144-316 and 144-317

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 5.050                   | 5.109                | 5.050                | 4.386                    | 4.402                 | 4.386                 |
| 0                         | 4.904                   | 4.955                | 4.915                | 4.253                    | 4.341                 | 4.265                 |
| 1                         | 5.600                   | 5.671                | 5.779                | 4.879                    | 4.988                 | 5.021                 |
| 2                         | 5.830                   | 5.911                | 6.140                | 5.095                    | 5.211                 | 5.338                 |
| 3                         | 6.009                   | 6.098                | 6.436                | 5.265                    | 5.387                 | 5.596                 |
| 7                         | 6.248                   | 6.350                | 6.986                | 5.508                    | 5.637                 | 6.078                 |
| 14                        | 6.475                   | 6.592                | 7.529                | 5.740                    | 5.878                 | 6.553                 |
| 21                        | 6.558                   | 6.683                | 7.791                | 5.831                    | 5.973                 | 6.783                 |
| 28                        | 6.616                   | 6.746                | 7.968                | 5.892                    | 6.038                 | 6.937                 |
| 60                        | 6.846                   | 6.993                | 8.510                | 6.121                    | 6.280                 | 7.412                 |
| 90                        | 6.948                   | 7.105                | 8.765                | 6.223                    | 6.389                 | 7.635                 |
| 120                       | 6.998                   | 7.159                | 8.895                | 6.272                    | 6.442                 | 7.749                 |
| 150                       | 7.039                   | 7.204                | 9.003                | 6.313                    | 6.487                 | 7.844                 |
| 180                       | 7.075                   | 7.243                | 9.088                | 6.348                    | 6.524                 | 7.918                 |
| 210                       | 7.102                   | 7.273                | 9.154                | 6.374                    | 6.553                 | 7.975                 |
| 240                       | 7.132                   | 7.305                | 9.220                | 6.403                    | 6.584                 | 8.033                 |
| 270                       | 7.185                   | 7.363                | 9.324                | 6.453                    | 6.638                 | 8.124                 |
| 300                       | 7.216                   | 7.396                | 9.392                | 6.482                    | 6.670                 | 8.184                 |
| 330                       | 7.266                   | 7.450                | 9.489                | 6.529                    | 6.720                 | 8.269                 |
| 360                       | 7.312                   | 7.499                | 9.579                | 6.572                    | 6.767                 | 8.348                 |

**Table C.12.** Camber prediction of 2 BTE 145 prestressed girders without overhang by using three methods and two types of section properties at plant B, including 144-316 and 144-317

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 3.682                   | 3.750                | 3.682                | 3.106                    | 3.130                 | 3.106                 |
| 0                         | 3.526                   | 3.586                | 3.582                | 2.965                    | 3.052                 | 3.019                 |
| 1                         | 4.035                   | 4.117                | 4.258                | 3.409                    | 3.521                 | 3.593                 |
| 2                         | 4.168                   | 4.259                | 4.500                | 3.534                    | 3.653                 | 3.799                 |
| 3                         | 4.248                   | 4.345                | 4.669                | 3.611                    | 3.736                 | 3.942                 |
| 7                         | 4.407                   | 4.519                | 5.083                | 3.774                    | 3.911                 | 4.294                 |
| 14                        | 4.528                   | 4.655                | 5.465                | 3.903                    | 4.051                 | 4.618                 |
| 21                        | 4.596                   | 4.733                | 5.693                | 3.975                    | 4.132                 | 4.812                 |
| 28                        | 4.643                   | 4.786                | 5.851                | 4.024                    | 4.187                 | 4.947                 |
| 60                        | 4.755                   | 4.916                | 6.236                | 4.139                    | 4.318                 | 5.274                 |
| 90                        | 4.804                   | 4.973                | 6.408                | 4.189                    | 4.375                 | 5.420                 |
| 120                       | 4.833                   | 5.007                | 6.513                | 4.218                    | 4.409                 | 5.509                 |
| 150                       | 4.852                   | 5.029                | 6.583                | 4.237                    | 4.432                 | 5.569                 |
| 180                       | 4.865                   | 5.045                | 6.633                | 4.250                    | 4.447                 | 5.612                 |
| 210                       | 4.874                   | 5.056                | 6.671                | 4.259                    | 4.459                 | 5.644                 |
| 240                       | 4.881                   | 5.065                | 6.700                | 4.266                    | 4.467                 | 5.668                 |
| 270                       | 4.886                   | 5.071                | 6.723                | 4.272                    | 4.474                 | 5.687                 |
| 300                       | 4.890                   | 5.076                | 6.741                | 4.276                    | 4.479                 | 5.703                 |
| 330                       | 4.893                   | 5.080                | 6.756                | 4.279                    | 4.483                 | 5.715                 |
| 360                       | 4.896                   | 5.083                | 6.768                | 4.281                    | 4.486                 | 5.726                 |

**Table C.13.** Camber prediction of 2 BTE 145 prestressed girders with overhang by using three methods and two types of section properties at plant B, including 144-366 and 144-367

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 4.948                   | 5.004                | 4.948                | 4.313                    | 4.328                 | 4.313                 |
| 0                         | 4.803                   | 4.852                | 4.815                | 4.180                    | 4.265                 | 4.193                 |
| 1                         | 5.487                   | 5.555                | 5.662                | 4.797                    | 4.901                 | 4.937                 |
| 2                         | 5.714                   | 5.791                | 6.017                | 5.010                    | 5.121                 | 5.248                 |
| 3                         | 5.890                   | 5.974                | 6.307                | 5.177                    | 5.294                 | 5.503                 |
| 7                         | 6.126                   | 6.223                | 6.847                | 5.417                    | 5.541                 | 5.977                 |
| 14                        | 6.350                   | 6.462                | 7.380                | 5.646                    | 5.778                 | 6.445                 |
| 21                        | 6.433                   | 6.552                | 7.637                | 5.735                    | 5.872                 | 6.671                 |
| 28                        | 6.490                   | 6.614                | 7.811                | 5.796                    | 5.936                 | 6.823                 |
| 60                        | 6.718                   | 6.858                | 8.343                | 6.023                    | 6.175                 | 7.290                 |
| 90                        | 6.819                   | 6.968                | 8.593                | 6.123                    | 6.282                 | 7.510                 |
| 120                       | 6.868                   | 7.022                | 8.721                | 6.172                    | 6.335                 | 7.623                 |
| 150                       | 6.910                   | 7.067                | 8.827                | 6.213                    | 6.379                 | 7.716                 |
| 180                       | 6.945                   | 7.106                | 8.910                | 6.247                    | 6.416                 | 7.789                 |
| 210                       | 6.972                   | 7.135                | 8.974                | 6.273                    | 6.444                 | 7.845                 |
| 240                       | 7.001                   | 7.166                | 9.039                | 6.301                    | 6.475                 | 7.902                 |
| 270                       | 7.054                   | 7.223                | 9.142                | 6.351                    | 6.528                 | 7.992                 |
| 300                       | 7.084                   | 7.256                | 9.209                | 6.380                    | 6.560                 | 8.051                 |
| 330                       | 7.134                   | 7.310                | 9.304                | 6.427                    | 6.610                 | 8.134                 |
| 360                       | 7.179                   | 7.358                | 9.392                | 6.469                    | 6.656                 | 8.211                 |



**Table C.14.** Camber prediction of 2 BTE 145 prestressed girders without overhang by using three methods and two types of section properties at plant B, including 144-366 and 144-367

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 3.610                   | 3.674                | 3.610                | 3.058                    | 3.081                 | 3.058                 |
| 0                         | 3.456                   | 3.513                | 3.511                | 2.918                    | 3.002                 | 2.972                 |
| 1                         | 3.926                   | 4.003                | 4.132                | 3.331                    | 3.436                 | 3.502                 |
| 2                         | 4.075                   | 4.161                | 4.393                | 3.469                    | 3.583                 | 3.724                 |
| 3                         | 4.192                   | 4.286                | 4.605                | 3.579                    | 3.699                 | 3.905                 |
| 7                         | 4.332                   | 4.440                | 5.001                | 3.724                    | 3.856                 | 4.243                 |
| 14                        | 4.469                   | 4.592                | 5.392                | 3.866                    | 4.010                 | 4.576                 |
| 21                        | 4.512                   | 4.642                | 5.581                | 3.916                    | 4.065                 | 4.737                 |
| 28                        | 4.542                   | 4.676                | 5.708                | 3.949                    | 4.103                 | 4.846                 |
| 60                        | 4.674                   | 4.826                | 6.098                | 4.083                    | 4.252                 | 5.178                 |
| 90                        | 4.727                   | 4.888                | 6.281                | 4.135                    | 4.313                 | 5.335                 |
| 120                       | 4.751                   | 4.917                | 6.375                | 4.160                    | 4.342                 | 5.415                 |
| 150                       | 4.771                   | 4.940                | 6.453                | 4.179                    | 4.365                 | 5.481                 |
| 180                       | 4.789                   | 4.962                | 6.514                | 4.197                    | 4.386                 | 5.533                 |
| 210                       | 4.803                   | 4.978                | 6.561                | 4.210                    | 4.402                 | 5.573                 |
| 240                       | 4.818                   | 4.995                | 6.609                | 4.225                    | 4.419                 | 5.614                 |
| 270                       | 4.849                   | 5.031                | 6.683                | 4.254                    | 4.452                 | 5.678                 |
| 300                       | 4.865                   | 5.049                | 6.733                | 4.268                    | 4.469                 | 5.720                 |
| 330                       | 4.894                   | 5.081                | 6.803                | 4.295                    | 4.499                 | 5.779                 |
| 360                       | 4.919                   | 5.111                | 6.867                | 4.319                    | 4.527                 | 5.834                 |

**Table C.15.** Camber prediction of 2 BTD 135 prestressed girders with overhang by using three methods and two types of section properties at plant C, including 13501 and 13502

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 4.270                   | 4.324                | 4.270                | 3.714                    | 3.729                 | 3.714                 |
| 0                         | 4.121                   | 4.169                | 4.152                | 3.578                    | 3.657                 | 3.609                 |
| 1                         | 4.708                   | 4.774                | 4.890                | 4.105                    | 4.202                 | 4.254                 |
| 2                         | 4.902                   | 4.976                | 5.200                | 4.286                    | 4.390                 | 4.525                 |
| 3                         | 5.053                   | 5.134                | 5.453                | 4.429                    | 4.538                 | 4.746                 |
| 7                         | 5.252                   | 5.344                | 5.924                | 4.631                    | 4.747                 | 5.158                 |
| 14                        | 5.443                   | 5.548                | 6.388                | 4.825                    | 4.949                 | 5.565                 |
| 21                        | 5.512                   | 5.624                | 6.613                | 4.900                    | 5.027                 | 5.761                 |
| 28                        | 5.559                   | 5.675                | 6.764                | 4.950                    | 5.081                 | 5.893                 |
| 60                        | 5.753                   | 5.883                | 7.228                | 5.141                    | 5.283                 | 6.299                 |
| 90                        | 5.837                   | 5.975                | 7.446                | 5.224                    | 5.372                 | 6.490                 |
| 120                       | 5.877                   | 6.020                | 7.558                | 5.264                    | 5.416                 | 6.588                 |
| 150                       | 5.911                   | 6.057                | 7.650                | 5.297                    | 5.452                 | 6.669                 |
| 180                       | 5.941                   | 6.089                | 7.723                | 5.325                    | 5.483                 | 6.732                 |
| 210                       | 5.963                   | 6.113                | 7.779                | 5.346                    | 5.506                 | 6.781                 |
| 240                       | 5.987                   | 6.140                | 7.835                | 5.369                    | 5.531                 | 6.831                 |
| 270                       | 6.032                   | 6.188                | 7.924                | 5.412                    | 5.576                 | 6.908                 |
| 300                       | 6.057                   | 6.216                | 7.983                | 5.435                    | 5.602                 | 6.960                 |
| 330                       | 6.099                   | 6.261                | 8.066                | 5.474                    | 5.645                 | 7.032                 |
| 360                       | 6.138                   | 6.302                | 8.143                | 5.510                    | 5.683                 | 7.099                 |

**Table C.16.** Camber prediction of 2 BTD 135 prestressed girders without overhang by using three methods and two types of section properties at plant C, including 13501 and 13502

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 4.043                   | 4.107                | 4.043                | 3.422                    | 3.438                 | 3.422                 |
| 0                         | 3.884                   | 3.940                | 3.934                | 3.277                    | 3.369                 | 3.326                 |
| 1                         | 4.420                   | 4.496                | 4.631                | 3.748                    | 3.862                 | 3.920                 |
| 2                         | 4.592                   | 4.678                | 4.923                | 3.907                    | 4.029                 | 4.169                 |
| 3                         | 4.727                   | 4.821                | 5.161                | 4.033                    | 4.162                 | 4.372                 |
| 7                         | 4.895                   | 5.003                | 5.605                | 4.206                    | 4.344                 | 4.750                 |
| 14                        | 5.058                   | 5.179                | 6.044                | 4.373                    | 4.522                 | 5.124                 |
| 21                        | 5.112                   | 5.241                | 6.255                | 4.434                    | 4.588                 | 5.304                 |
| 28                        | 5.149                   | 5.283                | 6.398                | 4.475                    | 4.633                 | 5.426                 |
| 60                        | 5.309                   | 5.460                | 6.836                | 4.634                    | 4.807                 | 5.798                 |
| 90                        | 5.375                   | 5.535                | 7.042                | 4.699                    | 4.880                 | 5.974                 |
| 120                       | 5.406                   | 5.570                | 7.147                | 4.731                    | 4.916                 | 6.064                 |
| 150                       | 5.431                   | 5.600                | 7.234                | 4.755                    | 4.944                 | 6.138                 |
| 180                       | 5.455                   | 5.626                | 7.303                | 4.778                    | 4.969                 | 6.196                 |
| 210                       | 5.472                   | 5.646                | 7.356                | 4.794                    | 4.988                 | 6.242                 |
| 240                       | 5.491                   | 5.667                | 7.409                | 4.812                    | 5.009                 | 6.287                 |
| 270                       | 5.528                   | 5.709                | 7.493                | 4.847                    | 5.047                 | 6.359                 |
| 300                       | 5.548                   | 5.731                | 7.548                | 4.865                    | 5.068                 | 6.406                 |
| 330                       | 5.583                   | 5.770                | 7.627                | 4.897                    | 5.104                 | 6.473                 |
| 360                       | 5.614                   | 5.805                | 7.699                | 4.926                    | 5.136                 | 6.534                 |

**Table C.17.** Camber prediction of 2 BTD 135 prestressed girders with overhang by using three methods and two types of section properties at plant C, including 13503 and 13504

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 4.269                   | 4.333                | 4.269                | 3.629                    | 3.645                 | 3.629                 |
| 0                         | 4.293                   | 4.167                | 4.155                | 3.656                    | 3.579                 | 3.529                 |
| 1                         | 4.895                   | 4.760                | 4.890                | 4.188                    | 4.105                 | 4.159                 |
| 2                         | 5.092                   | 4.954                | 5.198                | 4.371                    | 4.284                 | 4.422                 |
| 3                         | 5.246                   | 5.107                | 5.450                | 4.515                    | 4.426                 | 4.638                 |
| 7                         | 5.444                   | 5.304                | 5.919                | 4.717                    | 4.623                 | 5.039                 |
| 14                        | 5.634                   | 5.496                | 6.382                | 4.911                    | 4.815                 | 5.435                 |
| 21                        | 5.701                   | 5.563                | 6.605                | 4.985                    | 4.887                 | 5.627                 |
| 28                        | 5.746                   | 5.610                | 6.756                | 5.035                    | 4.936                 | 5.756                 |
| 60                        | 5.937                   | 5.803                | 7.218                | 5.223                    | 5.125                 | 6.151                 |
| 90                        | 6.019                   | 5.885                | 7.435                | 5.304                    | 5.206                 | 6.337                 |
| 120                       | 6.058                   | 5.925                | 7.547                | 5.342                    | 5.245                 | 6.432                 |
| 150                       | 6.090                   | 5.958                | 7.639                | 5.374                    | 5.277                 | 6.511                 |
| 180                       | 6.118                   | 5.987                | 7.711                | 5.401                    | 5.305                 | 6.573                 |
| 210                       | 6.140                   | 6.009                | 7.767                | 5.422                    | 5.326                 | 6.621                 |
| 240                       | 6.163                   | 6.033                | 7.823                | 5.444                    | 5.348                 | 6.669                 |
| 270                       | 6.208                   | 6.078                | 7.912                | 5.486                    | 5.390                 | 6.745                 |
| 300                       | 6.232                   | 6.102                | 7.970                | 5.508                    | 5.413                 | 6.795                 |
| 330                       | 6.274                   | 6.144                | 8.053                | 5.547                    | 5.452                 | 6.866                 |
| 360                       | 6.311                   | 6.183                | 8.129                | 5.581                    | 5.488                 | 6.931                 |

**Table C.18.** Camber prediction of 2 BTD 135 prestressed girders without overhang by using three methods and two types of section properties at plant C, including 13503 and 13504

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 4.122                   | 4.186                | 4.122                | 3.491                    | 3.507                 | 3.491                 |
| 0                         | 3.963                   | 4.019                | 4.011                | 3.347                    | 3.440                 | 3.395                 |
| 1                         | 4.511                   | 4.588                | 4.722                | 3.829                    | 3.944                 | 4.001                 |
| 2                         | 4.688                   | 4.774                | 5.020                | 3.992                    | 4.115                 | 4.255                 |
| 3                         | 4.826                   | 4.919                | 5.263                | 4.121                    | 4.251                 | 4.462                 |
| 7                         | 4.999                   | 5.106                | 5.716                | 4.299                    | 4.438                 | 4.848                 |
| 14                        | 5.166                   | 5.288                | 6.163                | 4.471                    | 4.620                 | 5.229                 |
| 21                        | 5.222                   | 5.351                | 6.379                | 4.533                    | 4.688                 | 5.414                 |
| 28                        | 5.260                   | 5.395                | 6.524                | 4.576                    | 4.734                 | 5.538                 |
| 60                        | 5.425                   | 5.577                | 6.970                | 4.740                    | 4.913                 | 5.918                 |
| 90                        | 5.494                   | 5.654                | 7.180                | 4.808                    | 4.988                 | 6.097                 |
| 120                       | 5.526                   | 5.691                | 7.288                | 4.840                    | 5.025                 | 6.189                 |
| 150                       | 5.553                   | 5.721                | 7.377                | 4.866                    | 5.055                 | 6.265                 |
| 180                       | 5.577                   | 5.748                | 7.447                | 4.889                    | 5.081                 | 6.324                 |
| 210                       | 5.594                   | 5.769                | 7.501                | 4.906                    | 5.100                 | 6.371                 |
| 240                       | 5.614                   | 5.791                | 7.555                | 4.925                    | 5.121                 | 6.417                 |
| 270                       | 5.653                   | 5.834                | 7.641                | 4.961                    | 5.161                 | 6.490                 |
| 300                       | 5.673                   | 5.857                | 7.697                | 4.980                    | 5.183                 | 6.538                 |
| 330                       | 5.709                   | 5.896                | 7.777                | 5.013                    | 5.219                 | 6.606                 |
| 360                       | 5.742                   | 5.932                | 7.851                | 5.042                    | 5.253                 | 6.669                 |

**Table C.19.** Camber prediction of 2 BTD 135 prestressed girders with overhang by using three methods and two types of section properties at plant C, including 13507 and 13508

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 4.663                   | 4.727                | 4.663                | 4.005                    | 4.021                 | 4.005                 |
| 0                         | 4.508                   | 4.565                | 4.539                | 3.864                    | 3.957                 | 3.895                 |
| 1                         | 5.144                   | 5.222                | 5.341                | 4.430                    | 4.544                 | 4.589                 |
| 2                         | 5.353                   | 5.440                | 5.678                | 4.625                    | 4.746                 | 4.880                 |
| 3                         | 5.516                   | 5.611                | 5.953                | 4.778                    | 4.905                 | 5.117                 |
| 7                         | 5.728                   | 5.838                | 6.464                | 4.994                    | 5.130                 | 5.560                 |
| 14                        | 5.932                   | 6.056                | 6.969                | 5.202                    | 5.347                 | 5.996                 |
| 21                        | 6.005                   | 6.136                | 7.213                | 5.282                    | 5.431                 | 6.207                 |
| 28                        | 6.055                   | 6.192                | 7.378                | 5.336                    | 5.488                 | 6.350                 |
| 60                        | 6.260                   | 6.414                | 7.881                | 5.539                    | 5.705                 | 6.785                 |
| 90                        | 6.349                   | 6.512                | 8.119                | 5.627                    | 5.800                 | 6.991                 |
| 120                       | 6.392                   | 6.559                | 8.240                | 5.670                    | 5.847                 | 7.096                 |
| 150                       | 6.428                   | 6.599                | 8.341                | 5.704                    | 5.885                 | 7.183                 |
| 180                       | 6.459                   | 6.633                | 8.420                | 5.734                    | 5.918                 | 7.251                 |
| 210                       | 6.482                   | 6.659                | 8.481                | 5.757                    | 5.943                 | 7.304                 |
| 240                       | 6.508                   | 6.687                | 8.542                | 5.781                    | 5.970                 | 7.357                 |
| 270                       | 6.556                   | 6.739                | 8.639                | 5.826                    | 6.018                 | 7.441                 |
| 300                       | 6.583                   | 6.769                | 8.703                | 5.851                    | 6.046                 | 7.496                 |
| 330                       | 6.627                   | 6.817                | 8.793                | 5.892                    | 6.091                 | 7.574                 |
| 360                       | 6.668                   | 6.861                | 8.876                | 5.930                    | 6.132                 | 7.646                 |

**Table C.20.** Camber prediction of 2 BTD 135 prestressed girders without overhang by using three methods and two types of section properties at plant C, including 13507 and 13508

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 4.100                   | 4.163                | 4.100                | 3.477                    | 3.493                 | 3.477                 |
| 0                         | 3.942                   | 3.997                | 3.990                | 3.333                    | 3.425                 | 3.381                 |
| 1                         | 4.487                   | 4.563                | 4.697                | 3.813                    | 3.927                 | 3.984                 |
| 2                         | 4.664                   | 4.748                | 4.993                | 3.976                    | 4.097                 | 4.237                 |
| 3                         | 4.801                   | 4.894                | 5.235                | 4.105                    | 4.232                 | 4.444                 |
| 7                         | 4.974                   | 5.080                | 5.686                | 4.281                    | 4.419                 | 4.829                 |
| 14                        | 5.140                   | 5.261                | 6.131                | 4.453                    | 4.601                 | 5.208                 |
| 21                        | 5.196                   | 5.324                | 6.346                | 4.515                    | 4.668                 | 5.392                 |
| 28                        | 5.235                   | 5.367                | 6.491                | 4.558                    | 4.714                 | 5.515                 |
| 60                        | 5.399                   | 5.549                | 6.935                | 4.722                    | 4.893                 | 5.894                 |
| 90                        | 5.468                   | 5.626                | 7.144                | 4.789                    | 4.968                 | 6.073                 |
| 120                       | 5.500                   | 5.663                | 7.251                | 4.821                    | 5.004                 | 6.164                 |
| 150                       | 5.526                   | 5.693                | 7.339                | 4.847                    | 5.034                 | 6.240                 |
| 180                       | 5.551                   | 5.720                | 7.409                | 4.870                    | 5.060                 | 6.299                 |
| 210                       | 5.568                   | 5.741                | 7.463                | 4.888                    | 5.079                 | 6.345                 |
| 240                       | 5.588                   | 5.763                | 7.517                | 4.906                    | 5.101                 | 6.391                 |
| 270                       | 5.627                   | 5.805                | 7.602                | 4.942                    | 5.140                 | 6.464                 |
| 300                       | 5.647                   | 5.828                | 7.658                | 4.961                    | 5.162                 | 6.512                 |
| 330                       | 5.683                   | 5.868                | 7.738                | 4.994                    | 5.198                 | 6.580                 |
| 360                       | 5.715                   | 5.904                | 7.811                | 5.024                    | 5.232                 | 6.642                 |

**Table C.21.** Camber prediction of 2 BTD 135 prestressed girders with overhang by using three methods and two types of section properties at plant C, including 13511 and 13512

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 4.010                   | 4.068                | 4.010                | 3.437                    | 3.452                 | 3.437                 |
| 0                         | 4.029                   | 3.906                | 3.900                | 3.458                    | 3.381                 | 3.340                 |
| 1                         | 4.597                   | 4.465                | 4.593                | 3.964                    | 3.879                 | 3.937                 |
| 2                         | 4.783                   | 4.648                | 4.883                | 4.138                    | 4.049                 | 4.188                 |
| 3                         | 4.929                   | 4.792                | 5.120                | 4.274                    | 4.183                 | 4.392                 |
| 7                         | 5.117                   | 4.979                | 5.562                | 4.465                    | 4.370                 | 4.773                 |
| 14                        | 5.298                   | 5.161                | 5.998                | 4.650                    | 4.551                 | 5.149                 |
| 21                        | 5.362                   | 5.225                | 6.208                | 4.720                    | 4.620                 | 5.331                 |
| 28                        | 5.405                   | 5.270                | 6.350                | 4.767                    | 4.666                 | 5.453                 |
| 60                        | 5.587                   | 5.453                | 6.785                | 4.947                    | 4.845                 | 5.828                 |
| 90                        | 5.665                   | 5.531                | 6.990                | 5.023                    | 4.922                 | 6.005                 |
| 120                       | 5.703                   | 5.569                | 7.095                | 5.060                    | 4.959                 | 6.095                 |
| 150                       | 5.733                   | 5.600                | 7.182                | 5.090                    | 4.989                 | 6.170                 |
| 180                       | 5.761                   | 5.628                | 7.250                | 5.117                    | 5.016                 | 6.229                 |
| 210                       | 5.781                   | 5.649                | 7.302                | 5.136                    | 5.036                 | 6.274                 |
| 240                       | 5.803                   | 5.671                | 7.356                | 5.157                    | 5.057                 | 6.320                 |
| 270                       | 5.846                   | 5.714                | 7.439                | 5.197                    | 5.097                 | 6.392                 |
| 300                       | 5.869                   | 5.738                | 7.494                | 5.219                    | 5.119                 | 6.439                 |
| 330                       | 5.909                   | 5.777                | 7.572                | 5.255                    | 5.156                 | 6.507                 |
| 360                       | 5.945                   | 5.814                | 7.644                | 5.288                    | 5.190                 | 6.568                 |



**Table C.22.** Camber prediction of 2 BTD 135 prestressed girders without overhang by using three methods and two types of section properties at plant C, including 13511 and 13512

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 3.856                   | 3.913                | 3.856                | 3.292                    | 3.308                 | 3.292                 |
| 0                         | 3.700                   | 3.751                | 3.749                | 3.151                    | 3.235                 | 3.199                 |
| 1                         | 4.215                   | 4.284                | 4.416                | 3.606                    | 3.710                 | 3.772                 |
| 2                         | 4.381                   | 4.459                | 4.695                | 3.760                    | 3.871                 | 4.012                 |
| 3                         | 4.511                   | 4.596                | 4.923                | 3.882                    | 3.999                 | 4.208                 |
| 7                         | 4.674                   | 4.772                | 5.348                | 4.049                    | 4.175                 | 4.573                 |
| 14                        | 4.833                   | 4.943                | 5.767                | 4.211                    | 4.347                 | 4.933                 |
| 21                        | 4.886                   | 5.003                | 5.970                | 4.271                    | 4.411                 | 5.107                 |
| 28                        | 4.922                   | 5.044                | 6.106                | 4.311                    | 4.454                 | 5.224                 |
| 60                        | 5.079                   | 5.216                | 6.525                | 4.466                    | 4.623                 | 5.584                 |
| 90                        | 5.144                   | 5.289                | 6.722                | 4.530                    | 4.694                 | 5.753                 |
| 120                       | 5.175                   | 5.324                | 6.823                | 4.560                    | 4.729                 | 5.839                 |
| 150                       | 5.200                   | 5.352                | 6.906                | 4.585                    | 4.756                 | 5.911                 |
| 180                       | 5.223                   | 5.378                | 6.972                | 4.607                    | 4.781                 | 5.967                 |
| 210                       | 5.240                   | 5.397                | 7.022                | 4.623                    | 4.799                 | 6.011                 |
| 240                       | 5.258                   | 5.418                | 7.073                | 4.641                    | 4.819                 | 6.055                 |
| 270                       | 5.295                   | 5.459                | 7.154                | 4.675                    | 4.857                 | 6.124                 |
| 300                       | 5.314                   | 5.480                | 7.206                | 4.693                    | 4.877                 | 6.169                 |
| 330                       | 5.348                   | 5.518                | 7.282                | 4.724                    | 4.912                 | 6.234                 |
| 360                       | 5.379                   | 5.552                | 7.351                | 4.752                    | 4.944                 | 6.293                 |

## **APPENDIX D**

**Comparison of Cambers for Different Types of Girders by Using Three Methods,  
and Gross Section Properties and Transformed Section Properties, and Specified  
Sealed Creep Coefficient and Sealed Shrinkage Data**

**Table D.1.** Camber prediction of 3 BTC 120 prestressed girders with overhang by using three methods and two types of section properties at plant A

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 4.562                   | 4.614                | 4.562                | 3.991                    | 4.003                 | 3.991                 |
| 0                         | 4.430                   | 4.476                | 4.444                | 3.701                    | 3.949                 | 3.885                 |
| 1                         | 4.998                   | 5.060                | 5.159                | 4.189                    | 4.480                 | 4.514                 |
| 2                         | 5.016                   | 5.079                | 5.265                | 4.213                    | 4.505                 | 4.608                 |
| 3                         | 5.166                   | 5.235                | 5.505                | 4.349                    | 4.652                 | 4.819                 |
| 7                         | 5.438                   | 5.518                | 6.033                | 4.602                    | 4.926                 | 5.284                 |
| 14                        | 5.604                   | 5.694                | 6.448                | 4.764                    | 5.103                 | 5.649                 |
| 21                        | 5.632                   | 5.724                | 6.596                | 4.798                    | 5.140                 | 5.779                 |
| 28                        | 5.685                   | 5.782                | 6.744                | 4.850                    | 5.198                 | 5.909                 |
| 60                        | 6.190                   | 6.311                | 7.625                | 5.298                    | 5.696                 | 6.684                 |
| 90                        | 6.345                   | 6.475                | 7.934                | 5.437                    | 5.852                 | 6.956                 |
| 120                       | 6.443                   | 6.580                | 8.126                | 5.524                    | 5.951                 | 7.125                 |
| 150                       | 6.523                   | 6.665                | 8.278                | 5.595                    | 6.031                 | 7.259                 |
| 180                       | 6.556                   | 6.700                | 8.345                | 5.625                    | 6.065                 | 7.318                 |
| 210                       | 6.581                   | 6.726                | 8.399                | 5.647                    | 6.091                 | 7.365                 |
| 240                       | 6.576                   | 6.721                | 8.405                | 5.643                    | 6.087                 | 7.371                 |
| 270                       | 6.556                   | 6.701                | 8.389                | 5.626                    | 6.069                 | 7.357                 |
| 300                       | 6.616                   | 6.765                | 8.501                | 5.678                    | 6.129                 | 7.456                 |
| 330                       | 6.672                   | 6.824                | 8.597                | 5.727                    | 6.184                 | 7.539                 |
| 360                       | 6.728                   | 6.884                | 8.692                | 5.776                    | 6.239                 | 7.623                 |

**Table D.2.** Camber prediction of 3 BTC 120 prestressed girders without overhang by using three methods and two types of section properties at plant A

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 4.103                   | 4.153                | 4.103                | 3.558                    | 3.569                 | 3.558                 |
| 0                         | 3.967                   | 4.012                | 3.995                | 3.434                    | 3.512                 | 3.463                 |
| 1                         | 4.469                   | 4.528                | 4.639                | 3.885                    | 3.979                 | 4.025                 |
| 2                         | 4.481                   | 4.542                | 4.735                | 3.905                    | 3.999                 | 4.108                 |
| 3                         | 4.614                   | 4.680                | 4.951                | 4.031                    | 4.128                 | 4.297                 |
| 7                         | 4.851                   | 4.928                | 5.427                | 4.264                    | 4.369                 | 4.711                 |
| 14                        | 4.992                   | 5.079                | 5.800                | 4.413                    | 4.523                 | 5.037                 |
| 21                        | 5.014                   | 5.103                | 5.933                | 4.443                    | 4.555                 | 5.153                 |
| 28                        | 5.059                   | 5.151                | 6.067                | 4.490                    | 4.604                 | 5.269                 |
| 60                        | 5.496                   | 5.612                | 6.860                | 4.901                    | 5.037                 | 5.961                 |
| 90                        | 5.628                   | 5.753                | 7.138                | 5.027                    | 5.171                 | 6.204                 |
| 120                       | 5.711                   | 5.843                | 7.311                | 5.106                    | 5.256                 | 6.355                 |
| 150                       | 5.779                   | 5.916                | 7.447                | 5.170                    | 5.325                 | 6.474                 |
| 180                       | 5.808                   | 5.946                | 7.508                | 5.197                    | 5.354                 | 6.527                 |
| 210                       | 5.829                   | 5.968                | 7.556                | 5.217                    | 5.376                 | 6.569                 |
| 240                       | 5.823                   | 5.963                | 7.562                | 5.213                    | 5.372                 | 6.574                 |
| 270                       | 5.804                   | 5.944                | 7.547                | 5.197                    | 5.355                 | 6.561                 |
| 300                       | 5.855                   | 5.999                | 7.649                | 5.244                    | 5.406                 | 6.650                 |
| 330                       | 5.903                   | 6.050                | 7.735                | 5.289                    | 5.454                 | 6.724                 |
| 360                       | 5.952                   | 6.102                | 7.820                | 5.333                    | 5.502                 | 6.799                 |

**Table D.3.** Camber prediction of 3 BTE 110 prestressed girders with overhang by using three methods and two types of section properties at plant B, including 144-270, 144-272 and 144-268

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 2.105                   | 2.126                | 2.105                | 1.896                    | 1.906                 | 1.896                 |
| 0                         | 2.048                   | 2.067                | 2.042                | 1.843                    | 1.869                 | 1.838                 |
| 1                         | 2.392                   | 2.420                | 2.454                | 2.160                    | 2.194                 | 2.211                 |
| 2                         | 2.438                   | 2.468                | 2.542                | 2.206                    | 2.241                 | 2.291                 |
| 3                         | 2.558                   | 2.591                | 2.713                | 2.319                    | 2.358                 | 2.446                 |
| 7                         | 2.648                   | 2.685                | 2.918                | 2.411                    | 2.453                 | 2.631                 |
| 14                        | 2.843                   | 2.888                | 3.263                | 2.599                    | 2.648                 | 2.943                 |
| 21                        | 2.918                   | 2.968                | 3.425                | 2.674                    | 2.727                 | 3.089                 |
| 28                        | 2.952                   | 3.004                | 3.507                | 2.709                    | 2.763                 | 3.164                 |
| 60                        | 3.042                   | 3.099                | 3.715                | 2.798                    | 2.857                 | 3.352                 |
| 90                        | 3.083                   | 3.143                | 3.812                | 2.839                    | 2.901                 | 3.439                 |
| 120                       | 3.102                   | 3.164                | 3.862                | 2.858                    | 2.922                 | 3.485                 |
| 150                       | 3.109                   | 3.172                | 3.890                | 2.866                    | 2.930                 | 3.511                 |
| 180                       | 3.116                   | 3.180                | 3.913                | 2.873                    | 2.938                 | 3.531                 |
| 210                       | 3.125                   | 3.189                | 3.934                | 2.882                    | 2.947                 | 3.550                 |
| 240                       | 3.156                   | 3.222                | 3.987                | 2.911                    | 2.978                 | 3.598                 |
| 270                       | 3.193                   | 3.261                | 4.050                | 2.946                    | 3.016                 | 3.655                 |
| 300                       | 3.204                   | 3.273                | 4.073                | 2.957                    | 3.027                 | 3.676                 |
| 330                       | 3.225                   | 3.295                | 4.111                | 2.976                    | 3.048                 | 3.710                 |
| 360                       | 3.246                   | 3.317                | 4.149                | 2.996                    | 3.069                 | 3.745                 |

**Table D.4.** Camber prediction of 3 BTE 110 prestressed girders without overhang by using three methods and two types of section properties at plant B, including 144-270, 144-272 and 144-268

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 1.739                   | 1.761                | 1.739                | 1.551                    | 1.561                 | 1.551                 |
| 0                         | 1.680                   | 1.699                | 1.687                | 1.496                    | 1.521                 | 1.503                 |
| 1                         | 1.958                   | 1.985                | 2.027                | 1.750                    | 1.783                 | 1.808                 |
| 2                         | 1.994                   | 2.023                | 2.101                | 1.786                    | 1.821                 | 1.874                 |
| 3                         | 2.090                   | 2.122                | 2.242                | 1.876                    | 1.914                 | 2.001                 |
| 7                         | 2.159                   | 2.196                | 2.412                | 1.946                    | 1.990                 | 2.153                 |
| 14                        | 2.311                   | 2.356                | 2.698                | 2.093                    | 2.145                 | 2.408                 |
| 21                        | 2.368                   | 2.418                | 2.832                | 2.150                    | 2.206                 | 2.528                 |
| 28                        | 2.394                   | 2.446                | 2.900                | 2.177                    | 2.235                 | 2.590                 |
| 60                        | 2.461                   | 2.518                | 3.072                | 2.244                    | 2.307                 | 2.744                 |
| 90                        | 2.490                   | 2.550                | 3.152                | 2.273                    | 2.339                 | 2.816                 |
| 120                       | 2.503                   | 2.564                | 3.194                | 2.286                    | 2.354                 | 2.853                 |
| 150                       | 2.506                   | 2.569                | 3.217                | 2.290                    | 2.359                 | 2.874                 |
| 180                       | 2.511                   | 2.574                | 3.236                | 2.295                    | 2.365                 | 2.890                 |
| 210                       | 2.517                   | 2.581                | 3.253                | 2.300                    | 2.371                 | 2.906                 |
| 240                       | 2.540                   | 2.606                | 3.298                | 2.323                    | 2.395                 | 2.946                 |
| 270                       | 2.569                   | 2.636                | 3.349                | 2.350                    | 2.424                 | 2.992                 |
| 300                       | 2.577                   | 2.645                | 3.369                | 2.357                    | 2.432                 | 3.009                 |
| 330                       | 2.592                   | 2.662                | 3.400                | 2.372                    | 2.448                 | 3.037                 |
| 360                       | 2.608                   | 2.679                | 3.431                | 2.387                    | 2.464                 | 3.066                 |

**Table D.5.** Camber prediction of 3 BTE 110 prestressed girders with overhang by using three methods and two types of section properties at plant B, including 144-274, 144-275 and 144-278

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 2.187                   | 2.209                | 2.187                | 1.960                    | 1.971                 | 1.960                 |
| 0                         | 2.128                   | 2.149                | 2.122                | 1.906                    | 1.934                 | 1.901                 |
| 1                         | 2.485                   | 2.514                | 2.548                | 2.233                    | 2.270                 | 2.285                 |
| 2                         | 2.532                   | 2.564                | 2.640                | 2.281                    | 2.318                 | 2.368                 |
| 3                         | 2.656                   | 2.692                | 2.818                | 2.397                    | 2.439                 | 2.528                 |
| 7                         | 2.748                   | 2.789                | 3.030                | 2.491                    | 2.537                 | 2.719                 |
| 14                        | 2.948                   | 2.998                | 3.387                | 2.685                    | 2.738                 | 3.041                 |
| 21                        | 3.026                   | 3.080                | 3.555                | 2.762                    | 2.819                 | 3.192                 |
| 28                        | 3.061                   | 3.117                | 3.640                | 2.797                    | 2.856                 | 3.269                 |
| 60                        | 3.152                   | 3.214                | 3.855                | 2.889                    | 2.953                 | 3.462                 |
| 90                        | 3.194                   | 3.259                | 3.956                | 2.930                    | 2.998                 | 3.553                 |
| 120                       | 3.213                   | 3.281                | 4.008                | 2.950                    | 3.019                 | 3.600                 |
| 150                       | 3.221                   | 3.289                | 4.037                | 2.958                    | 3.028                 | 3.626                 |
| 180                       | 3.228                   | 3.297                | 4.060                | 2.966                    | 3.036                 | 3.647                 |
| 210                       | 3.237                   | 3.307                | 4.082                | 2.974                    | 3.046                 | 3.667                 |
| 240                       | 3.268                   | 3.340                | 4.138                | 3.004                    | 3.077                 | 3.717                 |
| 270                       | 3.306                   | 3.380                | 4.202                | 3.040                    | 3.115                 | 3.775                 |
| 300                       | 3.318                   | 3.393                | 4.226                | 3.051                    | 3.127                 | 3.797                 |
| 330                       | 3.339                   | 3.415                | 4.265                | 3.071                    | 3.149                 | 3.832                 |
| 360                       | 3.361                   | 3.438                | 4.305                | 3.092                    | 3.171                 | 3.868                 |

**Table D.6.** Camber prediction of 3 BTE 110 prestressed girders without overhang by using three methods and two types of section properties at plant B, including 144-274, 144-275 and 144-278

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 1.683                   | 1.703                | 1.683                | 1.507                    | 1.517                 | 1.507                 |
| 0                         | 1.625                   | 1.643                | 1.632                | 1.454                    | 1.477                 | 1.461                 |
| 1                         | 1.895                   | 1.921                | 1.962                | 1.701                    | 1.733                 | 1.758                 |
| 2                         | 1.931                   | 1.958                | 2.033                | 1.737                    | 1.769                 | 1.822                 |
| 3                         | 2.024                   | 2.054                | 2.171                | 1.824                    | 1.860                 | 1.946                 |
| 7                         | 2.091                   | 2.126                | 2.336                | 1.893                    | 1.933                 | 2.093                 |
| 14                        | 2.240                   | 2.282                | 2.612                | 2.037                    | 2.085                 | 2.342                 |
| 21                        | 2.296                   | 2.342                | 2.742                | 2.092                    | 2.144                 | 2.459                 |
| 28                        | 2.322                   | 2.370                | 2.809                | 2.119                    | 2.172                 | 2.519                 |
| 60                        | 2.387                   | 2.440                | 2.975                | 2.184                    | 2.243                 | 2.669                 |
| 90                        | 2.416                   | 2.472                | 3.053                | 2.213                    | 2.275                 | 2.739                 |
| 120                       | 2.429                   | 2.486                | 3.094                | 2.226                    | 2.289                 | 2.776                 |
| 150                       | 2.432                   | 2.490                | 3.116                | 2.230                    | 2.294                 | 2.796                 |
| 180                       | 2.437                   | 2.496                | 3.134                | 2.234                    | 2.300                 | 2.812                 |
| 210                       | 2.442                   | 2.502                | 3.151                | 2.240                    | 2.306                 | 2.827                 |
| 240                       | 2.466                   | 2.527                | 3.194                | 2.262                    | 2.329                 | 2.866                 |
| 270                       | 2.494                   | 2.557                | 3.244                | 2.288                    | 2.358                 | 2.911                 |
| 300                       | 2.501                   | 2.565                | 3.263                | 2.296                    | 2.366                 | 2.928                 |
| 330                       | 2.516                   | 2.581                | 3.293                | 2.310                    | 2.381                 | 2.955                 |
| 360                       | 2.532                   | 2.598                | 3.324                | 2.325                    | 2.397                 | 2.983                 |



**Table D.7.** Camber prediction of 3 BTE 110 prestressed girders with overhang by using three methods and two types of section properties at plant B, including 144-284, 144-283 and 144-280

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 2.037                   | 2.056                | 2.037                | 1.842                    | 1.851                 | 1.842                 |
| 0                         | 1.981                   | 1.999                | 1.975                | 1.790                    | 1.814                 | 1.785                 |
| 1                         | 2.315                   | 2.341                | 2.374                | 2.099                    | 2.130                 | 2.147                 |
| 2                         | 2.360                   | 2.387                | 2.460                | 2.143                    | 2.176                 | 2.225                 |
| 3                         | 2.477                   | 2.507                | 2.626                | 2.254                    | 2.289                 | 2.376                 |
| 7                         | 2.564                   | 2.599                | 2.825                | 2.343                    | 2.382                 | 2.557                 |
| 14                        | 2.754                   | 2.796                | 3.159                | 2.526                    | 2.572                 | 2.860                 |
| 21                        | 2.828                   | 2.874                | 3.316                | 2.600                    | 2.649                 | 3.003                 |
| 28                        | 2.861                   | 2.910                | 3.396                | 2.634                    | 2.685                 | 3.075                 |
| 60                        | 2.949                   | 3.002                | 3.597                | 2.721                    | 2.777                 | 3.258                 |
| 90                        | 2.989                   | 3.045                | 3.691                | 2.761                    | 2.819                 | 3.343                 |
| 120                       | 3.008                   | 3.066                | 3.740                | 2.780                    | 2.839                 | 3.388                 |
| 150                       | 3.015                   | 3.073                | 3.767                | 2.787                    | 2.848                 | 3.413                 |
| 180                       | 3.022                   | 3.081                | 3.789                | 2.795                    | 2.856                 | 3.432                 |
| 210                       | 3.031                   | 3.091                | 3.809                | 2.803                    | 2.865                 | 3.451                 |
| 240                       | 3.061                   | 3.122                | 3.861                | 2.832                    | 2.895                 | 3.498                 |
| 270                       | 3.097                   | 3.160                | 3.922                | 2.866                    | 2.931                 | 3.553                 |
| 300                       | 3.108                   | 3.172                | 3.944                | 2.877                    | 2.943                 | 3.573                 |
| 330                       | 3.128                   | 3.194                | 3.981                | 2.896                    | 2.963                 | 3.607                 |
| 360                       | 3.149                   | 3.216                | 4.018                | 2.916                    | 2.984                 | 3.640                 |

**Table D.8.** Camber prediction of 3 BTE 110 prestressed girders without overhang by using three methods and two types of section properties at plant B, including 144-284, 144-283 and 144-280

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 1.806                   | 1.829                | 1.806                | 1.602                    | 1.613                 | 1.602                 |
| 0                         | 1.745                   | 1.766                | 1.752                | 1.546                    | 1.573                 | 1.553                 |
| 1                         | 2.032                   | 2.062                | 2.105                | 1.807                    | 1.843                 | 1.867                 |
| 2                         | 2.070                   | 2.101                | 2.181                | 1.845                    | 1.882                 | 1.935                 |
| 3                         | 2.168                   | 2.204                | 2.328                | 1.936                    | 1.978                 | 2.066                 |
| 7                         | 2.239                   | 2.279                | 2.503                | 2.009                    | 2.056                 | 2.223                 |
| 14                        | 2.395                   | 2.444                | 2.799                | 2.160                    | 2.216                 | 2.486                 |
| 21                        | 2.454                   | 2.507                | 2.938                | 2.218                    | 2.278                 | 2.610                 |
| 28                        | 2.480                   | 2.536                | 3.009                | 2.245                    | 2.308                 | 2.673                 |
| 60                        | 2.548                   | 2.610                | 3.187                | 2.314                    | 2.382                 | 2.832                 |
| 90                        | 2.578                   | 2.643                | 3.270                | 2.343                    | 2.415                 | 2.906                 |
| 120                       | 2.591                   | 2.658                | 3.313                | 2.357                    | 2.430                 | 2.945                 |
| 150                       | 2.594                   | 2.662                | 3.337                | 2.361                    | 2.436                 | 2.966                 |
| 180                       | 2.599                   | 2.667                | 3.356                | 2.366                    | 2.441                 | 2.983                 |
| 210                       | 2.605                   | 2.674                | 3.375                | 2.372                    | 2.448                 | 2.999                 |
| 240                       | 2.629                   | 2.700                | 3.421                | 2.394                    | 2.472                 | 3.040                 |
| 270                       | 2.658                   | 2.731                | 3.474                | 2.422                    | 2.502                 | 3.088                 |
| 300                       | 2.666                   | 2.740                | 3.494                | 2.429                    | 2.511                 | 3.106                 |
| 330                       | 2.682                   | 2.757                | 3.526                | 2.444                    | 2.527                 | 3.135                 |
| 360                       | 2.698                   | 2.775                | 3.559                | 2.459                    | 2.543                 | 3.164                 |

**Table D.9.** Camber prediction of 2 BTE 145 prestressed girders with overhang by using three methods and two types of section properties at plant B, including 144-311 and 144-334

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 5.037                   | 5.094                | 5.037                | 4.390                    | 4.405                 | 4.390                 |
| 0                         | 4.893                   | 4.942                | 4.903                | 4.258                    | 4.344                 | 4.270                 |
| 1                         | 5.708                   | 5.780                | 5.897                | 4.991                    | 5.100                 | 5.142                 |
| 2                         | 5.729                   | 5.803                | 6.012                | 5.022                    | 5.131                 | 5.243                 |
| 3                         | 5.737                   | 5.813                | 6.100                | 5.039                    | 5.147                 | 5.320                 |
| 7                         | 5.878                   | 5.963                | 6.509                | 5.193                    | 5.304                 | 5.679                 |
| 14                        | 6.336                   | 6.445                | 7.353                | 5.631                    | 5.760                 | 6.421                 |
| 21                        | 6.403                   | 6.519                | 7.609                | 5.706                    | 5.839                 | 6.645                 |
| 28                        | 6.434                   | 6.554                | 7.739                | 5.744                    | 5.878                 | 6.759                 |
| 60                        | 6.664                   | 6.798                | 8.241                | 5.971                    | 6.116                 | 7.200                 |
| 90                        | 6.838                   | 6.982                | 8.570                | 6.137                    | 6.291                 | 7.489                 |
| 120                       | 6.935                   | 7.085                | 8.761                | 6.230                    | 6.389                 | 7.657                 |
| 150                       | 6.967                   | 7.120                | 8.845                | 6.262                    | 6.424                 | 7.730                 |
| 180                       | 6.977                   | 7.132                | 8.885                | 6.273                    | 6.436                 | 7.765                 |
| 210                       | 6.974                   | 7.129                | 8.901                | 6.272                    | 6.435                 | 7.779                 |
| 240                       | 7.067                   | 7.228                | 9.060                | 6.359                    | 6.527                 | 7.919                 |
| 270                       | 7.207                   | 7.376                | 9.292                | 6.489                    | 6.665                 | 8.123                 |
| 300                       | 7.284                   | 7.458                | 9.428                | 6.561                    | 6.742                 | 8.242                 |
| 330                       | 7.346                   | 7.524                | 9.540                | 6.618                    | 6.804                 | 8.340                 |
| 360                       | 7.437                   | 7.622                | 9.700                | 6.704                    | 6.895                 | 8.480                 |

**Table D.10.** Camber prediction of 2 BTE 145 prestressed girders without overhang by using three methods and two types of section properties at plant B, including 144-311 and 144-334

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 3.695                   | 3.760                | 3.695                | 3.132                    | 3.154                 | 3.132                 |
| 0                         | 3.542                   | 3.599                | 3.595                | 2.992                    | 3.077                 | 3.045                 |
| 1                         | 4.109                   | 4.190                | 4.327                | 3.490                    | 3.599                 | 3.669                 |
| 2                         | 4.120                   | 4.203                | 4.412                | 3.509                    | 3.620                 | 3.742                 |
| 3                         | 4.120                   | 4.205                | 4.477                | 3.518                    | 3.629                 | 3.798                 |
| 7                         | 4.194                   | 4.289                | 4.779                | 3.604                    | 3.722                 | 4.055                 |
| 14                        | 4.483                   | 4.602                | 5.401                | 3.878                    | 4.018                 | 4.586                 |
| 21                        | 4.505                   | 4.632                | 5.590                | 3.910                    | 4.056                 | 4.747                 |
| 28                        | 4.521                   | 4.651                | 5.685                | 3.931                    | 4.080                 | 4.828                 |
| 60                        | 4.668                   | 4.812                | 6.055                | 4.076                    | 4.238                 | 5.144                 |
| 90                        | 4.779                   | 4.934                | 6.298                | 4.181                    | 4.353                 | 5.351                 |
| 120                       | 4.838                   | 5.000                | 6.438                | 4.238                    | 4.416                 | 5.471                 |
| 150                       | 4.855                   | 5.019                | 6.500                | 4.255                    | 4.436                 | 5.524                 |
| 180                       | 4.857                   | 5.024                | 6.529                | 4.258                    | 4.441                 | 5.549                 |
| 210                       | 4.852                   | 5.019                | 6.541                | 4.254                    | 4.437                 | 5.559                 |
| 240                       | 4.912                   | 5.084                | 6.659                | 4.309                    | 4.498                 | 5.660                 |
| 270                       | 5.003                   | 5.184                | 6.830                | 4.392                    | 4.589                 | 5.805                 |
| 300                       | 5.051                   | 5.237                | 6.930                | 4.437                    | 4.639                 | 5.891                 |
| 330                       | 5.089                   | 5.279                | 7.012                | 4.471                    | 4.678                 | 5.961                 |
| 360                       | 5.146                   | 5.343                | 7.130                | 4.524                    | 4.737                 | 6.061                 |

**Table D.11.** Camber prediction of 2 BTE 145 prestressed girders with overhang by using three methods and two types of section properties at plant B, including 144-316 and 144-317

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 5.050                   | 5.109                | 5.050                | 4.386                    | 4.402                 | 4.386                 |
| 0                         | 4.904                   | 4.955                | 4.915                | 4.253                    | 4.341                 | 4.265                 |
| 1                         | 5.718                   | 5.792                | 5.909                | 4.983                    | 5.096                 | 5.136                 |
| 2                         | 5.739                   | 5.816                | 6.025                | 5.014                    | 5.126                 | 5.237                 |
| 3                         | 5.746                   | 5.825                | 6.113                | 5.031                    | 5.142                 | 5.314                 |
| 7                         | 5.885                   | 5.974                | 6.522                | 5.183                    | 5.298                 | 5.672                 |
| 14                        | 6.340                   | 6.453                | 7.367                | 5.619                    | 5.752                 | 6.411                 |
| 21                        | 6.405                   | 6.526                | 7.623                | 5.692                    | 5.830                 | 6.635                 |
| 28                        | 6.436                   | 6.560                | 7.752                | 5.729                    | 5.869                 | 6.749                 |
| 60                        | 6.664                   | 6.803                | 8.255                | 5.955                    | 6.106                 | 7.189                 |
| 90                        | 6.837                   | 6.987                | 8.585                | 6.120                    | 6.280                 | 7.478                 |
| 120                       | 6.932                   | 7.089                | 8.776                | 6.212                    | 6.377                 | 7.645                 |
| 150                       | 6.964                   | 7.124                | 8.860                | 6.243                    | 6.411                 | 7.718                 |
| 180                       | 6.974                   | 7.135                | 8.900                | 6.254                    | 6.423                 | 7.753                 |
| 210                       | 6.971                   | 7.132                | 8.916                | 6.253                    | 6.422                 | 7.767                 |
| 240                       | 7.063                   | 7.231                | 9.076                | 6.339                    | 6.514                 | 7.907                 |
| 270                       | 7.202                   | 7.378                | 9.308                | 6.468                    | 6.651                 | 8.110                 |
| 300                       | 7.279                   | 7.460                | 9.444                | 6.539                    | 6.728                 | 8.229                 |
| 330                       | 7.339                   | 7.525                | 9.555                | 6.596                    | 6.789                 | 8.327                 |
| 360                       | 7.430                   | 7.622                | 9.715                | 6.681                    | 6.880                 | 8.467                 |

**Table D.12.** Camber prediction of 2 BTE 145 prestressed girders without overhang by using three methods and two types of section properties at plant B, including 144-316 and 144-317

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 3.682                   | 3.750                | 3.682                | 3.106                    | 3.130                 | 3.106                 |
| 0                         | 3.526                   | 3.586                | 3.582                | 2.965                    | 3.052                 | 3.019                 |
| 1                         | 4.088                   | 4.172                | 4.311                | 3.455                    | 3.569                 | 3.638                 |
| 2                         | 4.098                   | 4.185                | 4.395                | 3.475                    | 3.589                 | 3.710                 |
| 3                         | 4.098                   | 4.186                | 4.460                | 3.483                    | 3.598                 | 3.765                 |
| 7                         | 4.169                   | 4.268                | 4.760                | 3.567                    | 3.689                 | 4.019                 |
| 14                        | 4.452                   | 4.576                | 5.379                | 3.835                    | 3.980                 | 4.546                 |
| 21                        | 4.472                   | 4.604                | 5.566                | 3.864                    | 4.016                 | 4.705                 |
| 28                        | 4.487                   | 4.622                | 5.662                | 3.885                    | 4.039                 | 4.786                 |
| 60                        | 4.630                   | 4.781                | 6.030                | 4.027                    | 4.195                 | 5.098                 |
| 90                        | 4.739                   | 4.901                | 6.271                | 4.130                    | 4.309                 | 5.304                 |
| 120                       | 4.797                   | 4.965                | 6.411                | 4.185                    | 4.370                 | 5.423                 |
| 150                       | 4.813                   | 4.984                | 6.473                | 4.201                    | 4.389                 | 5.475                 |
| 180                       | 4.815                   | 4.988                | 6.502                | 4.205                    | 4.394                 | 5.500                 |
| 210                       | 4.809                   | 4.983                | 6.514                | 4.200                    | 4.390                 | 5.510                 |
| 240                       | 4.868                   | 5.047                | 6.631                | 4.254                    | 4.450                 | 5.609                 |
| 270                       | 4.957                   | 5.145                | 6.801                | 4.335                    | 4.540                 | 5.753                 |
| 300                       | 5.004                   | 5.198                | 6.900                | 4.378                    | 4.589                 | 5.838                 |
| 330                       | 5.041                   | 5.239                | 6.982                | 4.412                    | 4.627                 | 5.908                 |
| 360                       | 5.098                   | 5.302                | 7.100                | 4.464                    | 4.685                 | 6.007                 |

**Table D.13.** Camber prediction of 2 BTE 145 prestressed girders with overhang by using three methods and two types of section properties at plant B, including 144-366 and 144-367

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 4.948                   | 5.004                | 4.948                | 4.313                    | 4.328                 | 4.313                 |
| 0                         | 4.803                   | 4.852                | 4.815                | 4.180                    | 4.265                 | 4.193                 |
| 1                         | 5.603                   | 5.674                | 5.791                | 4.900                    | 5.008                 | 5.050                 |
| 2                         | 5.624                   | 5.697                | 5.904                | 4.930                    | 5.037                 | 5.149                 |
| 3                         | 5.632                   | 5.707                | 5.991                | 4.947                    | 5.053                 | 5.225                 |
| 7                         | 5.769                   | 5.853                | 6.392                | 5.096                    | 5.206                 | 5.577                 |
| 14                        | 6.218                   | 6.325                | 7.221                | 5.526                    | 5.654                 | 6.305                 |
| 21                        | 6.282                   | 6.397                | 7.472                | 5.599                    | 5.731                 | 6.526                 |
| 28                        | 6.313                   | 6.431                | 7.599                | 5.635                    | 5.769                 | 6.638                 |
| 60                        | 6.539                   | 6.671                | 8.093                | 5.859                    | 6.003                 | 7.071                 |
| 90                        | 6.709                   | 6.852                | 8.417                | 6.022                    | 6.175                 | 7.355                 |
| 120                       | 6.804                   | 6.953                | 8.604                | 6.112                    | 6.271                 | 7.520                 |
| 150                       | 6.835                   | 6.987                | 8.686                | 6.144                    | 6.304                 | 7.592                 |
| 180                       | 6.845                   | 6.998                | 8.725                | 6.154                    | 6.316                 | 7.626                 |
| 210                       | 6.842                   | 6.996                | 8.741                | 6.153                    | 6.315                 | 7.640                 |
| 240                       | 6.933                   | 7.093                | 8.898                | 6.238                    | 6.406                 | 7.778                 |
| 270                       | 7.071                   | 7.239                | 9.126                | 6.366                    | 6.541                 | 7.978                 |
| 300                       | 7.146                   | 7.319                | 9.259                | 6.436                    | 6.617                 | 8.095                 |
| 330                       | 7.206                   | 7.383                | 9.369                | 6.493                    | 6.677                 | 8.191                 |
| 360                       | 7.296                   | 7.479                | 9.526                | 6.577                    | 6.767                 | 8.329                 |

**Table D.14.** Camber prediction of 2 BTE 145 prestressed girders without overhang by using three methods and two types of section properties at plant B, including 144-366 and 144-367

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 3.610                   | 3.674                | 3.610                | 3.058                    | 3.081                 | 3.058                 |
| 0                         | 3.456                   | 3.513                | 3.511                | 2.918                    | 3.002                 | 2.972                 |
| 1                         | 4.009                   | 4.089                | 4.227                | 3.403                    | 3.511                 | 3.582                 |
| 2                         | 4.019                   | 4.102                | 4.310                | 3.422                    | 3.531                 | 3.653                 |
| 3                         | 4.019                   | 4.104                | 4.373                | 3.430                    | 3.540                 | 3.707                 |
| 7                         | 4.090                   | 4.184                | 4.667                | 3.513                    | 3.630                 | 3.958                 |
| 14                        | 4.370                   | 4.488                | 5.275                | 3.778                    | 3.917                 | 4.477                 |
| 21                        | 4.390                   | 4.516                | 5.460                | 3.807                    | 3.953                 | 4.634                 |
| 28                        | 4.406                   | 4.535                | 5.553                | 3.828                    | 3.976                 | 4.713                 |
| 60                        | 4.548                   | 4.692                | 5.914                | 3.969                    | 4.130                 | 5.022                 |
| 90                        | 4.656                   | 4.810                | 6.152                | 4.071                    | 4.242                 | 5.224                 |
| 120                       | 4.714                   | 4.874                | 6.289                | 4.126                    | 4.303                 | 5.341                 |
| 150                       | 4.729                   | 4.893                | 6.349                | 4.142                    | 4.322                 | 5.393                 |
| 180                       | 4.732                   | 4.897                | 6.378                | 4.146                    | 4.327                 | 5.417                 |
| 210                       | 4.726                   | 4.892                | 6.390                | 4.141                    | 4.323                 | 5.427                 |
| 240                       | 4.784                   | 4.956                | 6.505                | 4.194                    | 4.382                 | 5.525                 |
| 270                       | 4.873                   | 5.053                | 6.671                | 4.275                    | 4.471                 | 5.667                 |
| 300                       | 4.920                   | 5.105                | 6.769                | 4.318                    | 4.520                 | 5.751                 |
| 330                       | 4.956                   | 5.146                | 6.850                | 4.352                    | 4.557                 | 5.819                 |
| 360                       | 5.012                   | 5.208                | 6.965                | 4.403                    | 4.615                 | 5.918                 |



**Table D.15.** Camber prediction of 2 BTD 135 prestressed girders with overhang by using three methods and two types of section properties at plant C, including 13501 and 13502

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 4.270                   | 4.324                | 4.270                | 3.714                    | 3.729                 | 3.714                 |
| 0                         | 4.121                   | 4.169                | 4.152                | 3.578                    | 3.657                 | 3.609                 |
| 1                         | 4.600                   | 4.663                | 4.771                | 4.010                    | 4.104                 | 4.150                 |
| 2                         | 5.184                   | 5.268                | 5.551                | 4.535                    | 4.651                 | 4.832                 |
| 3                         | 5.193                   | 5.280                | 5.644                | 4.553                    | 4.669                 | 4.914                 |
| 7                         | 5.407                   | 5.510                | 6.202                | 4.769                    | 4.896                 | 5.401                 |
| 14                        | 5.309                   | 5.412                | 6.275                | 4.704                    | 4.826                 | 5.466                 |
| 21                        | 5.292                   | 5.397                | 6.378                | 4.700                    | 4.822                 | 5.556                 |
| 28                        | 5.314                   | 5.424                | 6.510                | 4.728                    | 4.852                 | 5.671                 |
| 60                        | 5.328                   | 5.443                | 6.698                | 4.755                    | 4.881                 | 5.836                 |
| 90                        | 5.396                   | 5.517                | 6.888                | 4.822                    | 4.953                 | 6.002                 |
| 120                       | 5.412                   | 5.535                | 6.949                | 4.839                    | 4.972                 | 6.055                 |
| 150                       | 5.462                   | 5.589                | 7.062                | 4.887                    | 5.023                 | 6.155                 |
| 180                       | 5.531                   | 5.663                | 7.198                | 4.951                    | 5.093                 | 6.273                 |
| 210                       | 5.573                   | 5.708                | 7.286                | 4.990                    | 5.134                 | 6.350                 |
| 240                       | 5.565                   | 5.700                | 7.289                | 4.983                    | 5.128                 | 6.353                 |
| 270                       | 5.630                   | 5.770                | 7.409                | 5.044                    | 5.192                 | 6.458                 |
| 300                       | 5.641                   | 5.782                | 7.442                | 5.054                    | 5.204                 | 6.487                 |
| 330                       | 5.689                   | 5.833                | 7.533                | 5.098                    | 5.251                 | 6.566                 |
| 360                       | 5.718                   | 5.864                | 7.595                | 5.125                    | 5.281                 | 6.620                 |

**Table D.16.** Camber prediction of 2 BTD 135 prestressed girders without overhang by using three methods and two types of section properties at plant C, including 13501 and 13502

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 4.043                   | 4.107                | 4.043                | 3.422                    | 3.438                 | 3.422                 |
| 0                         | 3.884                   | 3.940                | 3.934                | 3.277                    | 3.369                 | 3.326                 |
| 1                         | 4.319                   | 4.392                | 4.518                | 3.661                    | 3.771                 | 3.824                 |
| 2                         | 4.845                   | 4.943                | 5.254                | 4.124                    | 4.260                 | 4.451                 |
| 3                         | 4.849                   | 4.950                | 5.342                | 4.138                    | 4.275                 | 4.526                 |
| 7                         | 5.018                   | 5.138                | 5.868                | 4.311                    | 4.463                 | 4.974                 |
| 14                        | 4.922                   | 5.041                | 5.937                | 4.252                    | 4.398                 | 5.033                 |
| 21                        | 4.898                   | 5.021                | 6.034                | 4.244                    | 4.391                 | 5.116                 |
| 28                        | 4.910                   | 5.037                | 6.159                | 4.261                    | 4.412                 | 5.222                 |
| 60                        | 4.911                   | 5.044                | 6.336                | 4.278                    | 4.432                 | 5.373                 |
| 90                        | 4.963                   | 5.103                | 6.515                | 4.329                    | 4.490                 | 5.526                 |
| 120                       | 4.974                   | 5.116                | 6.573                | 4.342                    | 4.505                 | 5.575                 |
| 150                       | 5.014                   | 5.161                | 6.680                | 4.380                    | 4.547                 | 5.666                 |
| 180                       | 5.073                   | 5.225                | 6.808                | 4.434                    | 4.606                 | 5.775                 |
| 210                       | 5.107                   | 5.263                | 6.891                | 4.465                    | 4.641                 | 5.846                 |
| 240                       | 5.097                   | 5.253                | 6.894                | 4.458                    | 4.634                 | 5.849                 |
| 270                       | 5.153                   | 5.314                | 7.007                | 4.508                    | 4.689                 | 5.945                 |
| 300                       | 5.160                   | 5.323                | 7.038                | 4.516                    | 4.698                 | 5.971                 |
| 330                       | 5.200                   | 5.367                | 7.124                | 4.552                    | 4.738                 | 6.044                 |
| 360                       | 5.224                   | 5.393                | 7.182                | 4.573                    | 4.762                 | 6.094                 |

**Table D.17.** Camber prediction of 2 BTD 135 prestressed girders with overhang by using three methods and two types of section properties at plant C, including 13503 and 13504

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 4.269                   | 4.333                | 4.269                | 3.629                    | 3.645                 | 3.629                 |
| 0                         | 4.293                   | 4.167                | 4.155                | 3.656                    | 3.579                 | 3.529                 |
| 1                         | 4.784                   | 4.650                | 4.771                | 4.092                    | 4.008                 | 4.057                 |
| 2                         | 5.379                   | 5.237                | 5.548                | 4.620                    | 4.532                 | 4.722                 |
| 3                         | 5.387                   | 5.246                | 5.641                | 4.638                    | 4.548                 | 4.801                 |
| 7                         | 5.596                   | 5.455                | 6.197                | 4.850                    | 4.756                 | 5.277                 |
| 14                        | 5.492                   | 5.354                | 6.270                | 4.785                    | 4.688                 | 5.340                 |
| 21                        | 5.472                   | 5.335                | 6.372                | 4.780                    | 4.682                 | 5.427                 |
| 28                        | 5.491                   | 5.355                | 6.504                | 4.806                    | 4.707                 | 5.540                 |
| 60                        | 5.501                   | 5.367                | 6.691                | 4.831                    | 4.731                 | 5.700                 |
| 90                        | 5.566                   | 5.433                | 6.881                | 4.896                    | 4.796                 | 5.863                 |
| 120                       | 5.581                   | 5.448                | 6.941                | 4.912                    | 4.813                 | 5.914                 |
| 150                       | 5.630                   | 5.497                | 7.054                | 4.959                    | 4.859                 | 6.011                 |
| 180                       | 5.699                   | 5.567                | 7.189                | 5.022                    | 4.923                 | 6.127                 |
| 210                       | 5.740                   | 5.608                | 7.277                | 5.060                    | 4.962                 | 6.202                 |
| 240                       | 5.731                   | 5.599                | 7.281                | 5.053                    | 4.954                 | 6.205                 |
| 270                       | 5.796                   | 5.664                | 7.400                | 5.113                    | 5.015                 | 6.307                 |
| 300                       | 5.806                   | 5.675                | 7.433                | 5.123                    | 5.025                 | 6.335                 |
| 330                       | 5.853                   | 5.722                | 7.523                | 5.166                    | 5.068                 | 6.413                 |
| 360                       | 5.882                   | 5.751                | 7.585                | 5.192                    | 5.095                 | 6.465                 |

**Table D.18.** Camber prediction of 2 BTD 135 prestressed girders without overhang by using three methods and two types of section properties at plant C, including 13503 and 13504

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 4.122                   | 4.186                | 4.122                | 3.491                    | 3.507                 | 3.491                 |
| 0                         | 3.963                   | 4.019                | 4.011                | 3.347                    | 3.440                 | 3.395                 |
| 1                         | 4.408                   | 4.482                | 4.607                | 3.741                    | 3.851                 | 3.903                 |
| 2                         | 4.946                   | 5.044                | 5.357                | 4.215                    | 4.351                 | 4.543                 |
| 3                         | 4.951                   | 5.052                | 5.447                | 4.229                    | 4.366                 | 4.619                 |
| 7                         | 5.127                   | 5.247                | 5.984                | 4.409                    | 4.561                 | 5.077                 |
| 14                        | 5.029                   | 5.149                | 6.055                | 4.349                    | 4.496                 | 5.137                 |
| 21                        | 5.006                   | 5.129                | 6.154                | 4.341                    | 4.489                 | 5.222                 |
| 28                        | 5.018                   | 5.146                | 6.281                | 4.360                    | 4.511                 | 5.331                 |
| 60                        | 5.021                   | 5.154                | 6.462                | 4.378                    | 4.532                 | 5.485                 |
| 90                        | 5.075                   | 5.215                | 6.645                | 4.431                    | 4.592                 | 5.641                 |
| 120                       | 5.087                   | 5.229                | 6.703                | 4.445                    | 4.608                 | 5.691                 |
| 150                       | 5.129                   | 5.276                | 6.813                | 4.484                    | 4.651                 | 5.784                 |
| 180                       | 5.189                   | 5.341                | 6.943                | 4.540                    | 4.712                 | 5.895                 |
| 210                       | 5.224                   | 5.380                | 7.027                | 4.572                    | 4.748                 | 5.967                 |
| 240                       | 5.214                   | 5.371                | 7.031                | 4.564                    | 4.741                 | 5.970                 |
| 270                       | 5.272                   | 5.433                | 7.146                | 4.617                    | 4.798                 | 6.069                 |
| 300                       | 5.280                   | 5.443                | 7.178                | 4.624                    | 4.807                 | 6.096                 |
| 330                       | 5.320                   | 5.487                | 7.265                | 4.661                    | 4.848                 | 6.170                 |
| 360                       | 5.345                   | 5.514                | 7.325                | 4.684                    | 4.873                 | 6.221                 |

**Table D.19.** Camber prediction of 2 BTD 135 prestressed girders with overhang by using three methods and two types of section properties at plant C, including 13507 and 13508

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 4.663                   | 4.727                | 4.663                | 4.005                    | 4.021                 | 4.005                 |
| 0                         | 4.508                   | 4.565                | 4.539                | 3.864                    | 3.957                 | 3.895                 |
| 1                         | 5.027                   | 5.101                | 5.212                | 4.328                    | 4.438                 | 4.477                 |
| 2                         | 5.657                   | 5.757                | 6.060                | 4.891                    | 5.026                 | 5.210                 |
| 3                         | 5.668                   | 5.770                | 6.161                | 4.911                    | 5.046                 | 5.297                 |
| 7                         | 5.896                   | 6.018                | 6.767                | 5.142                    | 5.291                 | 5.822                 |
| 14                        | 5.789                   | 5.910                | 6.847                | 5.074                    | 5.216                 | 5.891                 |
| 21                        | 5.769                   | 5.893                | 6.959                | 5.070                    | 5.212                 | 5.988                 |
| 28                        | 5.793                   | 5.922                | 7.103                | 5.100                    | 5.245                 | 6.112                 |
| 60                        | 5.806                   | 5.941                | 7.307                | 5.129                    | 5.277                 | 6.289                 |
| 90                        | 5.878                   | 6.021                | 7.513                | 5.200                    | 5.354                 | 6.467                 |
| 120                       | 5.895                   | 6.040                | 7.579                | 5.219                    | 5.374                 | 6.525                 |
| 150                       | 5.949                   | 6.098                | 7.703                | 5.270                    | 5.429                 | 6.631                 |
| 180                       | 6.023                   | 6.177                | 7.850                | 5.338                    | 5.503                 | 6.759                 |
| 210                       | 6.067                   | 6.225                | 7.946                | 5.380                    | 5.548                 | 6.841                 |
| 240                       | 6.058                   | 6.217                | 7.950                | 5.372                    | 5.541                 | 6.845                 |
| 270                       | 6.128                   | 6.292                | 8.080                | 5.437                    | 5.610                 | 6.958                 |
| 300                       | 6.139                   | 6.305                | 8.116                | 5.448                    | 5.622                 | 6.988                 |
| 330                       | 6.190                   | 6.359                | 8.215                | 5.494                    | 5.673                 | 7.074                 |
| 360                       | 6.221                   | 6.393                | 8.282                | 5.523                    | 5.704                 | 7.132                 |

**Table D.20.** Camber prediction of 2 BTD 135 prestressed girders without overhang by using three methods and two types of section properties at plant C, including 13507 and 13508

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 4.100                   | 4.163                | 4.100                | 3.477                    | 3.493                 | 3.477                 |
| 0                         | 3.942                   | 3.997                | 3.990                | 3.333                    | 3.425                 | 3.381                 |
| 1                         | 4.385                   | 4.458                | 4.583                | 3.725                    | 3.834                 | 3.887                 |
| 2                         | 4.921                   | 5.018                | 5.330                | 4.198                    | 4.333                 | 4.524                 |
| 3                         | 4.926                   | 5.026                | 5.419                | 4.212                    | 4.348                 | 4.600                 |
| 7                         | 5.101                   | 5.220                | 5.953                | 4.392                    | 4.542                 | 5.056                 |
| 14                        | 5.004                   | 5.122                | 6.024                | 4.331                    | 4.477                 | 5.117                 |
| 21                        | 4.981                   | 5.102                | 6.122                | 4.324                    | 4.470                 | 5.201                 |
| 28                        | 4.994                   | 5.120                | 6.249                | 4.343                    | 4.492                 | 5.309                 |
| 60                        | 4.997                   | 5.128                | 6.429                | 4.361                    | 4.513                 | 5.462                 |
| 90                        | 5.050                   | 5.189                | 6.611                | 4.414                    | 4.573                 | 5.618                 |
| 120                       | 5.062                   | 5.203                | 6.669                | 4.428                    | 4.588                 | 5.668                 |
| 150                       | 5.104                   | 5.250                | 6.778                | 4.467                    | 4.632                 | 5.761                 |
| 180                       | 5.164                   | 5.315                | 6.907                | 4.522                    | 4.693                 | 5.871                 |
| 210                       | 5.199                   | 5.353                | 6.991                | 4.554                    | 4.728                 | 5.943                 |
| 240                       | 5.190                   | 5.344                | 6.995                | 4.547                    | 4.721                 | 5.946                 |
| 270                       | 5.247                   | 5.406                | 7.110                | 4.599                    | 4.778                 | 6.044                 |
| 300                       | 5.255                   | 5.416                | 7.141                | 4.606                    | 4.787                 | 6.071                 |
| 330                       | 5.295                   | 5.460                | 7.228                | 4.644                    | 4.828                 | 6.145                 |
| 360                       | 5.320                   | 5.487                | 7.288                | 4.666                    | 4.853                 | 6.196                 |

**Table D.21.** Camber prediction of 2 BTD 135 prestressed girders with overhang by using three methods and two types of section properties at plant C, including 13511 and 13512

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 4.010                   | 4.068                | 4.010                | 3.437                    | 3.452                 | 3.437                 |
| 0                         | 4.029                   | 3.906                | 3.900                | 3.458                    | 3.381                 | 3.340                 |
| 1                         | 4.492                   | 4.361                | 4.480                | 3.872                    | 3.787                 | 3.841                 |
| 2                         | 5.054                   | 4.915                | 5.213                | 4.375                    | 4.284                 | 4.472                 |
| 3                         | 5.062                   | 4.924                | 5.300                | 4.391                    | 4.299                 | 4.547                 |
| 7                         | 5.260                   | 5.120                | 5.823                | 4.592                    | 4.495                 | 4.998                 |
| 14                        | 5.163                   | 5.026                | 5.892                | 4.529                    | 4.430                 | 5.058                 |
| 21                        | 5.143                   | 5.008                | 5.988                | 4.524                    | 4.424                 | 5.141                 |
| 28                        | 5.162                   | 5.027                | 6.112                | 4.548                    | 4.447                 | 5.248                 |
| 60                        | 5.171                   | 5.038                | 6.288                | 4.571                    | 4.469                 | 5.400                 |
| 90                        | 5.233                   | 5.100                | 6.467                | 4.632                    | 4.530                 | 5.554                 |
| 120                       | 5.248                   | 5.115                | 6.524                | 4.648                    | 4.546                 | 5.603                 |
| 150                       | 5.295                   | 5.161                | 6.630                | 4.692                    | 4.590                 | 5.695                 |
| 180                       | 5.360                   | 5.227                | 6.757                | 4.753                    | 4.651                 | 5.804                 |
| 210                       | 5.399                   | 5.266                | 6.840                | 4.789                    | 4.688                 | 5.875                 |
| 240                       | 5.390                   | 5.257                | 6.843                | 4.782                    | 4.680                 | 5.878                 |
| 270                       | 5.452                   | 5.320                | 6.956                | 4.839                    | 4.738                 | 5.976                 |
| 300                       | 5.462                   | 5.330                | 6.987                | 4.848                    | 4.747                 | 6.002                 |
| 330                       | 5.507                   | 5.374                | 7.072                | 4.889                    | 4.789                 | 6.076                 |
| 360                       | 5.534                   | 5.402                | 7.130                | 4.915                    | 4.814                 | 6.126                 |

**Table D.22.** Camber prediction of 2 BTD 135 prestressed girders without overhang by using three methods and two types of section properties at plant C, including 13511 and 13512

| Time after Transfer, days | Ig & Incremental method | Ig & Naaman's Method | Ig & Tadros's Method | Itr & Incremental method | Itr & Naaman's Method | Itr & Tadros's Method |
|---------------------------|-------------------------|----------------------|----------------------|--------------------------|-----------------------|-----------------------|
| 0                         | 3.856                   | 3.913                | 3.856                | 3.292                    | 3.308                 | 3.292                 |
| 0                         | 3.700                   | 3.751                | 3.749                | 3.151                    | 3.235                 | 3.199                 |
| 1                         | 4.118                   | 4.185                | 4.308                | 3.522                    | 3.622                 | 3.679                 |
| 2                         | 4.624                   | 4.713                | 5.012                | 3.971                    | 4.094                 | 4.284                 |
| 3                         | 4.629                   | 4.720                | 5.096                | 3.984                    | 4.108                 | 4.356                 |
| 7                         | 4.794                   | 4.902                | 5.599                | 4.152                    | 4.290                 | 4.788                 |
| 14                        | 4.702                   | 4.810                | 5.665                | 4.094                    | 4.227                 | 4.845                 |
| 21                        | 4.680                   | 4.791                | 5.758                | 4.087                    | 4.220                 | 4.925                 |
| 28                        | 4.692                   | 4.807                | 5.878                | 4.104                    | 4.241                 | 5.028                 |
| 60                        | 4.695                   | 4.815                | 6.047                | 4.120                    | 4.260                 | 5.173                 |
| 90                        | 4.745                   | 4.872                | 6.218                | 4.170                    | 4.316                 | 5.321                 |
| 120                       | 4.757                   | 4.886                | 6.273                | 4.183                    | 4.331                 | 5.368                 |
| 150                       | 4.796                   | 4.929                | 6.376                | 4.220                    | 4.372                 | 5.456                 |
| 180                       | 4.853                   | 4.991                | 6.498                | 4.273                    | 4.429                 | 5.561                 |
| 210                       | 4.886                   | 5.027                | 6.577                | 4.303                    | 4.463                 | 5.629                 |
| 240                       | 4.877                   | 5.019                | 6.581                | 4.296                    | 4.456                 | 5.632                 |
| 270                       | 4.931                   | 5.078                | 6.689                | 4.345                    | 4.510                 | 5.725                 |
| 300                       | 4.939                   | 5.086                | 6.719                | 4.353                    | 4.519                 | 5.750                 |
| 330                       | 4.978                   | 5.129                | 6.801                | 4.388                    | 4.557                 | 5.821                 |
| 360                       | 5.001                   | 5.154                | 6.856                | 4.409                    | 4.581                 | 5.869                 |



## **Appendix E**

**Properties of Prestressed Bridge Girders, including BTC 120, BTE 110, BTE 145  
and BTD 135**

**Table E.1.** Properties of four types of prestressed bridge girders

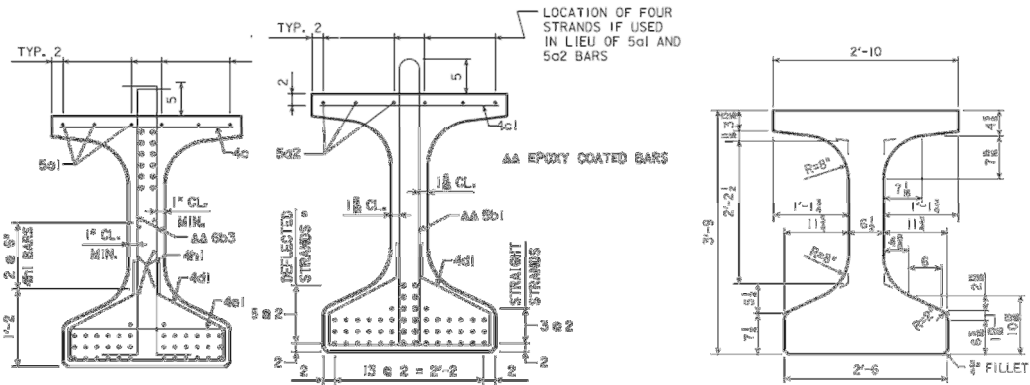
| Girder Type | span length | overall length | no. of straight strand | no. of deflected strand | weight, tons |
|-------------|-------------|----------------|------------------------|-------------------------|--------------|
| BTC 120     | 120'-0"     | 121'-4"        | 38                     | 12                      | 43.7         |
| BTE 110     | 110'-0"     | 111'-4"        | 26                     | 4                       | 46.8         |
| BTE 145     | 145'-0"     | 146'-4"        | 42                     | 10                      | 61.5         |
| BTD 135     | 135'-0"     | 136'-4"        | 42                     | 12                      | 53.2         |

**Table E.2.** Comparison of properties of gross section and transformed section at release

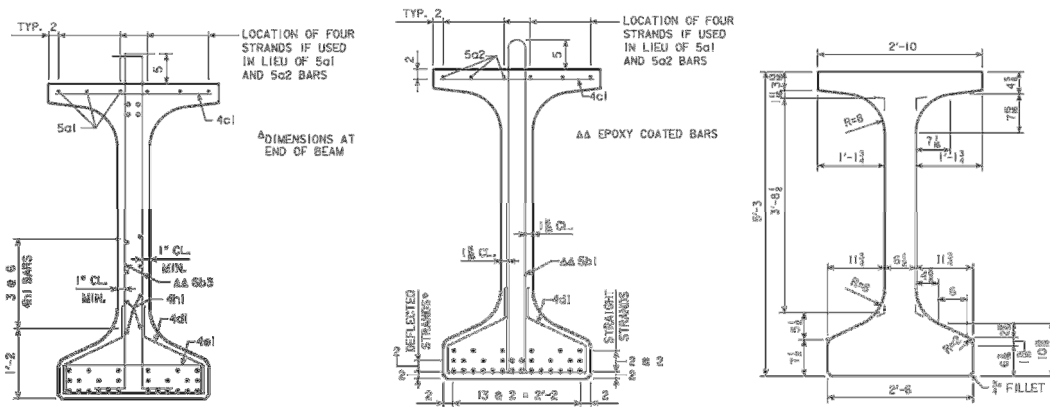
| Girder Type | Plant | Girder I.D.               | Ig, in <sup>4</sup> | Ag, in <sup>2</sup> | y bar for gross, in | Average Itr, in <sup>4</sup> | Average Atr, in <sup>2</sup> | Average y bar for transformed, in |
|-------------|-------|---------------------------|---------------------|---------------------|---------------------|------------------------------|------------------------------|-----------------------------------|
| BTC 120     | A     | 103-09, 103-10, 103-11    | 178971              | 691.8               | 20.74               | 190884                       | 739.8                        | 20.14                             |
| BTE 110     | B     | 144-270, 144-272, 144-268 | 422790              | 807.4               | 28.75               | 450005                       | 849.6                        | 28.09                             |
|             |       | 144-274, 144-275, 144-278 | 422790              | 807.4               | 28.75               | 451355                       | 851.8                        | 28.05                             |
|             |       | 144-284, 144-283, 144-280 | 422790              | 807.4               | 28.75               | 448880                       | 847.8                        | 28.11                             |
| BTE 145     | B     | 144-311, 144-334          | 422790              | 807.4               | 28.75               | 454232                       | 864.9                        | 27.77                             |
|             |       | 144-316, 144-317          | 422790              | 807.4               | 28.75               | 454968                       | 866.3                        | 27.75                             |
|             |       | 144-366, 144-367          | 422790              | 807.4               | 28.75               | 454108                       | 864.6                        | 27.77                             |
| BTD 135     | C     | 13501, 13502              | 285860              | 748.8               | 24.64               | 306922                       | 805.7                        | 23.81                             |
|             |       | 13503, 13504              | 285860              | 748.8               | 24.64               | 306926                       | 805.7                        | 23.81                             |
|             |       | 13507, 13508              | 285860              | 748.8               | 24.64               | 306776                       | 805.3                        | 23.81                             |
|             |       | 13511, 13512              | 285860              | 748.8               | 24.64               | 305695                       | 802.2                        | 23.85                             |

**Table E.3.** Material properties of concrete at release

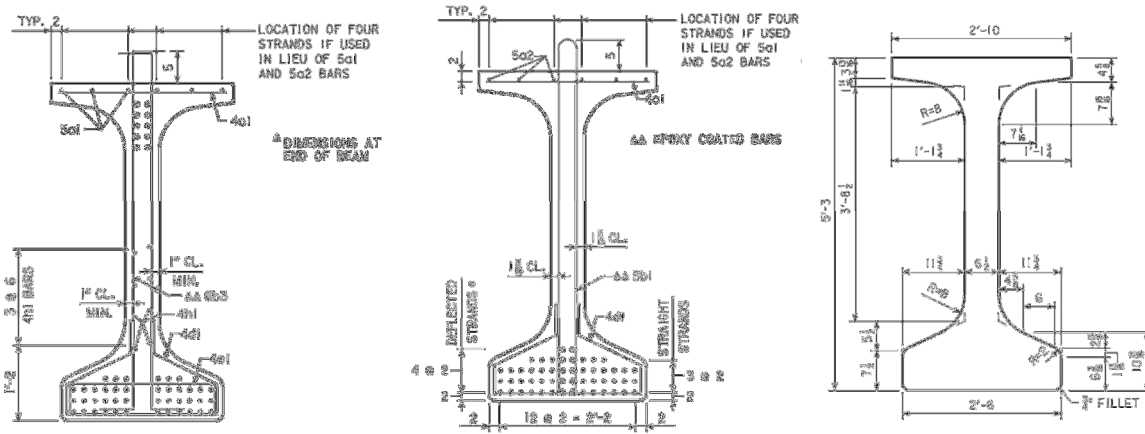
| Girder Type | Plant | Girder I.D.               | Release Concrete Strength, psi | Release Modulus of Elasticity of Concrete, ksi |
|-------------|-------|---------------------------|--------------------------------|--|
| BTC 120     | A     | 103-09, 103-10, 103-11    | 8610                           | 5761   |
| BTE 110     | B     | 144-270, 144-272, 144-268 | 6090                           | 4449   |
|             |       | 144-274, 144-275, 144-278 | 5598                           | 4266   |
|             |       | 144-284, 144-283, 144-280 | 6550                           | 4614   |
| BTE 145     | B     | 144-311, 144-334          | 8066                           | 5120   |
|             |       | 144-316, 144-317          | 7750                           | 5019   |
|             |       | 144-366, 144-367          | 8121                           | 5138   |
| BTD 135     | C     | 13501, 13502              | 8121                           | 5306   |
|             |       | 13503, 13504              | 8118                           | 5305   |
|             |       | 13507, 13508              | 8218                           | 5338   |
|             |       | 13511, 13512              | 8992                           | 5583   |



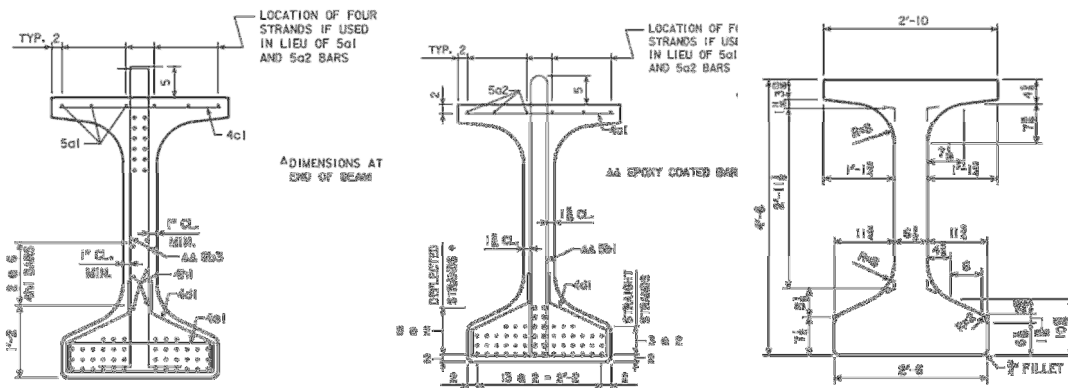
**Figure E.1.** Cross section of the end span, the mid-span and the gross cross section of BTC 120 girder



**Figure E.2.** Cross section of the end span, the mid-span and the gross cross section of BTE 110 girder



**Figure E.3.** Cross section of the end span, the mid-span and the gross cross section of BTE 145 girder



**Figure E.4.** Cross section of the end span, the mid-span and the gross cross section of BTD 135 girder