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Stochastic finite element analysis of moisture damage in hot mix asphalt

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Stochastic finite element analysis of moisture damage in hot mix asphalt

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ABSTRACT

Moisture damage is one of the major problems that can be faced by a pavement during the design life. It can tremendously reduce a pavement's strength and consequently its life. Moisture sensitivity testing of asphalt mixtures is critical for ensuring performance expectations are met. Moisture susceptibility is most commonly tested using the modified Lottman test. The shift towards mechanistic design calls for the utilization of a more fundamental test to evaluate moisture damage. The evolution of unconfined dynamic modulus and creep (flow number) tests as performance tests for inclusion in the Superpave mix design process make these candidate tests for inclusion in moisture sensitivity testing. The challenge in moisture sensitivity testing is the ability to capture the various mechanisms that cause moisture damage. Previous research has recommended the use of the dynamic modulus test for moisture damage evaluation. The dynamic modulus test results can be used to develop master curves that can be used to predict pavement performance at any temperature and/or frequency.

An objective of this study was to identify the appropriate test that can identify whether a mix is moisture susceptible or not. Indirect tensile test, dynamic modulus test and flow number test were investigated to satisfy this objective. Another objective was to use finite element modeling to evaluate the moisture susceptibility and variability of a mixture.

In the present study, sixteen field procured mixtures were subjected to five different modes of moisture conditioning: 1. unconditioned without water submersion testing, 2. unconditioned with water submersion testing, 3. moisture saturation with water submersion testing, 4. moisture saturation with freeze/thaw conditioning without water submersion testing, and 5. moisture saturation with freeze/thaw conditioning and with water submersion testing. These samples were tested for flow number.

Dynamic modulus tests were performed on both moisture conditioned and unconditioned samples. The results were used to develop mastercurves. The dynamic modulus results were used as input to a finite element model in which stochastic variation of the results were incorporated in the model. The model was validated by the results from the flow number test.

The methodology was applied on sixteen projects and the results were compared to the results achieved using the AASHTO T283 methodology and dynamic modulus test results. The dynamic modulus test results show consistency with AASHTO T283 in identifying moisture sensitivity of a mixture. This dissertation outlines a method for evaluating hot mix asphalt moisture susceptibility utilizing dynamic modulus testing and is compatible with the proposed performance testing for accompanying Superpave volumetric mix design. The results of the proposed mixture dynamic modulus moisture susceptibility method can also be used in the new M-E PDG for evaluating the moisture susceptibility effects of the tested mixtures. This in part allows for the evaluation of this environmental effect in the M-E PDG.

The results show that the dynamic modulus test has good potential to identify the moisture susceptibility of the material provided that it is combined with the field and loading conditions. The flow number test also showed good potential when it was analyzed using the Ohio State model. The data showed consistency but a comparison to field performance is needed to identify whether the results are correlated to field performance or not. The finite element analysis showed that the results' variability increase with moisture conditioning and that moisture conditioned samples are more susceptible to rutting. Finite element model is a good tool to be combined with the dynamic modulus test to be able to evaluate the moisture susceptibility based on site condition.

CHAPTER 1 INTRODUCTION

1.1 Background

Pavements are subjected to a variety stresses during their operational lives. A properly designed pavement will perform adequately during its design life and the distresses will not exceed the allowable limits. A good design is one that provides the expected performance with appropriate economic considerations. One of the factors that lead to premature failure of pavements is moisture sensitivity. The presence of water in pavements can be detrimental if combined with other factors such as freeze-thaw cycling. Many factors can affect the moisture sensitivity of a mix, and can be divided into three main categories. The first category is the material properties, which include the physical and chemical properties of the asphalt and the aggregates. The second category is the mixture properties, which include asphalt content, film thickness, and the permeability of the mixture (interconnectivity of the air voids). The third category is the external factors; these factors include construction, traffic, and environmental factors (Santucci 2002).

Moisture damage has been a major concern to asphalt technologists for many years. Researchers have been searching for a test that differentiates between good and poor performing asphalt concrete mixtures from stripping potential since the 1920's (Solaimanian et al. 2003). Since the 1920's, it has been known that the problem relates to the loss of adhesion between asphalt and aggregate and the loss of cohesion within the asphalt binder. The challenge has been to find a test that identifies moisture susceptible mixes (Solaimanian et al. 2003). The standard test used to identify the moisture susceptibility of asphalt mixtures is the modified Lottman test, AASHTO T283. AASHTO T283 was used with Marshall mix design methodology and with the development of the Superpave mix design methodology, the same method was adopted with the modification of the compaction method. Although AASHTO

T283 has been used for several years as the standard test for moisture sensitivity, it assists in minimizing the problem and it does not appear to be a very accurate indicator of stripping (Brown et al. 2001). Two of the tests that have the potential to replace indirect tensile strength testing contained within AASHTO T283 are the dynamic modulus and flow number tests. The advantage of using these two tests is that they are performed by the Asphalt Mixture Performance Tester (AMPT) and are used to predict the mixture performance. An advantage of the dynamic modulus test is that it is the main input for level 1 design in the Mechanistic-Empirical Pavement Design Guide (M-E PDG) (NCHRP 2004).

The finite element method was introduced by R. Courant (1943). The use of the method has increased significantly with the advancement in computer technology. Currently, the method is used in several applications. Stochastic finite element analysis is a modification to the finite element method to include statistical variability in the finite element analysis.

1.2 Problem statement

AASHTO T283 is the standard test used in the moisture susceptibility evaluation of asphalt mixtures. The results of the test are not very representative of the expected behavior of asphalt mixtures. The dynamic modulus test measures a fundamental property of the mixture. The results of the dynamic modulus test can be used directly in the M-E PDG and are considered very good representation of the expected field performance of the mixture. Further research is still needed to study how the dynamic modulus results are affected by moisture. The flow number test was studied in NCHRP Report 589 (Solaimanian et al. 2007) as a candidate test for moisture susceptibility evaluation and the results of that research were not in favor of using the flow number test in moisture susceptibility evaluation. The results from the mechanistic tests can be used in the modeling of the pavement performance. This is done through finite element analysis of the pavement. Although the finite element method was used several times in modeling pavement performance, statistical distribution of the test results was not used in pavement modeling.

1.3 Objectives

This research has four main objectives. The first objective of is to evaluate the usefulness of the dynamic modulus and flow number tests in moisture susceptibility evaluation. The second objective is to compare the results to those achieved using the AASHTO T283 test. The third objective is to study the effect of different methods of sample conditioning and testing conditions on the material behavior. The fourth objective is to quantify the effect of the moisture damage on the pavement and to study the variability in the test data.

1.4 Methodology and approach

The first objective of this research was achieved by running dynamic modulus and flow number tests on sixteen field procured/laboratory compacted specimens at different conditioning/test conditions. The dynamic modulus test was performed on unconditioned samples and samples conditioned by moisture saturation with a freeze-thaw cycle at various frequencies and test temperatures. The same samples were then tested for flow number. The second objective was achieved by testing samples using the AASHTO T283 procedure and comparing the results to those achieved using the dynamic modulus and flow number tests. To fulfill the third objective, flow number testing was performed on samples with four different conditioning/testing conditions. The four conditions were: unconditioned without water submersion, moisture saturated with water submersion testing, moisture saturation with freeze/thaw conditioning without water submersion testing, and moisture saturation with freeze/thaw conditioning and with water submersion testing. Five of the sixteen mixes were tested under a fifth condition, which is unconditioned with water submersion to study the effect of the water submersion of the samples. The comparison between the results of the unconditioned set of sample and the conditioned set was used to evaluate the moisture damage. The fourth objective was studied by performing a stochastic finite element analysis using the laboratory results to be able to quantify the moisture damage and the variability of the laboratory data.

1.5 Hypothesis

The laboratory testing was performed under two main hypotheses that were tested statistically.

- The first hypothesis was that the dynamic modulus test results are directly affected by moisture conditioning of the samples. The effect of moisture was studied on the dynamic modulus value, the phase angle, and the combined effect of dynamic modulus and phase angle represented by the loss modulus and the storage modulus.
- The second hypothesis was that although the flow number test is not recommended for the evaluation of the moisture susceptibility of an asphalt mixture, it can still have value by investigating other parameters that can be calculated from the test results.

Some additional hypotheses were addressed by answering the following questions:

- Which test procedure better simulates moisture damage: AASHTO T283, dynamic modulus, or flow number?
- Do these HMA mixture tests rank the HMA mixtures the same?
- Is there a difference between the results from the different conditioning/testing conditions?
- Does the finite element analysis add value to the moisture study by quantifying the amount of damage the pavement is subjected to?

1.6 Significance of work

The significance of this research work is that it employs tests that are commonly used in the asphalt industry and uses them to evaluate the moisture susceptibility of the mixes. The research also examines the tests from a perspective different from what was done in previous research. Finally the use of stochastic finite element analysis is not common in modeling asphalt pavement performance. This modeling will integrate the statistical properties of the tested material with the moisture conditioning effect.

1.7 Dissertation organization

This dissertation is divided into nine chapters. The first chapter is an introduction, which gives a brief background about the topic and a problem statement. In this chapter the research objectives and hypothesis are presented, the methodology is outlined, and the significance of the research is presented. Chapter 2 of this dissertation discusses past research and studies that have been related to moisture damage or moisture susceptibility. Included is a brief description of the research conducted along with major findings of the studies that directly apply to this research. The chapter also includes a survey of the major research that was conducted in the field of asphalt concrete modeling. Chapter 3 outlines the experimental plan and procedures used to sample, prepare, and test specimens for this research. Chapter 4 presents the results of the dynamic modulus testing. Chapter 5 presents the results of the flow number testing with a selection of the parameter that best represents the moisture susceptibility of the mixes. Chapter 6 presents the results from the AASHTO T283 testing. Chapter 7 presents a statistical analysis comparing the different tests and recommending the most appropriate test. The finite element analysis that was performed is presented in Chapter 8. The chapter includes the assumptions, formulation and results of the finite element analysis that was performed. Chapter 9 presents the summary, conclusions, and recommendations for further research.

CHAPTER 2 LITERATURE REVIEW

2.1 Moisture susceptibility

The presence of water in an asphalt pavement is unavoidable. Several sources can lead to the presence of water in the pavement. Water can infiltrate into the pavement from the surface via cracks in the surface of the pavement, the interconnectivity of the air void system or cracks, from the bottom due to an increase in the ground water level, or from the sides. Inadequate drying of aggregate during the mixing process can lead to the presence of water in the pavement as well (Santucci 2002).

Moisture damage can be defined as the loss of strength and durability in asphalt mixtures due to the effects of moisture (Little and Jones 2003). Premature failure may result due to stripping when critical environmental conditions act together with poor and/or incompatible materials and traffic (Brown et al. 2001). Moisture susceptibility is a problem that typically leads to the stripping of the asphalt binder from the aggregate and this makes an asphalt concrete mixture ravel and disintegrate (Brown et al. 2001). Moisture damage can occur due to three main mechanisms: 1) loss of cohesion of the asphalt film; 2) failure of the adhesion between the aggregate particles and the asphalt film; and 3) degradation of aggregate particles due to freezing (Brown et al. 2001). There are six contributing processes that have been attributed to causing moisture damage in asphalt mixtures: detachment, displacement, spontaneous emulsification, pore-pressure induced damage, hydraulic scour, and environmental effects (Little and Jones 2003; Roberts et al. 1996). Not one of the above factors necessarily works alone in damaging an asphalt concrete pavement, as they can work in a combination of the processes.

2.2 Causes of moisture damage

Moisture can damage HMA in two ways: 1) Loss of bond between asphalt cement or mastic and fine and coarse aggregate or 2) Weakening of mastic due to the presence of moisture. There are six contributing factors that have been attributed to causing moisture damage in HMA: detachment, displacement, spontaneous emulsification, pore-pressure induced damage, hydraulic scour, and environmental effects (Roberts et al. 1996, Little and Jones, 2003). Not one of the above factors necessarily works alone in damaging an HMA pavement, as they can work in a combination of the processes. Therefore a need exists to examine the adhesive interface between aggregates and asphalt and the cohesive strength and durability of mastics (Graff 1986, Roberts et al. 1996, Little and Jones 2003, Cheng et al. 2003). A loss of the adhesive bond between aggregate and asphalt can lead to stripping and raveling while a loss of cohesion can lead to a weakened pavement that is susceptible to premature cracking and pore pressure damage (Majidzadeh and Brovold 1968, Kandhal 1994, Birgisson et al. 2003). A brief discussion about these factors is presented in the following part.

2.2.1 Detachment

Detachment is the separation of an asphalt film from an aggregate surface by a thin film of water without an obvious break in the film (Majidzah and Brovold 1968). Adhesive bond energy theory explains the rationale behind detachment. In order for detachment not to happen, a good bond must develop between asphalt and aggregate; this is known as wettability (Scott 1978). As free surface energy of adhesion or surface tension decreases the bond between the aggregate and asphalt increases. In the presence of water, an asphalt mixture can be considered a four phase system consisting of aggregate, asphalt, air, and water. The presence of water reduces the surface energy of the system since aggregate surfaces have a stronger preference for water than asphalt (Majidzadeh and Brovold 1968). The adhesive bond strengths were calculated by Cheng et al. (2002) by measuring the surface energies of components, the asphalt-aggregate interface, in the presence of water and when under dry conditions.

2.2.2 Displacement

Displacement can occur at a break in the asphalt film at the aggregate surface where water can intrude and displace asphalt from aggregate (Fromm 1974, Tarrer and Wagh 1991). An incomplete coating of aggregate particles, inadequate coating at sharp edges of aggregates, or pinholes in the asphalt film can cause the break in the asphalt film. Scott (1978) used the chemical reaction theory to explain stripping as a detachment mechanism. The pH of water at the point of film rupture can increase the process of displacement and therefore increasing the separation of asphalt from aggregate (Scott 1978, Tarrer and Wagh 1991, Little and Jones 2003).

2.2.3 Spontaneous emulsification

Spontaneous emulsification occurs due to inverted emulsion of water droplets in asphalt cement (Little and Jones 2003). Water diffuses into asphalt cement and attaches itself to an aggregate causing a separation between asphalt and aggregate. A loss of adhesive bond occurs between asphalt and aggregate. Clays and asphalt additives can further aggravate the emulsification process (Scott 1978, Fromm 1974, Asphalt Institute 1981).

2.2.4 Pore pressure

Pore pressure can develop in an HMA pavement due to entrapped water or water that traveled into air void systems in vapor form (Little and Jones, 2003, Kandhal 1994). The pore pressure in an HMA pavement can increase due to repeated traffic loading and/or increases in temperature as well. If an HMA pavement is permeable, then water can escape and flow out. However, if it is not permeable, the resulting increased pore pressure may surpass the tensile strength of an HMA and strips asphalt film from an aggregate, causing micro-cracking (Majidzadeh and Brovold 1968, Little and Jones, 2003). Micro-cracking can develop in a mastic under repeated loading thus resulting in an adhesive and/or cohesive failure (Little and Jones 2003). The rate of micro-cracking is accelerated by an increase in pore pressure and the presence of water in HMA. The air void system or permeability of a pavement is an important property in order to control pore pressure in an HMA pavement.

2.2.5 Hydraulic scour

Hydraulic scour (stripping) occurs at a pavement surface and is a result of repeated traffic tires on a saturated pavement surface. Water is sucked into a pavement by tire rolling action (Little and Jones 2003). Hydraulic scour may occur due to osmosis or pullback (Fromm 1974). Osmosis is the movement of water molecules from an area of high concentration to an area of low concentration. In the case of HMA, osmosis occurs in the presence of salts or salt solutions in aggregate pores. The movement of these molecules creates a pressure gradient that sucks water through the asphalt film (Mack 1964, Little and Jones 2003). The salt solution moves from an area of high concentration to an area of low concentration. Cheng et al. (2002) show that there is a considerable amount of water that diffuses through the asphalt cement and asphalt mastics can hold a significant amount of water.

2.2.6 Environmental effects

Factors such as temperature, air, and water have deleterious effects on the durability of HMA (Terrel and Shute 1989, Tandon et al. 1998). Other mechanisms such as a high water table, freeze/thaw cycles, and aging of binder can affect the durability of HMA (Scherocman et al. 1986, Terrel and Al-Swailmi 1994, Choubane et al. 2000). Other considerations such as construction (segregation and raveling) and traffic are also important.

2.3 Adhesion theories

Four theories are used to describe the adhesion characteristics between asphalt and aggregate. The four theories are chemical reaction, surface energy, molecular orientation, and mechanical adhesion (Terrel and Al-Swailmi 1994). Surface tension of asphalt cement and aggregate, chemical composition of asphalt and aggregate, asphalt viscosity, surface texture of aggregates, aggregate porosity, aggregate clay/silt content, aggregate moisture content, and temperature at the time of mixing with asphalt cement and aggregate are material properties that affect adhesion (Terrel and Al-Swailmi 1994). A brief explanation of the four theories is presented in the following parts.

2.3.1 Chemical reaction

The reaction of acidic and basic components of asphalt and aggregate form water insoluble compounds that resist stripping (Terrel and Al-Swailmi 1992). A chemical bond forms that allows an asphalt-aggregate mix to resist stripping. The use of basic instead of acidic aggregates can lead to better adhesion of asphalt to aggregates (Terrel and Al-Swailmi 1992).

2.3.2 Surface energy and molecular orientation

Surface energy can be described by how well asphalt or water coats aggregate particles (Terrel and Al-Swailmi 1992). Water is a better wetting agent because of its lower viscosity and lower surface tension than asphalt (Little and Jones 2003). Using surface energy theory to calculate adhesive bond energies between asphalt and aggregate and cohesive strength of a mastic is rather complex and will be discussed further under the *Tests on Loose Mixtures* in Section 2.5.1.

The structuring of asphalt molecules at an asphalt-aggregate interface is molecular orientation. The adhesion between asphalt and aggregate is facilitated by a surface energy reduction at the aggregate surface where asphalt is adsorbed onto a surface (Terrel and Al-Swailmi 1992, Little and Jones 2003).

2.3.3 Mechanical adhesion

Mechanical adhesion is a function of various aggregate physical properties such as surface texture, porosity, absorption, surface coatings, surface area, and particle size (Terrel and Al-Swailmi 1992, Little and Jones 2003). In short, an aggregate with desirable properties that will not show a propensity to moisture damage within an HMA is desired.

2.4 Cohesion theories

According to Little and Jones (2003), cohesion is developed in a mastic and it is influenced by the rheology of the filled binder. The cohesive strength of a mastic is a function of the interaction between the asphalt cement and mineral filler, not just of the individual components alone. The cohesive strength of a mastic is weakened due to the presence of water through increased saturation and void swelling or expansion (Terrel and Al-Swailmi 1992, Little and Jones 2003). Cheng et al. (2002) showed that the cohesive strength can be damaged in various mixtures by the diffusion of water into asphalt mastics.

2.5 Tests for determining moisture susceptibility

Due to the detrimental effects of moisture, it is important to test the susceptibility of an asphalt mixture to moisture damage. Many tests are available; some of them are tests for asphalt binder while others are for asphalt mixes. The tests for asphalt mixes are divided into tests for loose mixes and tests for compacted mixes. Despite of the availability of tests for moisture susceptibility, none of them provides high correlation with field performance (Bausano 2006).

2.5.1 Tests on loose mixtures and asphalt binders

Moisture susceptibility tests that are performed on loose mixtures are conducted on asphalt coated particles in the presence of water. The two main advantages of these tests are testing simplicity and inexpensive nature in comparison to compacted specimen test expenses. Another significant advantage is the use of simple equipment and procedures to conduct experiments (Solaimanian et al. 2003). The tests are summarized in Table 2-1.

Table 2-1 Moisture Sensitivity Tests on Loose Samples (Solaimanian et al. 2003)

Test Method	ASTM	AASHTO	Other
Methylene Blue			Technical Bulletin 145, International Slurry Seal Association (ISSA 1989)
Film Stripping			California Test 302 (1999)
Static Immersion	D1664-80*	T182-84	
Dynamic Immersion			No standard exists
Chemical Immersion			Standard Method TMH1 (Road Research Laboratory 1986, England)
Quick Bottle			Virginia Highway and Transportation Research Council (Maupin 1980)
Boiling	D3625-96		Tex 530-C Kennedy et al. (1984)
Rolling Bottle			Isacsson and Jorgensen (1987)
Net Adsorption			SHRP-A-341 (Curtis et al. 1993)
Surface Energy			Thelen (1958) Cheng et al. (2002)
Pneumatic Pull-Off			Youtcheff and Aurilio (1997)

*No longer available as ASTM standard.

2.5.1.1 Methylene blue test

The methylene blue test is used to identify "dirty" aggregates which contain harmful clays and dust (Solaimanian et al. 2003). If dust or harmful clays are on aggregate particles, they affect the adhesion of the asphalt binder to the aggregate particles and thus a potential for stripping may occur in the HMA. This test is used to identify aggregates that contain clays or dust. Since no asphalt is used, this test cannot measure a potential for HMA stripping.

2.5.1.2 Static immersion test (AASHTO T182)

A sample of HMA mix is cured for 2 hours at 60ºC before being placed in a jar and covered with water. The jar is left undisturbed for 16 to 18 hours in a water bath at 25ºC. Again the amount of stripping is visually estimated by looking at the HMA sample in the jar. The results of this test are given as either less than or greater than 95% of an aggregate surface is stripped (Solaimanian et al. 2003).

2.5.1.3 Dynamic immersion test

The dynamic immersion test (DIM) is similar to the static immersion test, but the DIM test is used to accelerate the stripping effect. Loose mixture is agitated in a jar filled with water in order to produce a dynamic effect (Solaimanian et al. 2003). Again, the results show that as the period of agitation increases, the amount of stripping increases, however the tests fail to simulate pore pressure and traffic which is the case with all loose mixture tests.

2.5.1.4 Film stripping test (California Test 302)

The film stripping test is a modified version of the static immersion test (AASHTO T182-84). A loose mixture of asphalt coated aggregates is aged in an oven at 60ºC for 15 to 18 hours before being placed in a jar filled with water to cool. The jar with loose mix is rotated at 35 revolutions per minute (rpm) for 15 minutes to stir up the mix. Baffels in a jar stir up the mix to accelerate the stripping process. After 15 minutes the sample is removed, the loose mixture is viewed under a fluorescent light, and the percentage of stripping is estimated. The results of this test are given in percentage of total aggregate surface stripped (Solaimanian et al. 2003).

2.5.1.5 Rolling bottle test

Isacsson and Jorgenson (1987) developed the Rolling Bottle Test in Sweden in 1987. The test is similar to the DIM in that aggregate chips are coated in asphalt and placed in a glass jar filled with water. The glass jar is rotated to agitate loose HMA. A visual inspection is completed to note how much asphalt has been stripped from aggregates (Solaimanian et al. 2003).

2.5.1.6 Chemical immersion test

A loose sample of asphalt coated aggregate is placed in boiling water while increasing the amount of sodium carbonate. The concentration of sodium carbonate is slowly increased until stripping occurs and the concentration of sodium carbonate is recorded. The recorded number is referred to as the Riedel and Weber (R&W) number. Zero refers to distilled water, 1 refers to 0.41 g of sodium carbonate and 9 refers to the highest concentration of sodium carbonate or 106 g. The sample is removed from the water and sodium carbonate solution and examined for stripping (Solaimanian et al. 2003).

2.5.1.7 Boiling water test

Several versions of a boiling water test have been developed by various state agencies including one from the Texas State Department of Highways and Public Transportation (Kennedy et al. 1983 and 1984). A visual inspection of stripping is made after the sample has been subjected to the action of water at an elevated temperature for a specified time (Kennedy et al. 1983 and 1984, Solaimanian et al. 2003). This test identifies mixes that are susceptible to moisture damage, but it does not account for mechanical properties nor include the effects of traffic (Kennedy et al. 1983 and 1984; Solaimanian et al. 2003).

2.5.1.8 Surface reaction test

A major problem with the tests previously presented tests is the dependence on visual observation for identifying stripping. The surface reaction test allows a researcher to quantify the level of stripping on loose asphalt mixtures. This procedure was developed by Ford et al. (1974). The surface reaction test evaluates the reactivity of calcareous or siliceous aggregates and reaction response to the presence of highly toxic and corrosive acids. As part of the chemical reaction, gas is emitted, which generates a pressure and this pressure is proportional to the aggregate surface area (Solaimanian et al. 2003). This test is based on the premise that different levels (severity) of stripping result in exposed surface areas of aggregates.

2.5.1.9 Net adsorption test

The Strategic Highway Research Program (SHRP) developed a test called the net adsorption test (NAT) in the early 1990's and is documented under SHRP-A-341 (Curtis et al. 1993). This test examines the asphalt-aggregate system and its affinity and compatibility (Solaimanian et al. 2003). In addition, this test also evaluates the sensitivity of the asphalt-aggregate pair. In terms of other tests, the NAT yields mixed results when compared to the indirect tensile test with moisture conditioned specimens (Solaimanian et al. 2003). The NAT was modified by researchers at the University of Nevada - Reno and the results were correlated with the environmental conditioning chamber (ECS) (Scholz et al. 1994). The water sensitivity of a binder as estimated by NAT showed little or no correlation to wheel-tracking tests on the mixes according to SHRP-A-402 (Scholz et al. 1994).

2.5.1.10 Wilhelmy plate test and universal sorption device

Researchers at Texas A&M University have led in investigating cohesive and adhesive failure models based on surface energy theory and a moisture diffusion model based on results from the Universal Sorption Device (USD) (Cheng et al. 2003). The principle behind surface energy theory is that the surface energy of an asphalt and aggregate is a function of the adhesive bond between asphalt and aggregate and the cohesive bonding within asphalt (Solaimanian et al. 2003). The Wilhelmy plate is used to determine the surface free energy of an asphalt binder where the dynamic contact angle is measured between asphalt and a liquid solvent (Cheng et al. 2003, Solaimanian et al. 2003). The USD test is used to determine the surface free energy of an aggregate (Cheng et al. 2003, Solaimanian et al. 2003). The surface free energy is then used to compute the adhesive bond between an asphalt binder and aggregate. Cheng et al. (2002) showed that the adhesive bond per unit area of aggregate is highly dependent on the aggregate and asphalt surface energies. Also, this test shows that stripping occurs because the affinity of an aggregate for water is much greater than that for asphalt thus weakening the bond at the asphalt-aggregate interface (Cheng et al. 2002).

Current research at Texas A & M University (Bhasin et al. 2006, Masad et al. 2006) has shown that the moisture resistance of asphalt-aggregate combinations depends on surface energies of asphalt binders and aggregates. The factors considered are film thickness, aggregate shape characteristics, surface energy, air void distribution and permeability. The ratio of adhesive bond energy under dry conditions to adhesive bond energy under wet conditions can be used to identify moisture susceptible asphalt-aggregate combinations and a ratio of 0.80 should be used as a criterion to separate good and poor combinations of materials. Dynamic mechanical analysis tests were conducted to evaluate a mixtures ability to accumulate damage under dry and moisture conditions. A mechanistic approach using a form of the Paris law was used for the evaluation of moisture damage. The mechanical properties are influenced by aggregate gradation, aggregate shape characteristics, and film thickness. This approach captures the influence of moisture on crack growth and is able to distinguish good and poor performing HMA mixtures.

2.5.2 Tests on compacted mixtures

Tests conducted on compacted mixtures include laboratory compacted specimens, field cores, and/or slabs compacted in a laboratory or taken from the field. Table 2-2 provides moisture sensitivity tests which have been performed on compacted specimens. From these tests, physical, fundamental/mechanical properties can be measured while accounting for traffic/water action and pore pressure effects (Solaimanian et al. 2003). Some disadvantages of conducting tests on compacted mixtures are the expensive laboratory testing equipment, longer testing times, and potentially labor intensive test procedures.

2.5.2.1 Immersion-compression test

The immersion-compression test (ASTM D1075-07 (2007) and AASHTO T165-55 (1997)) is among the first moisture sensitivity tests developed based on testing 100mm diameter compacted specimens. This test consists of compacting two groups of specimens: a control group and a moisture conditioned group at an elevated temperature (48.8°C water bath) for four days (Roberts et al. 1996). The compressive strength of the conditioned and control group are then measured (Roberts, et al. 1996). The average strength of the conditioned specimens over that of the control specimens is a measure of strength lost due to moisture damage (Solaimanian et al. 2003). Most agencies specify a minimum retained compressive strength of 70%. The test details are presented in ASTM Special Technical Publication 252 (Goode 1959).

Table 2-2 Moisture Sensitivity Tests on Compacted Samples (Solaimanian et al. 2003)

Test Method	ASTM	AASHTO	Other
Moisture Vapor Susceptbility			California Test 307 (2000) Developed in late 1940's
Immersion-Compression	D1075-07	T165-55	ASTM STP 252 (Goode 1959)
Marshal Immersion			Stuart (1986)
Freeze/thaw Pedestal Test			Kennedy et al. (1982)
Original Lottman Indirect Tension			NCHRP Report 246 (Lottman 1982); Transportation Research Record 515 (1974)
Modified Lottman Indirect Tension		T283-89	NCHRP Report 274 (Tunnicliff and Root 1984), Tex 531-C
Tunnicliff-Root	D4867-09		NCHRP Report 274 (Tunnicliff and Root 1984)
ECS with Resilient Modulus			SHRP-A-403 (Al-Swailmi and Terrel 1994)
Hamburg Wheel Tracking			Tex-242-F
Asphalt Pavement Analyzer			Pavement Technology Inc., Operating Manual
ECS/SPT			NCHRP 9-34 (2002)
Multiple Freeze/thaw			No standard exists

2.5.2.2 Marshall immersion test

The procedure for producing and conditioning two groups of specimens is identical to the immersion-compression test. The only difference is the Marshall stability test is used as the strength parameter as opposed to the compression test (Solaimanian et al. 2003). There is no documented number for the minimum retained Marshall stability.

2.5.2.3 Moisture vapor susceptibility

The moisture vapor susceptibility test was developed by the California Department of Transportation (California Test Method 307 (2000)). A California kneading compactor is used to compact two specimens. The compacted surface of each specimen is sealed with an aluminum cap and a silicone sealant is applied to prevent the loss of moisture (Solaimanian, et al. 2003). After the specimens have been conditioned at an elevated temperature and suspended over water, testing of the specimens commences. The Hveem stabilometer is used to test both dry and moisture conditioned specimens. A minimum Hveem stabilometer value is required for moisture conditioned specimens, which is less than that required for dry specimens used in the mix design (Solaimanian et al. 2003).

2.5.2.4 Repeated pore water pressure stressing and double-punch method

The repeated pore water pressure stressing and double punch method was developed by Jimenez (1974) at the University of Arizona. This test accounts for the effects of dynamic traffic loading and mechanical properties. In order to capture the effects of pore water pressure, the specimens are conditioned by a cyclic stress under water. After the specimen has undergone the pore pressure stressing the tensile strength is measured using the double punch equipment. Compacted specimens are tested through steel rods placed at either end of the specimen in a punching configuration.

2.5.2.5 Original Lottman method

The original Lottman test was developed at the University of Idaho by Robert Lottman (1978). The laboratory procedure consists of compacting three sets of 100mm diameter by 63.5mm Marshall specimens to be tested dry or under accelerated moisture conditioning (Lottman et al. 1974). Below are the following laboratory conditions for each of the groups:

- Group 1: Control group, dry;
- Group 2: Vacuum saturated with water for 30-minutes; and
- Group 3: Vacuum saturation followed by freeze cycle at -18°C for 15- hours and then subjected to a thaw at 60°C for 24-hours.

After the conditioning phase the indirect tensile equipment is used to conduct tensile resilient modulus and tensile strength of conditioned and dry specimens. All specimens are tested at 13°C or 23°C at a loading rate of 1.65mm/min. The severity of moisture damage is based on a ratio of conditioned to dry specimens (TSR) (Lottman et al. 1974, Lottman 1982). A minimum TSR value of 0.70 is recommended (NCHRP 246). Laboratory compacted specimens were compared to field cores and plotted against each other on a graph. The laboratory and field core specimens line up fairly close to the line of equality.

2.5.2.6 Modified Lottman test (AASHTO T283)

"Resistance of Compacted Bituminous Mixture to Moisture Induced Damage" AASHTO T283, is the most commonly used test method for determining moisture susceptibility of HMA. This test is similar to the original Lottman test with only a few exceptions which are:

- Two groups, control versus moisture conditioned,

- Vacuum saturation until a saturation level of 70% to 80% is achieved, and
- Test temperature and loading rate changed to 50mm/min at 25ºC.

A minimum TSR value of 0.70 is recommended, but many agencies specify a TSR value of 0.80 (Roberts et al., 1996). AASHTO T283 was adopted by the Superpave system as the moisture test method of choice even though AASHTO T283 was developed for Marshall mixture design. State highway agencies have reported mixed results when using AASHTO T283 and comparing the results to field performance (Stroup-Gardiner et al. 1992, Solaimanian et al. 2003). NCHRP Project 9-13 looked at different factors affecting test results such as types of compaction, diameter of specimen, degree of saturation, and freeze/thaw cycles. Conclusions from looking at the previously mentioned factors can be seen in the NCHRP report 444 (Epps et al. 2000). The researchers concluded that either AASHTO T283 does not evaluate moisture susceptibility or the criterion, TSR, is incorrectly specified. NCHRP 9-13 examined mixtures that have historically been moisture susceptible and ones that have not. The researchers also examined the current criteria using Marshall and Hveem compaction. A recent study at the University of Wisconsin found no relationship exists between TSR and field performance in terms of pavement distress index and moisture damage (surface raveling and rutting) (Kanitpong and Bahia 2006). Additional factors such as production and construction, asphalt binder and gradation play important roles whereas mineralogy does not appear to be an important factor in relation to pavement performance.

AASHTO T283 was developed based on 100mm Marshall compacted specimens. With the transition from 100mm Marshall compacted specimens to 150mm Superpave compacted specimens, the standard allowed the use of either 150 or 100mm samples and the requirements remained the same. Research was done to investigate the effect of the different sample sizes. It was discovered that three freeze/thaw cycles for conditioning are needed when using specimens created using 150mm Superpave specimens (Bausano et al. 2006, Kvasnak 2006). However, to continue using one freeze/thaw cycle and maintain the same probability level as attained with a TSR value for 0.80 for 100mm Marshall compacted specimens, a TSR value of 0.87 and 0.85 should be used for 150mm and 100mm Superpave compacted specimens, respectively. If an 0.80 TSR for 150mm Superpave specimens is used, this would correspond to a TSR ratio of 0.80 for 100mm Marshall specimens (Bausano et al 2006, Kvasnak 2006).

2.5.2.7 Texas freeze/thaw pedestal test

The water susceptibility test was developed by Plancher et al. (1980) at the Western Research Institute but was later modified into the Texas freeze/thaw pedestal by Kennedy et al. (1983). Even though this test is rather empirical in nature, it is fundamentally designed to maximize the effects of bond and to minimize the effects of mechanical properties such as gradation, density, and aggregate interlock by using a uniform gradation (Kennedy et al. 1983). An HMA briquette is made according to the procedure outlined by Kennedy et al. (1982). The specimen is then placed on a pedestal in a jar of distilled water and covered. The specimen is subjected to thermal cycling and inspected each day for cracks. The number of cycles to induce cracking is a measure of the water susceptibility (Kennedy et al. 1983). The benefits of running this test are some key failures can be seen:

- Bond failure at the asphalt-aggregate interface (stripping) and
- Fracture of the thin asphalt films bonding aggregate particles (cohesive failure) by formation of ice crystals (Solaimanian et al. 2003).

2.5.2.8 ASTM D4867-09 (Tunnicliff-Root Test Procedure)

"Standard Test Method for Effect of Moisture on Asphalt Concrete Paving Mixtures," ASTM D4867 is comparable to AASHTO T283. The only difference between AASHTO T283 and

ASTM D4867 is that the curing of loose mixture at 60°C in an oven for 16 hours is eliminated in ASTM D4867. A minimum TSR of 0.70 to 0.80 are specified by highway agencies (Roberts et al. 1996).

2.5.2.9 Hamburg Wheel-Tracking Device (HWTD)

The Hamburg wheel tracking device was developed by Esso A.G. and is manufactured by Helmut-Wind, Inc. of Hamburg, Germany (Aschenbrener et al. 1995, Romero and Stuart 1998). Two samples of hot mix asphalt beams with each beam having a geometry of 260mm wide, 320mm long, and 40mm thick are used. This device measures the effects of rutting and moisture damage by running a steel wheel over the compacted beams immersed in hot water (typically 50ºC) (Aschenbrener et al. 1995). The steel wheel is 47mm wide and applies a load of 705N while traveling at a maximum velocity of 340mm/sec in the center of the sample. A sample of HMA is loaded for 20,000 passes or when 20mm of permanent deformation occurs (Aschenbrener et al. 1995). Some important results the HWTD gives are:

- Postcompaction consolidation: Deformation measured after 1,000 wheel passes;
- Creep Slope: Number of wheel passes to create a 1mm rut depth due to viscous flow;
- Stripping Slope: Inverse of the rate of deformation in the linear region of the deformation curve; and
- Stripping Inflection Point: Number of wheel passes at the intersection of the creep slope and stripping slope (Aschenbrener et al. 1995).

2.5.2.10 Asphalt Pavement Analyzer (APA)

The APA is a type of loaded wheel test. Rutting, moisture susceptibility, and fatigue cracking can all be examined with an APA. The predecessor to the APA is the Georgia Loaded Wheel Tester (GLWT). Similar to the GLWT, an APA can test either cylindrical or rectangular specimens. Using either specimen geometry, the conditioned and unconditioned samples are subjected to a steel wheel that transverses a pneumatic tube, which lies on top of an asphalt sample. As the wheel passes back and forth over the tube, a rut is created in a sample. Numerous passes lead to a more defined rut and eventually, stress fractures can begin to manifest as cracks. Modeling these ruts and cracks helps to predict how different combinations of aggregate and binder for given criteria such as temperature and loading, will react under varying circumstances. The conditioning of a sample is based upon the characteristic an APA is testing. One of the main differences between an APA and a GLWT is an APA's ability to test samples under water as well as in air. Testing submerged samples allows researchers to examine moisture susceptibility of mixes (Cooley et al. 2000).

APA results are comparable to field data. A study that compared WesTrack, a full-scale test track, data with APA results found a strong relationship between field data and laboratory data (Williams and Prowell 1999). An additional study at the University of Tennessee revealed that an APA sufficiently predicted the potential for rutting of 30 HMAs commonly used in Tennessee (Jackson and Baldwin 1999). A study using the APA showed that there is a strong relationship between water absorbed and APA test data. When the APA results were compared to those of AASHTO T283, there were no strong relationship between TSR results and APA test results. The variability of the rut depth data was high, so the study recommended using at least three replicates (Kvasnak 2006).

To test moisture susceptible HMA samples, specimens are created in the same manner as the specimens for testing rutting potential without moisture. The samples are placed in an APA, which has an inner box that can be filled with water. The samples are completely submerged at all times during testing; therefore effects of evaporation do not need to be taken into account. The water bath is heated to a desired test temperature and the air in the chamber is also heated to the same desired test temperature.

2.5.2.11 Flexural Fatigue Beam Test with Moisture Conditioning

Moisture damage has been known to accelerate fatigue damage in pavements. Therefore, conditioning of flexural fatigue beams was completed by Shatnawi et al. (1995). Laboratory compacted beams were prepared from HMA sampled at jobs and corresponding field fatigue beams were cut from the pavement. The conditioning of the beams is as follows:

- Partial vacuum saturation of 60% to 80%;
- Followed by 3 repeated 5-hour cycles at 60ºC followed by 4-hours at 25ºC while remaining submerged; and
- One 5-hour cycle at -18ºC (Shatnawi et al. 1995).

The specimens are then removed from a conditioning chamber and tested according to AASHTO T321. Initial stiffness and fatigue performance were affected significantly by conditioning the specimens (Shatnawi et al. 1995).

2.5.2.12 Environmental Conditioning System (ECS)

The ECS was developed by Oregon State University as part of the SHRP-A-403 and later modified at Texas Technological University (Alam et al. 1998). The ECS subjects a membrane encapsulated HMA specimen that is 102mm in diameter by 102mm in height to cycles of temperature, repeated loading, and moisture conditioning (Terrel and Al-Swailmi 1994, Al-Swailmi and Terrel 1992a, Al-Swailmi and Terell 1992b, Terrel and Al-Swailmi 1993). Some important fundamental material properties are obtained from using an ECS. These properties are resilient modulus (M_R) before and after conditioning, air permeability, and a visual estimation of stripping after a specimen has been split open (Al-Swailmi and Terrel 1994). One of the significant advantages of using an ECS is the ability to influence the HMA specimens to traffic loading and the resulting effect of pore water pressure (Solaimanian et al. 2003) which is close to field conditions. The downfall of the test is that it does not provide a better relationship to field observation than what was observed using AASHTO T283. Also, AASHTO T283 is much less expensive to perform and less complex than the ECS.

2.5.2.13 ECS/Simple Performance Test Procedures

As a result of NCHRP Projects 9-19 (NCHRP reports 465), 9-29 (NCHRP reports 513), and 1-37 (M-EPDG) (Witzack et al. 2002, Bonaquist et al. 2003, and NCHRP 2004); new test procedures such as asphalt mixture performance tests (AMPTs) are being evaluated. According to Witczak et al. (2002), an AMPT is defined as “A test method(s) that accurately and reliably measures a mixture response or characteristic or parameter that is highly correlated to the occurrence of pavement distress (e.g. cracking and rutting) over a diverse range of traffic and climatic conditions.” The mechanical tests being looked at are the dynamic modulus $|E^*|$, repeated axial load (F_N), and static axial creep tests (F_T). These tests are conducted at elevated temperatures to determine a mixtures resistance to permanent deformation. The dynamic modulus test is conducted at an intermediate and lower test temperature to determine a mixtures susceptibility to fatigue cracking. Witczak et al. (2002) have shown that dynamic modulus, flow time, and flow number yield promising correlations to field performance.

NCHRP 9-34 is currently looking at the aforementioned tests along with the ECS to develop new test procedures to evaluate moisture damage (Solaimanian et al. 2003). Solaimanian et al. (2006) reported that the results of the Phase I and Phase II testing of NCHRP 9-34 show that the dynamic complex modulus (DCM) test should be coupled with the ECS for moisture sensitivity testing. This key finding of NCHRP project 9-34 (NCHRP report 589) show that the ECS/DCM test appears to separate good performing mixes from poor performing mixes in the field compared with TSR testing from ASTM D4867 and that the flow number test has high variability and this makes it not recommended for use in moisture susceptibility testing (Solaimanian et. al 2007). Bausano (2006) used the dynamic modulus test to determine the moisture susceptibility of the mixes at rutting temperature and the results were good in distinguishing the expected mix behavior. The researcher recommended in that study to try intermediate and midrange temperature to study the effect of moisture at those temperatures (Bausano 2006).

2.6 Dynamic modulus test

Dynamic modulus is one of the oldest mechanistic tests to be used to measure the fundamental properties of asphalt concrete. Dynamic modulus testing has been studied since the early 1960's by Papazian (1962) and became a standard test in 1979 by the American Society for Testing and Materials (ASTM) under D3497 'Standard Test Method for Dynamic Modulus of Asphalt Concrete Mixtures' (ASTM 2003). A sinusoidal (haversine) compressive axial stress is applied to a test specimen, under the testing procedure for dynamic modulus. The testing procedure includes using various frequencies and temperatures to capture the linear visco-elastic properties of the asphalt concrete.

Dynamic modulus is a measure of the relative stiffness of a mix. Mixes that tend to have good rut resistance at high service temperatures, likewise have a corresponding high stiffness. Although the tradeoff is at intermediate temperatures, stiffer mixes are often more prone to cracking for thicker pavements (NCHRP 2004). For this reason, dynamic modulus testing is conducted over a range of test temperatures and frequencies to measure the linear visco-elastic properties of asphalt concrete mixtures. The tested ranges of temperature and frequencies are used to develop a master curve for each mixture in order to exhibit the properties of the mixture over a range of reduced temperatures and/or frequencies. The use of dynamic modulus in moisture susceptibility evaluation was studied and reported to have good results in NCHRP Report 589 (Solaimanian et. al 2007)

The dynamic complex modulus is determined by applying a uniaxial sinusoidal vertical compressive load to an unconfined or confined HMA cylindrical sample as shown in Figure 2-1.

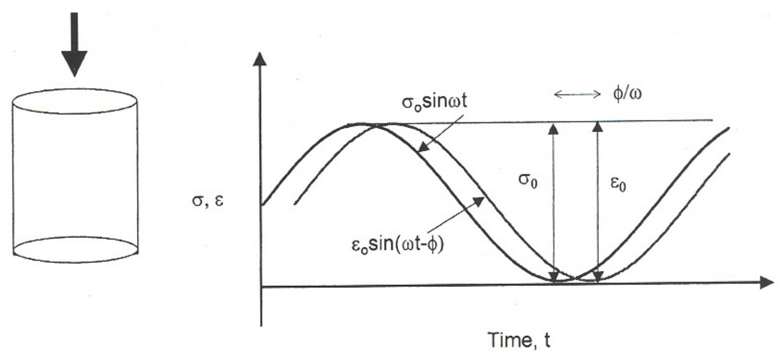


Figure 2-1 Haversine Loading Pattern or Stress Pulse for the Dynamic Modulus Test (Witczak et al. 2002)

The stress-to-strain relationship under a continuous sinusoidal load pattern for a linear viscoelastic material is defined by the dynamic complex modulus, E*. The dynamic modulus, |E*|, is the absolute value of the dynamic complex modulus. Mathematically, |E*| is equal to the maximum peak dynamic stress (σ_o) divided by the peak recoverable strain (ε_o):

$$|E^*| = \frac{\sigma_o}{\varepsilon_o} \tag{2-1}$$

The real and imaginary parts of the dynamic modulus can be written as

$$E^* = E' + iE'' \quad (2\text{-}2)$$

The previous equation shows that E* has two components; a real and an imaginary component. E' is referred to as the storage or elastic modulus component, while E" is referred to as the loss or viscous modulus. The angle by which the peak recoverable strain lags behind the peak dynamic stress is referred to as the phase angle, φ. The phase angle is an indicator of the viscous properties of the material being evaluated.

Mathematically, this is expressed as

$$E^* = |E^*|\cos\phi + i\,|E^*|\sin\phi \quad (2\text{-}3)$$

$$\phi = \frac{t_i}{t_p} \times 360 \quad (2\text{-}4)$$

where:

t_i = time lag between a cycle of stress and strain(s),

t_p = time for a stress cycle(s), and

i = imaginary number.

For a purely viscous material, the phase angle is 90°, while for a purely elastic material the phase angle is 0° (Witczak et al. 2002). The dynamic modulus, a measurable, “fundamental” property of an HMA mixture is the relative stiffness of a mix. Mixes that have a high stiffness at elevated temperatures are less likely to deform. But, stiffer mixes at an intermediate test temperature are more likely to crack for thicker pavements (Shenoy and Romero 2002).

2.7 Dynamic modulus master curves

The asphalt mixtures are thermorheologically simple materials and the time-temperature superposition principle is applicable in the linear viscoelastic state. The dynamic modulus and phase angle of asphalt mixtures can be shifted along the frequency axis to form single characteristic master curves at a desired reference temperature or frequency that is fitted to a sigmoidal function. The sigmoidal function reaches asymptotically the limiting mix stiffness. At low temperatures, the limiting mix stiffness is dependent on the glassy modulus of the binder, while at high temperatures, the limiting mix stiffness is dependent on the modulus of aggregate skeleton (Pellinen 2008).

Typically the shift factors α_T are obtained from the Williams-Landel-Ferry (WLF) equation (Williams et al. 1955):

$$\log \alpha_T = \frac{C_1(T - T_S)}{C_2 + T - T_S} \tag{2-5}$$

where:

C_1 and C_2 are constants,

T_s is the reference temperature, and

T is the temperature of each individual test.

A new method of developing the master curve for asphalt mixtures was developed in research conducted by Pellinen and Witczak (2002) at the University of Maryland. In this study, master curves were constructed fitting a sigmoidal function to the measured compressive dynamic modulus test data using non-linear least squares regression techniques (Pellinen and Witczak

2002). The shift can be done by solving the shift factors simultaneously with the coefficients of the sigmoidal function. The sigmoidal function is defined by equation 2-6 (Williams et al. 1955).

$$\log\left|E^*\right| = \delta + \frac{\alpha}{1 + e^{\beta - \gamma\left(\log(f_r) + \alpha_T\right)}} \tag{2-6}$$

where:

$\log|E^*|$ = log of dynamic modulus;

δ = minimum modulus value;

f_r = reduced frequency;

α = span of modulus values;

α_T = shift factor according to temperature; and

β, γ = shape parameters.

2.8 Repeated load test (flow number) test

The flow number test (i.e. repeated load test, dynamic creep test) is based on the repeated loading and unloading of an HMA specimen where the permanent deformation of a specimen is recorded as a function of the number of load cycles. The stress applied to the specimen is divided into two parts; seating stress and deviator stress. The deviator stress is applied for 0.1 second followed by a 0.9 second rest period for the specimen at the seating stress. There are three types of phases that occur during a repeated load test: primary, secondary, and tertiary flow. In the primary flow region, there is a decrease in strain rate with time followed by a constant strain rate in the secondary flow region, and finally an increase in strain rate in the tertiary flow region. Tertiary flow signifies that a specimen is beginning to deform significantly and the individual aggregate that makes up the skeleton of the mix is moving past each other "flow". The flow number is based upon the onset of tertiary flow (or the minimum strain rate recorded during the course of the test) (Witczak et al. 2002). The following description is shown graphically in Figure 2-2.

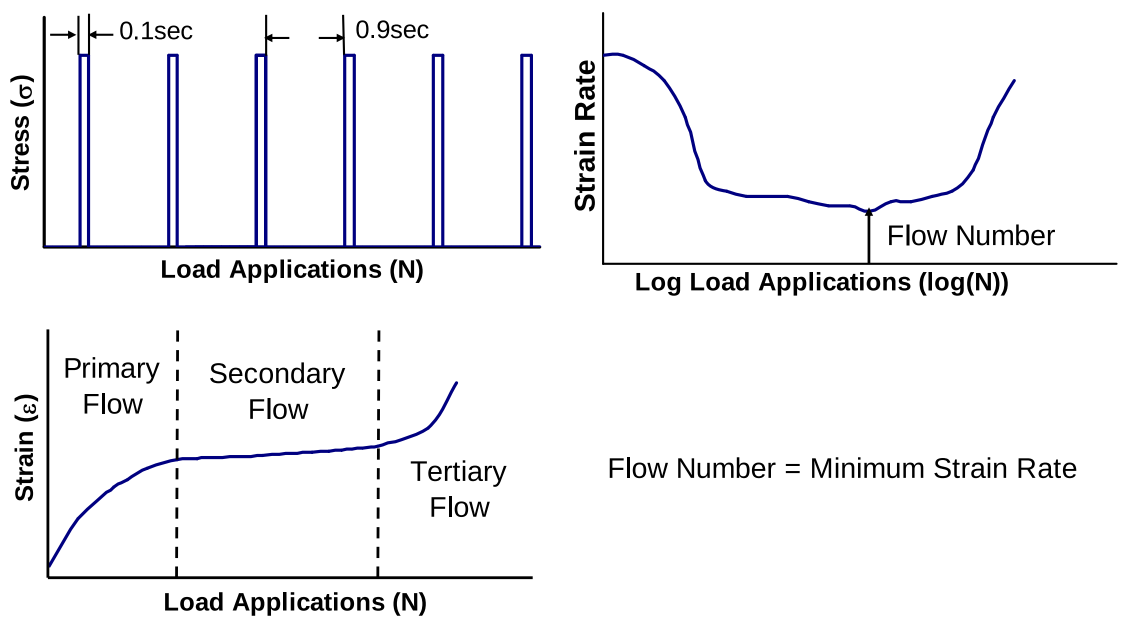


Figure 2-2 Flow Number Loading (Robinette 2005)

Flow number is defined as the number of load applications when shear deformation begins (Witczak et al. 2002). Flow number testing is similar to pavement loading because pavement loading is not continuous; there is a dwell period between loadings. This allows a pavement a certain amount of time to recover some strain induced by the loading. There is good correlation between field performance and the flow number. The flow number test could be used as a means of comparing mixes for rut susceptibility (Zhou and Scullion 2003). It was reported in

NCHRP Report 589 that flow number test results are not satisfactory when it comes to moisture damage prediction (Solaimanian et. al 2007).

The calculation of flow number was presented in NCHRP report 513 (Bonaquist et al. 2003). There is a three-step process for flow number calculation. The procedure consists of 1) numerical calculation of the strain rate; 2) smoothing of the creep data; and 3) identification of the minimum smoothed creep rate as this is where the flow number occurs. The following equation was used to determine the creep rate:

$$\frac{d(\varepsilon_p)_i}{dN} = \frac{(\varepsilon_p)_{i+\Delta N} - (\varepsilon_p)_{i-\Delta N}}{2\Delta N} \qquad (2\text{-}7)$$

where:

$\frac{d(\varepsilon_p)_i}{dN}$ = rate of change of strain with respect to cycles or creep rate at i cycle (1/cycle),

$(\varepsilon_p)_{i+\Delta N}$ = strain at i+ΔN cycles,

$(\varepsilon_p)_{i-\Delta N}$ = strain at i-ΔN cycles, and

ΔN = number of cycles sampling points.

The next step required that the data be smoothed through a running average of five points. Two creep rates before and after and including the creep rate at that instant was used. Equation 2-8 was used to determine the smoothed creep rate:

$$\frac{d\varepsilon_i^{'}}{dN} = \frac{1}{5}\left(\frac{d\varepsilon_{i-2\Delta N}}{dN} + \frac{d\varepsilon_{i-\Delta N}}{dN} + \frac{d\varepsilon_i}{dN} + \frac{d\varepsilon_{i+\Delta N}}{dN} + \frac{d\varepsilon_{i+2\Delta N}}{dN}\right) \qquad (2\text{-}8)$$

where:

$\frac{d\varepsilon_i^{'}}{dN}$ = smoothed creep rate at i sec (1/cycles),

$\frac{d\varepsilon_{i-2\Delta N}}{dN}$ = creep rate at i-2ΔN cycles (1/cycles),

$\frac{d\varepsilon_{i-\Delta N}}{dN}$ = creep rate at i-ΔN cycles (1/cycles),

$\frac{d\varepsilon_{i}}{dN}$ = creep rate at i cycles (1/cycles),

$\frac{d\varepsilon_{i+\Delta N}}{dN}$ = creep rate at i+ΔN cycles (1/cycles), and

$\frac{d\varepsilon_{i+2\Delta N}}{dN}$ = creep rate at i+2ΔN cycles (1/cycles).

The final step is to determine the cycle where the minimum creep rate occurs in the data set. If no minimum occurred during the test, then the flow number is reported as being greater than or equal to the number of loads applied during the course of the test. When several minimum creep rates occurred in a data set, then the first minimum value is reported as the flow number.

2.9 Ohio State model

One way to analyze the flow number test results is the Ohio State Model. This model is presented by Huang (2004). It assumes a linear relationship between log the strain and log the number of load repetitions. The formula of this relationship is:

$$\frac{\varepsilon_p}{N} = A(N)^{-m} \tag{2-9}$$

where:

ε_p is permanent strain at a specific loading cycle,

N is the loading cycle, and

A and m are regression constants.

Khedr (1986) analyzed the parameters of this relationship and concluded that the parameter (m) is dependent on the material type. Stress-strain pattern and intensity, stress level, and dissipated plastic strain energy during the dynamic loading affect the parameter (A). The lines achieved are nearly parallel, which means that (m) is constant for all samples of the same material tested under various conditions and is independent of the stress level and temperature, Figure 2-3. Studying the parameter (A) and applying regression analysis, the result achieved showed that (A) is a function of the applied deviator stress and the resilient modulus.

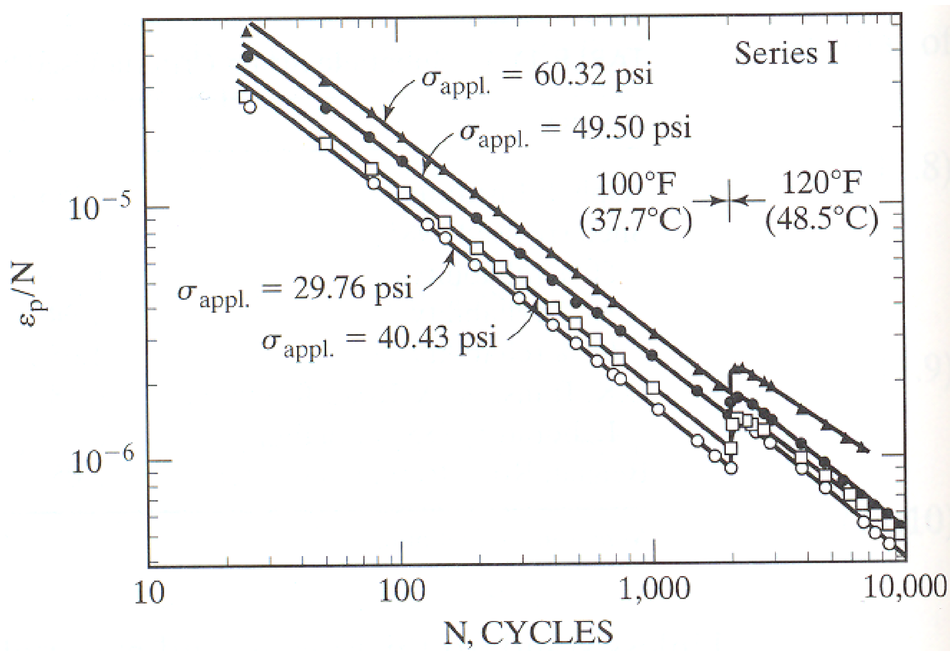


Figure 2-3 Relationship Between ε_p/N and N (1 psi = 6.9 kPa), after (Khedr 1986)

The relationship between log A and log (M_R/σ_d) is a straight line, Figure 2-4 (Khedr 1986)

$$A = a\left(\frac{M_R}{\sigma_d}\right)^{-b} \quad \textbf{(2-10)}$$

where:

A is the regression constant from equation 2-9,

M_R is the resilient modulus,

σ_d is the applied deviator stress, and

a and b are material dependent regression constants.

Majidzadeh et al (1978) applied these two relationships. They tested specimens by varying the deviator stress and the temperature. The variation in parameter (m) came out to be insignificant. They generalized the results by taking an average value for (m) which represents the all tested samples and then calculated the normalized value of the parameter (A). The relationship (2-10) was analyzed using the normalized (A) value and both equations came out to be applicable to all samples tested in that research.

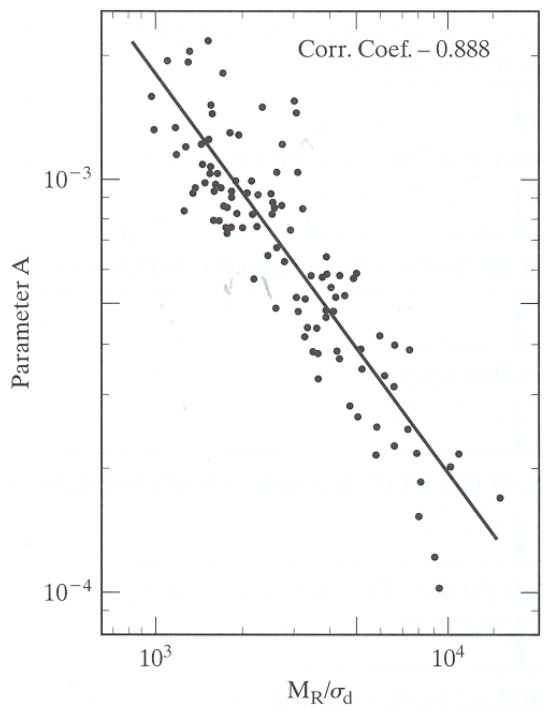


Figure 2-4 Relationship Between Parameter A and M_R/σ_d, After (Khedr 1986)

2.10 Asphalt pavement analysis and modeling

2.10.1 The beginnings of asphalt pavement analysis

Asphalt pavement mixtures have been around since 1874 (Roberts et al. 2002), with informal pavement design procedures starting in 1920 (Vesic and Domaschuk 1964). In 1885, Joseph Boussinesq developed a method for determining induced stresses and strains in an infinite elastic half-space based on a point load (Coduto 1999). These equations were based on a linear elastic material and have been applied to asphalt pavements. Donald Burmister was the first researcher to apply elastic layer theories developed by Love and Timeshenko to determine stress and displacement of a pavement structure (Burmister 1943). Burmister realized that most pavements were multi-layer systems and that the theories that were developed by Boussinesq (infinite elastic half-space) and Boit and later Pickett (infinitely elastic second layer) were not applicable to such systems. Burmister deemed that settlement was the most important aspect to consider in pavement design. Burmister used the basic Boussinesq equations to develop his own set of equations for a two-layered system. A correction coefficient was employed and compared to that of the Boussinesq results, to verify the solutions. The correction coefficient was a function of the radius of the load to the thickness of the first layer and the ratio of the elastic modulus of the second layer to that of the first layer. Burmister demonstrated through example pavements how the graphical representation of the correction coefficient could be used in various material and loading conditions for the determination of layer thicknesses. In addition, an approach for a three-layer system was presented. In the discussion of the paper by Burmister (1943), T.A. Middlebrook, U.S. Engineer Department, War Department cited that there was no field knowledge of the true stress-strain characteristics to warrant the use of the developed method by Burmister. It was also noted that pavement failures are not by deflections but rather the stresses and strains that are developed under loading (Huang 2003).

In an effort to better understand the mechanisms of pavement failure, the critical location where the failure originates needed to be identified. There are two major modes of failure for flexible pavement: permanent deformation and fatigue cracking. Kerkhoven and Dormon (1953) determined that the critical location where rutting was believed to occur could be readily attributed to compressive strains at the surface of the subgrade. The interface of the other pavement layers should also be examined to ensure that higher compressive strains do not persist. The mode of fatigue cracking was found to be the horizontal strains at the bottom of the asphalt layer (Saal and Pell 1960).

In an effort to validate the mechanistic functions of Boussinesq and Burmister, an analysis of the AASHO Road Tests was conducted by Vesic and Domaschuk (1964). The true stress-strain characteristics of a pavement under a variety of loading and environmental conditions were readily available from this field study. It was determined that the stress distribution and the deflection basins closely approximated the Boussinesq results. This does not discount Burmister's findings but demonstrates that there is a need to better understand the mechanics of flexible pavement, because field results inherently have greater variability and uncontrollable environmental conditions. Areas where additional study was suggested were the effects of pavement temperature, the presence of moisture, and the rate of load application.

2.10.2 Rheological models for asphalt concrete

To better understand flexible pavements response to loading an explanation of the models used to describe the interaction of loading and the response of flexible pavements was identified by Lytton et al. (1993). Lytton et al. (1993) present in detail the different models that are used to describe the elastic, plastic, viscoelastic, and viscoelastoplastic models as they apply to the different distresses and temperatures that a pavement endures throughout its life. At low temperatures a linear elastic or viscoelastic model is appropriate, with Maxwell, Kelvin-Voigt, and Burger components in series or in parallel as illustrated in Figure 2-5. The Burger model with Kelvin model elements in series can capture the viscoelastoplastic behavior of a flexible pavement at the higher temperatures. The reason that a series of Kelvin models are required is that a single Kelvin model is not adequate to capture the retarded strain that takes place over time.

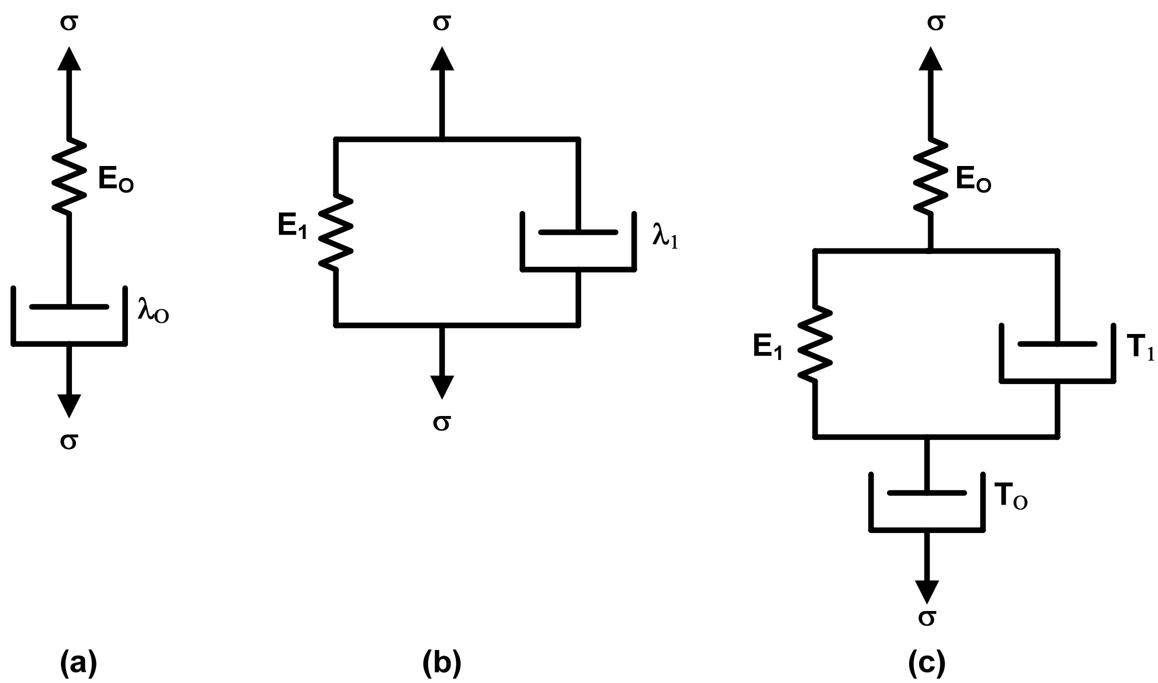


Figure 2-5 Mechanical Models: (a) Maxwell, (b) Kelvin-Voigt, and (c) Burger

For higher temperatures, flexible pavements response is said to best be described by a viscoelastoplastic model. A viscoelastoplastic model (Figure 2-6) is representative of a repeated load, where a load is placed on a pavement and there is instantaneous deformation followed by some creep; and with the unloading of the pavement, there is an instantaneous elastic rebound followed by creep recovery. Figure 2-6 displays a single loading cycle and the materials response due to the loading.

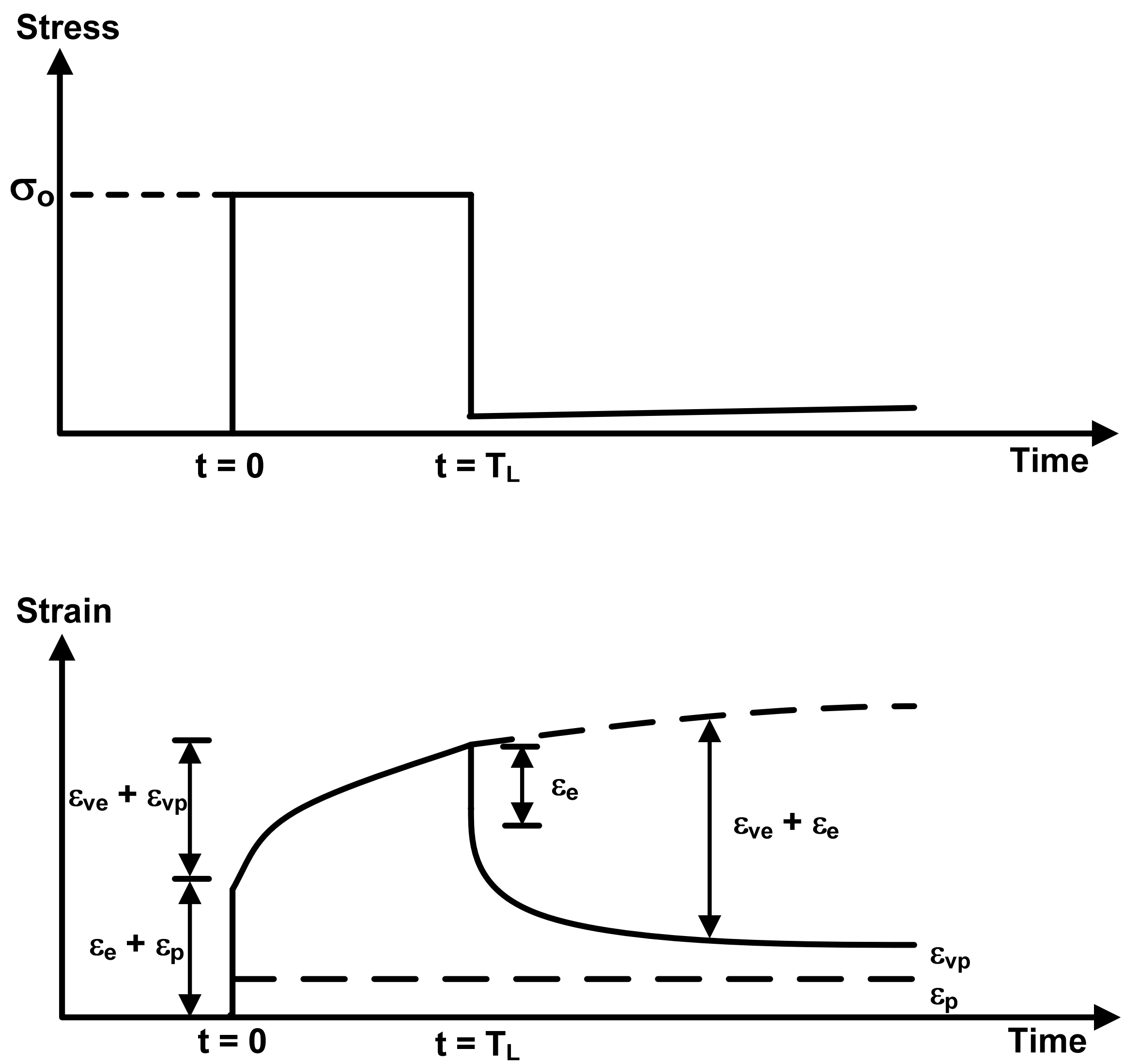


Figure 2-6 Viscoelastoplastic Component Model (Lytton et al. 1993)

In Figure 2-6, ε_e is the elastic strain - recoverable and time independent, ε_p is the plastic strain - irrecoverable and time independent, ε_{ve} is the viscoelastic strain - recoverable and time dependent, and ε_{vp} is the viscoplastic strain - irrecoverable and time dependent (Uzan et al. 1985).

2.10.3 Finite element modeling of asphalt concrete

The first research that studied asphalt as viscoelastic material was that done by Secor and Monismith (1961). The first application of the finite element analysis was the research by Duncan et al. (1968), in which the elastic theory was applied. Owen and Hinton (1980) developed a two dimensional (2D) finite element analysis program. The model that Owen and Hinton uses is a four parameter model with a spring and dashpot in series and a second spring and dashpot in parallel to the first series. Additionally, one of the dashpots is modeled with a friction slider to account for the initial viscoelastic response prior to initial yielding followed by viscoplastic response. Lytton et al. (1993) developed a similar 2D finite element program, with only minor modifications based on a viscoelastoplastic model. Two main finite element programs were developed in the 1980s: ILLI-PAVE (Raad and Figueron 1980) and MICH-PAVE (Harichandron et al. 1989). The two programs are used in the analysis of the pavement structures for mechanistic pavement.

Collop et al. (2003) have developed a finite element program named CAPA-3D which uses the viscoelastoplastic model to determine the stresses throughout an element due to loading. This program uses the Burger model for material characterization as it was mainly concerned with permanent deformation. The program allows for the development of the pavement structure where each layer is characterized by its Young's Modulus, Poisson's ratio, and thickness. Collop et al. (2003) ran a simulation with a load of 700kPa at 20°C to show the stress, accumulated strain and damage, and equivalent viscosities throughout the element, due to a single load application. The simulations illustrated that the location of the maximum strain was dependent on the stress-dependence of the flexible pavement. Stress-dependent pavements showed the greatest stress at approximately one-half the thickness of the asphalt layer, whereas non-stress-dependent pavements showed more of an even distribution of vertical strain. Elseifi et al. (2006) used the finite element analysis method to compare the material response when the material was modeled as elastic or as viscoelastic. The conclusion of this study was that the viscoelastic simulation results in a more accurate simulation of the pavement response (Elseifi et al. 2006).

2.11 Stochastic finite element analysis

The stochastic finite element model (SFEM) approach was developed by Ghanem and Spanos (1991). SFEM provides an extension for the deterministic finite element method to incorporate uncertainties. The stochastic finite element method is defined as a combination between the finite element method and probabilistic analysis (Haldar and Mahadevan 2000). There are two main approaches to perform a stochastic finite element analysis. The first approach is the intrusive approach, in which the variability is applied to the inputs and then implemented in the stiffness matrix. The second approach is the non-intrusive approach, in which a finite element software is used as a black box and the variability is applied to the input. In this case, the user obtains several stiffness matrices (Herzog et al. 2007). Although several studies were done on asphalt cement concrete using the finite element method, the number of studies that are reported to use the stochastic finite element approach is very limited. The majority of the research that utilized the finite element method did a sensitivity analysis, which can include pavement thickness, effect of different tire loads, etc. The first research that used SFEM in asphalt pavement application is the research done by Lua and Sues (1996). The researchers documented that ignoring uncertainties and spatial variability in pavements implies a false sense of accuracy. The researchers also concluded that including spatial variability is a more accurate representation of the field physical conditions (Lua and Sues 1996). Another research study (Stolle 2002) used the stochastic finite element simulation to backcalculate the layer and subgrade moduli variability that corresponds to the scatter achieved using the falling weight deflectometer (FWD). It was concluded that stochastic finite element method provided a powerful tool for evaluating the sensitivity of the response of the system parameters. (Stolle 2002).

CHAPTER 3 EXPERIMENTAL PLAN AND TEST SETUP

3.1 Experimental plan

Loose samples were procured from sixteen projects that were constructed within the state of Iowa. The mixes were selected to cover a wide range of material properties. The mixes sampled include base course, intermediate course, and surface course mixes. Three traffic levels were considered; <3, 3-10, and >10 million equivalent single axle loads (ESALs). Two nominal maximum aggregate mixes (NMAS); 12.5 and 19.0mm were used and three binder performance grades (PG 58-25, PG 64-22, and PG 70-28) are represented. The properties of the mixes are presented in Table 3-1. The samples were compacted using a Pine Superpave gyratory compactor to obtain samples that are 100mm in diameter and approximately 150mm in height. All samples were compacted to 7±1% air voids. The experimental plan was developed to be able to test the samples under different conditions that might occur in the field. The samples were subjected to five different modes of moisture conditioning: 1. unconditioned without water submersion testing, 2. unconditioned with water submersion testing, 3. moisture saturation with water submersion testing, 4. moisture saturation with freeze/thaw conditioning without water submersion testing, and 5. moisture saturation with freeze/thaw conditioning and with water submersion testing. Five replicates were tested in each condition for each mix. The five conditions were tested under the flow number test scheme. Condition 2 was only tested on five of the sixteen mixes. It was not possible to run the dynamic modulus test in the case of water submersion because the test protocol dictates the use of external linear variable differential transformers (LVDTs) on the sides of the specimen. As a result dynamic modulus test was performed on unconditioned samples (condition 1) and samples conditioned with one freeze-thaw cycle (condition 4). The test was performed at two different temperatures (4 and 21°C) and nine frequencies (0.1, 0.3, 0.5, 1.0, 3.0, 5.0, 10.0, 15.0, and 25.0Hz). The samples used in the dynamic modulus testing were then used in the flow number testing. Ten samples not five were tested in condition 4 because the samples were used in conditions 4 and 5 for flow number testing. Ten gyratory compacted samples 100mm in diameter and 62.5mm in height with 7±1% air voids. The samples were split into two groups with equal average air voids. One of the groups was used as a control and the second group was conditioned with one freeze/thaw cycle (condition 4). Table 3-2 summarizes the testing plan, where each X represents a sample tested.

Table 3-1 Properties of Sampled Mixes

Project Name	NMAS (mm)	Binder PG	Traffic Level Million ESALs	Designation
HWY 330 Base	19.0	64-22	<3	330B
HWY 218, Tripoli	19.0	64-22	<3	218
I-80 Base	19.0	64-22	>10	I80B
I-235 Intermediate	19.0	70-28	>10	235I
6th St. Nevada	12.5	64-22	<3	6N
Dedham	12.5	58-28	<3	Ded
Rose Street	12.5	64-22	<3	Rose
F-52	12.5	58-28	<3	F52
Northwestern Avenue	12.5	64-22	<3	NW
HW 4	12.5	58-28	<3	HW4
HWY 330 Int.	12.5	64-22	3-10	330I
Jewell	12.5	64-22	3-10	Jewell
HWY 330 Surface	12.5	64-22	3-10	330S
I-80 Surface	12.5	64-22	>10	I80S
I-235 Surface	12.5	70-28	>10	235S
Altoona	12.5	64-22	>10	ALT

Table 3-2 Samples Tested at the Different Conditions

Test	Condition 1	Condition 2*	Condition 3	Condition 4	Condition 5
Dynamic Modulus	XXXXX			XXXXX XXXXX	
Flow Number	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX
AASHTO T283	XXXXX			XXXXX	

* This condition was applied to five mixtures only.

A summary of the experimental plan is presented in Figure 3-1.

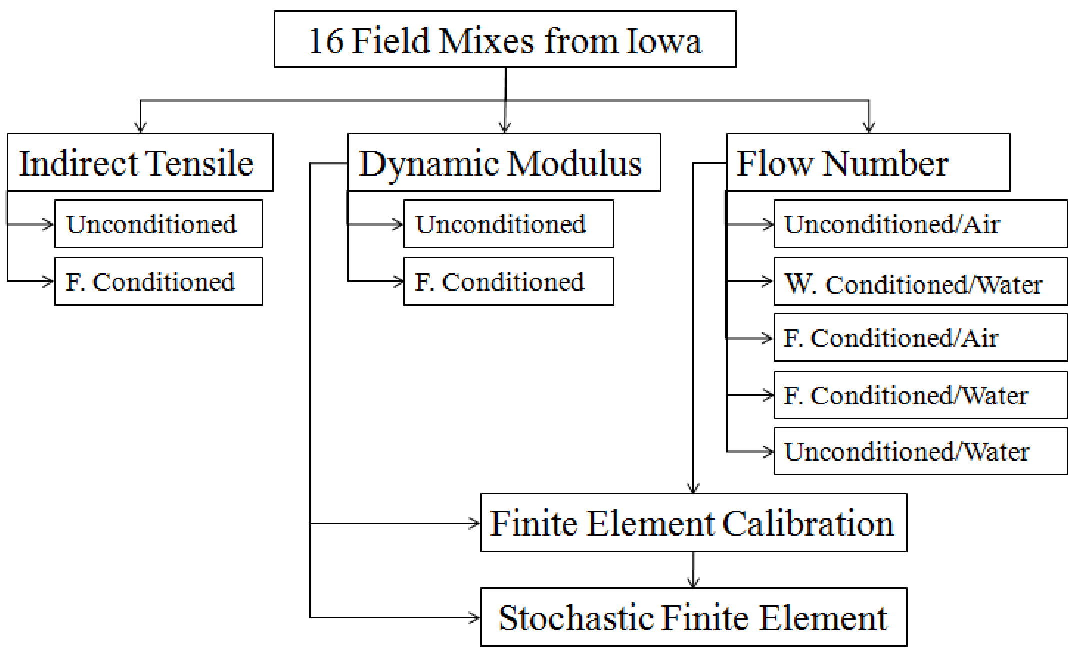


Figure 3-1 Summary of the Experimental Plan

3.2 Sample conditioning

The conditioning of the samples was done in accordance with AASHTO T283 Resistance of Compacted Bituminous Mixture to Moisture Induced Damage (AASHTO 1993). Specimens were compacted according to section 4.2.3 in AASHTO T283 and divided into two subsets so that each subset had the same average air voids. The dry subset (control group) deviated from the standard specification as the samples were placed in an environmental chamber rather than being wrapped with plastic or placed in a heavy-duty, leak-proof plastic bag and stored in a water bath at 25±0.5°C for 2 hours ± 10 minutes prior to testing. The conditioning of the conditioned subset specimens was done by placing the samples in a pycnometer with a spacer. Approximately 25mm of water was placed above the specimen. The specimens were vacuum saturated for 5 to 10 minutes at 13-67 kPa. The specimens were left submerged in water bath for 5 to 10 minutes after vacuum saturating. The mass of the saturated, surface dry specimen was determined after partial vacuum saturation. Next, the volume of absorbed water was calculated. Finally, the degree of saturation was calculated. If the degree of saturation was between 70% and 80% testing proceeded. If the degree of saturation was less than 70%, the vacuum saturation procedure was repeated. If saturation was greater than 80%, the specimen was considered damaged and discarded. If the sample required a freeze/thaw cycle, each vacuum saturated specimen was tightly covered with plastic wrap and placed in a plastic bag with approximately 10±0.5 ml of water, and sealed. The plastic bags were then placed in a freezer at -18±3°C for a minimum of 16 hours. After the freeze/thaw cycle, the final steps are the same for moisture conditioning with or without freeze/thaw cycling. The next step is to place the samples in a water bath at 60±1°C for 24±1 hour with 25mm of water above the specimens. The specimens were then removed and placed in a water bath at 25±0.5°C for 2 hours ± 10 minutes. Approximately 25mm of water should be above the specimens. Not more than 15 minutes should be required for the water bath to reach 25±0.5°C. If needed, ice could be used to prevent temperature increase. The specimens are then ready for testing.

3.3 Dynamic modulus test

The test setup was derived from NCHRP Report 547 (Witczak 2005). The test was performed using a universal servo-hydraulic testing system inside a temperature controlled environmental chamber that was set to the designated test temperature. The test was a strain controlled test, in which the strain was maintained at 80 microstrain to be able to capture the linear visco-elastic behavior of the material. The vertical deformation measurements were obtained using four LVDTs with a 100-mm gage length. They were attached to the specimen by aluminum buttons which were fixed on the specimen surface using Epoxy glue. One average strain measurement was obtained from the four LVDTs and this average strain was then used to control the test. The test setup is shown in Figure 3-2.

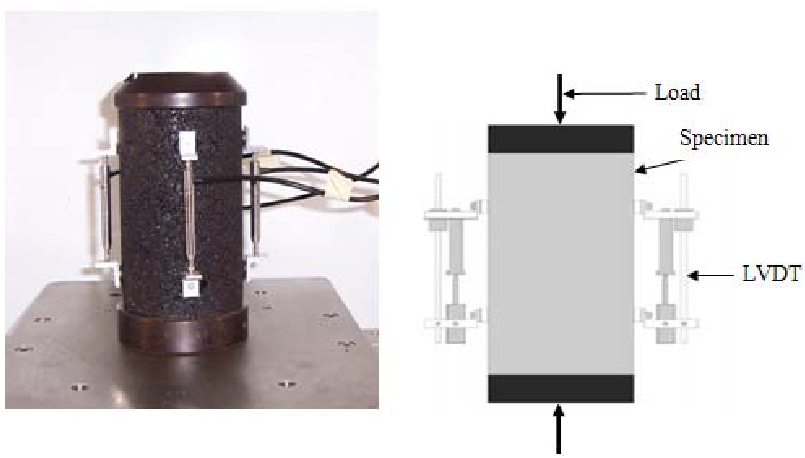


Figure 3-2 Dynamic modulus test setup (NCHRP Report 547)

The test was performed at two different temperatures (4 and 21°C) and nine frequencies (0.1, 0.3, 0.5, 1.0, 3.0, 5.0, 10.0, 15.0, and 25.0Hz). At each frequency-temperature combination, the dynamic modulus value and the phase angle were calculated. The concept of time-temperature superposition was applied to the results from these temperatures and frequencies to develop a master curve for each mix. The master curve can be used to predict the modulus at other temperatures and frequencies. The use of more frequencies and less temperatures is more practical because it reduces the testing time.

3.4 Flow number test

The testing procedure described herein was derived from NCHRP report 465 (Witzack et al. 2002) and NCHRP report 513 (Bonaquist et al. 2003). This testing protocol has been referred to as Protocol W1: Simple Performance Test for Permanent Deformation Based Upon Repeated Load Test of Asphalt Concrete Mixtures.

A 100-mm diameter by 150-mm high cylindrical specimen was tested under a repeated haversine compressive stress at a single effective temperature unconfined. A UTM 14P machine was used to conduct the tests with a temperature controlled testing chamber. The load was applied for a duration of 0.1-sec and a dwell period of 0.9-sec. No design axial stress levels have been stipulated in the NCHRP 465 or 513 Protocols. The deviator stress used in testing the sixteen mixtures was 600kPa (87psi) which is analogous to the load used in the Superpave gyratory compactor. Since no confining pressure was used, the axial stress is the deviator stress stated (600kPa). The effective test temperature was selected to be 37^{o}C, which is representative of the effective rutting temperature in the state of Iowa. The temperature inside the environmental chamber was checked using a probe inserted in a dummy sample. The strains for these tests were measured directly through the machines actuator as opposed to affixing axial LVDTs to the sides of the specimen. Affixing axial LVDTs to the side of the specimen is not suitable to the test conditions because of the high deformation levels expected during the test.

Specimens were placed in the testing chamber for a minimum of two hours as specified in Protocol W1 to ensure that the test temperature was obtained in the test specimens. After the test temperature had been reached, the specimen was then centered under the loading platens so as to not place an eccentric load on the specimen. The test was conducted in accordance with the aforementioned parameters. Depending on the test condition designated for the sample, the sample was either placed in water or not. The water in the container was at the designated test temperature. The test setup is shown in Figure 3-3.

Figure 3-3 Flow Number Test Setup

The loading regime was applied to the specimens for a total of 40,000 continuous cycles or until the specimen failed and results in excessive tertiary deformation, which ever occurred first. Excessive deformation was considered 100,000μstrain. The exact length of the test was variable from one mixture to the next because of the different material properties.

3.5 Indirect tensile strength testing

The testing procedure described herein is derived from the AASHTO T283 Resistance of Compacted Bituminous Mixture to Moisture Induced Damage (AASHTO 1993). The indirect tensile strength of the dry and conditioned specimens was determined at 25°C. The specimen was placed between two bearing plates in the testing machine such that the load is applied along the diameter of the specimen as shown in Figure 3-4. A Universal Testing Machine was used to conduct the testing.

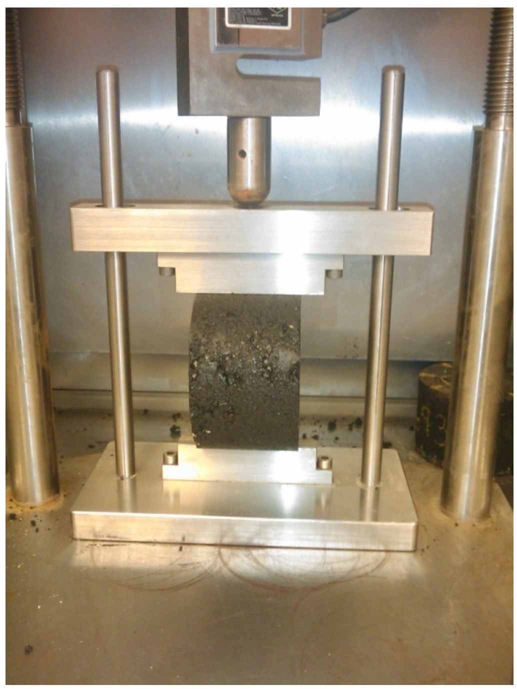


Figure 3-4 Indirect Tensile Strength Test Setup

The load is applied at a constant rate of movement of the testing machine head of 50mm per minute. The maximum load is recorded and placed in the equation 3-1 in order to calculate tensile strength.

$$S_t = \frac{2000 \times P}{\pi \times t \times D} \tag{3-1}$$

where:

S_t = tensile strength (kPa),

P = maximum load (N),

t = specimen thickness (mm), and

D = specimen diameter (mm).

A numerical index or resistance of an HMA mixture to the effects of water is the ratio of the original strength that is retained to that of the moisture conditioned strength.

$$TSR = \frac{S_2}{S_1} \tag{3-2}$$

where:

TSR = tensile strength ratio,

S2 = average tensile strength of conditioned subset, and

S1 = average tensile strength of dry subset.

CHAPTER 4 DYNAMIC MODULUS TEST RESULTS AND ANALYSIS

4.1 Approach

The dynamic modulus was performed on two groups of samples: control and moisture conditioned samples. The dynamic modulus values and phase angles were calculated for the mixes at the different frequency-temperature combinations. The approach of this analysis was to evaluate the change of dynamic modulus and its associated parameters (phase angle, storage modulus, and loss modulus) and see which of these parameters is linked directly to moisture damage. A visual representation of the results is presented by plotting the mastercurves for the different mixes for both the control and conditioned groups.

4.2 Dynamic modulus test results

The results of the dynamic modulus test and phase angle for both the control and conditioned groups are presented in appendix B. The E* ratios were then calculated by dividing the dynamic modulus results from the moisture conditioned group over those from the control group (Table 4-1). The lower the E* ratio, the greater the effect of moisture conditioning on a specific mix. The E* ratios appear to vary with test temperature and frequency. The general trend is that the E* ratio decreases with an increase in temperature and/or a decrease in frequency. This variation provides the impetus for performing a statistical analysis to check the variability in the results. The phase angle ratios are presented in Table 4-2. The increase in the phase angle ratio indicates greater moisture damage. The general trend is that the phase angle values increase with moisture conditioning. This means that the moisture conditioned samples are more viscous compared to the control samples. The phase angle ratio decreases with the decrease in test frequency and an increase in test temperature.

Table 4-1 E* Ratios

Mix Name	Temp	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
6N	4	0.97	0.93	1.01	0.89	0.86	0.84	0.79	0.83	0.78
6N	21	1.02	1.00	1.00	0.97	0.94	0.93	0.91	0.88	0.81
218	4	1.04	1.02	1.03	1.02	1.05	1.01	1.01	1.01	1.00
218	21	1.16	1.16	1.14	1.13	1.23	1.13	1.07	1.05	0.94
235I	4	0.90	0.88	0.88	0.87	0.83	0.84	0.84	0.84	0.84
235I	21	0.90	0.90	0.90	0.89	0.87	0.86	0.84	0.85	0.83
235s	4	1.15	1.13	1.14	1.13	1.18	1.12	1.11	1.11	1.09
235s	21	1.21	1.20	1.19	1.19	1.30	1.21	1.17	1.20	1.11
330B	4	0.93	0.92	0.95	0.93	0.96	0.91	0.91	0.93	0.93
330B	21	1.10	1.11	1.12	1.12	1.22	1.16	1.11	1.04	1.04
330I	4	1.07	1.04	1.04	1.03	1.03	1.02	0.99	1.02	1.01
330I	21	1.17	1.17	1.16	1.16	1.15	1.18	1.16	1.14	1.15
330s	4	0.99	0.99	0.98	0.98	0.96	0.94	0.93	0.92	0.89
330s	21	0.85	0.83	0.82	0.82	0.79	0.80	0.84	0.88	0.88
ALT	4	0.99	0.99	0.98	0.97	0.96	0.95	0.95	0.95	0.93
ALT	21	1.11	1.12	1.11	1.10	1.10	1.09	1.09	1.08	1.04
Ded	4	0.90	0.90	0.91	0.92	0.94	0.85	0.88	0.86	0.96
Ded	21	1.12	1.11	1.12	1.11	1.25	1.08	1.05	0.92	0.86
F52	4	1.02	1.02	1.02	1.02	0.98	0.95	0.96	0.92	0.85
F52	21	1.11	1.09	1.07	1.05	1.06	1.02	0.95	0.86	0.81
HW4	4	0.92	0.92	0.91	0.89	0.87	0.87	0.86	0.85	0.89
HW4	21	0.67	0.66	0.66	0.68	0.64	0.71	0.81	0.87	0.90
I80B	4	1.01	1.01	1.02	1.01	1.00	1.01	0.99	0.98	1.00
I80B	21	0.98	1.02	1.03	1.03	1.03	1.04	1.06	1.00	1.01
I80s	4	0.93	0.88	0.91	0.90	0.92	0.86	0.86	0.87	0.83
I80s	21	0.91	0.93	0.93	0.91	0.94	0.87	0.86	0.85	0.79
Jewell	4	1.06	1.03	1.04	1.01	1.06	1.00	0.99	1.00	0.98
Jewell	21	1.20	1.19	1.18	1.18	1.28	1.19	1.17	1.14	1.12
NW	4	0.91	0.89	0.90	0.90	0.92	0.89	0.87	0.88	0.88
NW	21	1.05	1.07	1.07	1.07	1.17	1.09	1.06	1.05	1.04
Rose	4	0.94	0.89	0.88	0.89	0.87	0.84	0.83	0.84	0.79
Rose	21	0.85	0.84	0.84	0.82	0.79	0.75	0.75	0.73	0.69

Table 4-2 Phase Angle Ratios

Mix Name	Temp	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
6N	4	1.83	1.21	1.25	1.21	1.25	1.17	1.13	1.15	1.36
6N	21	1.14	1.12	1.12	1.13	1.13	1.12	1.14	1.15	1.08
218	4	1.19	1.01	1.09	1.07	1.06	1.10	1.06	1.06	1.24
218	21	1.03	1.02	1.02	1.02	0.98	1.01	1.03	1.02	1.00
235I	4	1.26	1.16	1.16	1.14	1.23	1.12	1.19	1.19	1.20
235I	21	1.08	1.09	1.08	1.07	1.04	1.06	1.02	1.05	1.03
235s	4	0.93	0.93	0.93	0.94	0.96	0.99	0.92	0.98	1.03
235s	21	0.99	0.99	1.00	1.00	0.96	1.00	0.96	1.02	0.99
330B	4	0.98	1.09	1.07	1.04	1.04	0.99	1.04	1.12	1.28
330B	21	1.06	1.00	1.00	1.00	0.97	1.00	0.93	1.02	1.00
330I	4	1.23	1.12	1.10	1.10	1.06	1.05	1.06	1.09	1.35
330I	21	1.01	1.00	1.00	1.00	0.97	0.99	0.95	0.99	1.00
330s	4	1.20	1.17	1.21	1.27	1.32	1.28	1.31	1.36	1.53
330s	21	1.11	1.11	1.12	1.14	1.12	1.17	1.13	1.18	1.26
ALT	4	2.25	1.28	1.17	1.13	1.12	1.12	1.16	1.20	1.38
ALT	21	1.05	1.03	1.02	1.03	1.01	1.04	1.05	1.03	1.05
Ded	4	1.12	1.05	1.06	1.03	1.07	0.97	0.96	1.05	1.25
Ded	21	1.02	0.99	0.98	0.99	0.99	1.01	1.00	1.02	1.10
F52	4	1.38	1.10	1.09	1.10	1.13	1.05	1.07	1.07	1.67
F52	21	1.05	1.05	1.07	1.06	1.00	1.05	1.08	1.10	1.05
HW4	4	1.22	1.20	1.15	1.16	1.25	1.11	1.15	1.09	1.09
HW4	21	1.15	1.17	1.21	1.27	1.25	1.32	1.39	1.39	1.45
I80B	4	1.22	1.18	1.12	1.10	1.11	1.09	1.03	1.00	1.03
I80B	21	0.97	0.99	1.01	1.02	1.01	1.00	0.97	0.99	1.04
I80s	4	1.73	1.30	1.28	1.24	1.20	1.16	1.17	1.26	1.50
I80s	21	1.14	1.14	1.13	1.13	1.15	1.12	1.15	1.16	1.19
Jewell	4	1.25	1.17	1.13	1.11	1.10	1.07	1.09	1.10	1.17
Jewell	21	0.97	0.99	0.99	0.99	0.98	0.97	0.98	0.98	0.92
NW	4	1.45	1.35	1.22	1.34	1.34	1.28	1.40	1.59	1.80
NW	21	1.30	1.28	1.26	1.25	1.25	1.25	1.24	1.32	1.26
Rose	4	1.17	1.09	1.11	1.10	1.15	1.06	1.03	1.06	1.26
Rose	21	1.04	1.02	1.03	1.03	1.00	1.01	1.00	0.97	0.93

4.3 Statistical analysis

A statistical analysis was performed to test the hypothesis that the results at different temperature-frequency combinations are statistically different. A pair-wise comparison using a level of significance (α) of 0.05 was performed between the ratios for the sixteen mixes at each of the temperature – frequency combinations to those at the other frequency-temperature combinations. The results of this statistical analysis are presented in Table 4-3 and show that there are statistical differences between the results. This means that the temperature and the loading frequency are significant factors and that they affect the extent of moisture damage to which the mix is subjected. The same analysis was performed on the phase angle ratio (Table 4-4). The analysis also showed that many of the temperature-frequency combinations are statistically different from the other combinations.

Figures 4-1 and 4-2 show the E* ratio distribution for all the mixes with respect to temperature and frequency, respectively. It appears from Figure 4-1 that the range of ratios at 21^{o}C is larger than that at 4^{o}C. The Tukey-Kramer all pair comparison method was used to test whether the mixes are statistically different from each other or not. This was used to group the mixes that show no statistical difference from each other. The results of the comparison are presented in Tables 4-5 and 4-6 for the E* ratio and phase angle ratio results, respectively. Ranking of the mixes at the different temperature-frequency combinations using E* ratios are presented in Table 4-7, while those using phase angle ratios are presented in Table 4-8.

Table 4-3 Statistical Comparison between the Different Temperature-Frequency Combinations for E* Ratios*

Temp-Freq.	**4-15Hz**	**4-10Hz**	**4-5Hz**	**4-3Hz**	**4-1Hz**	**4-0.5Hz**	**4-0.3Hz**	**4-0.1Hz**	**21-25Hz**	**21-15Hz**	**21-10Hz**	**21-5Hz**	**21-3Hz**	**21-1Hz**	**21-0.5Hz**	**21-0.3Hz**	**21-0.1Hz**
4-25Hz	**0.0011**	0.1652	**0.0018**	0.0591	**0.0001**	**0.0001**	**0.0001**	**0.0008**	0.1919	0.2087	0.2519	0.336	0.1698	0.5000	0.7161	0.6452	0.1379
4-15Hz		0.0958	0.2506	0.7577	**0.0001**	**0.0001**	**0.0002**	**0.0039**	0.0722	0.0813	0.1013	0.1374	0.0837	0.2366	0.3186	0.8034	0.3511
4-10Hz			0.0631	0.5643	**0.0003**	**0.0004**	**0.0002**	**0.0025**	0.1113	0.1244	0.1529	0.2118	0.1154	0.3482	0.5019	0.8812	0.2143
4-5Hz				0.8056	**0.0001**	**0.0001**	**0.0001**	**0.0038**	**0.0456**	0.0511	0.0645	0.0893	0.0587	0.1711	0.2287	0.6528	0.4506
4-3Hz					**0.0006**	**0.0001**	**0.0001**	**0.0009**	**0.0339**	**0.0375**	**0.0490**	0.0673	**0.0385**	0.1369	0.1868	0.6553	0.3667
4-1Hz						0.0846	0.1321	0.1866	**0.0075**	**0.0080**	**0.0104**	**0.0133**	**0.0145**	**0.0290**	**0.0244**	0.0769	0.7566
4-0.5Hz							0.6091	0.4711	**0.0039**	**0.0042**	**0.0055**	**0.0069**	**0.0084**	**0.0164**	**0.0127**	**0.0452**	0.5411
4-0.3Hz								0.3351	**0.0035**	**0.0038**	**0.0049**	**0.0062**	**0.0085**	**0.0153**	**0.0108**	**0.0350**	0.5749
4-0.1Hz									**0.0027**	**0.0027**	**0.0031**	**0.0033**	**0.0041**	**0.0070**	**0.0026**	**0.0107**	0.2949
21-25Hz										0.8845	0.4546	0.1230	0.2473	0.1659	0.1010	0.0510	**0.0175**
21-15Hz											0.1380	**0.0186**	0.1997	0.1107	0.0810	**0.0467**	**0.0154**
21-10Hz												**0.0362**	0.1309	0.1826	0.1069	0.0608	**0.0183**
21-5Hz													0.0535	0.3466	0.1437	0.0731	**0.0190**
21-3Hz														**0.0155**	**0.0337**	**0.0300**	**0.0123**
21-1Hz															0.2209	0.0929	**0.0181**
21-0.5Hz																0.0817	**0.0055**
21-0.3Hz																	**0.0047**

***Numbers in bold are statistically significant at α=0.05**

Table 4-4 Statistical Comparison between the Different Temperature-Frequency Combinations for E* Ratios*

Temp-Freq.	4-15Hz	4-10Hz	4-5Hz	4-3Hz	4-1Hz	4-0.5Hz	4-0.3Hz	4-0.1Hz	21-25Hz	21-15Hz	21-10Hz	21-5Hz	21-3Hz	21-1Hz	21-0.5Hz	21-0.3Hz	21-0.1Hz
4-25Hz	**0.0152**	**0.0128**	**0.0151**	**0.0307**	**0.0078**	**0.0102**	**0.0305**	0.8363	**0.0043**	**0.0036**	**0.0044**	**0.0052**	**0.0028**	**0.0056**	**0.0039**	**0.0094**	**0.0105**
4-15Hz		0.2295	0.1674	0.9498	**0.0197**	0.0539	0.9251	**0.0023**	**0.0012**	**0.0004**	**0.0009**	**0.0022**	**0.0002**	**0.0046**	**0.0059**	**0.0375**	0.0563
4-10Hz			0.7255	0.3183	**0.0314**	0.2543	0.6224	**0.0012**	**0.0023**	**0.0006**	**0.0015**	**0.0048**	**0.0004**	**0.0116**	**0.0151**	0.1055	0.1363
4-5Hz				0.0680	**0.0046**	0.1146	0.3951	**0.0004**	**0.0007**	**0.0001**	**0.0004**	**0.0020**	**0.0001**	**0.0060**	**0.0117**	0.0806	0.1259
4-3Hz					**0.0015**	**0.0138**	0.9599	**0.0020**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0002**	**0.0008**	**0.0090**	**0.0233**
4-1Hz						0.4392	0.0545	**0.0002**	0.0704	**0.0150**	**0.0313**	0.0919	**0.0101**	0.1352	0.1529	0.5820	0.5869
4-0.5Hz							**0.0209**	**0.0001**	**0.0379**	**0.0117**	**0.0272**	0.0657	**0.0091**	0.0802	0.0958	0.3534	0.3936
4-0.3Hz								**0.0002**	**0.0042**	**0.0029**	**0.0077**	**0.0175**	**0.0033**	**0.0206**	**0.0291**	0.0726	0.1019
4-0.1Hz									**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0002**	**0.0002**	**0.0003**	**0.0007**
21-25Hz										0.1762	0.5805	0.9067	0.1152	0.9632	0.7744	0.3241	0.5569
21-15Hz											0.4156	0.2418	0.1907	0.4685	0.9118	0.1200	0.3477
21-10Hz												0.1984	0.0563	0.5680	0.9324	0.1200	0.3816
21-5Hz													**0.0010**	0.8996	0.5501	0.1420	0.4630
21-3Hz														**0.0109**	0.2717	**0.0045**	0.0745
21-1Hz															0.4995	**0.0389**	0.3265
21-0.5Hz																**0.0158**	0.1850
21-0.3Hz																	0.8462

***Numbers in bold are statistically significant at α=0.05**

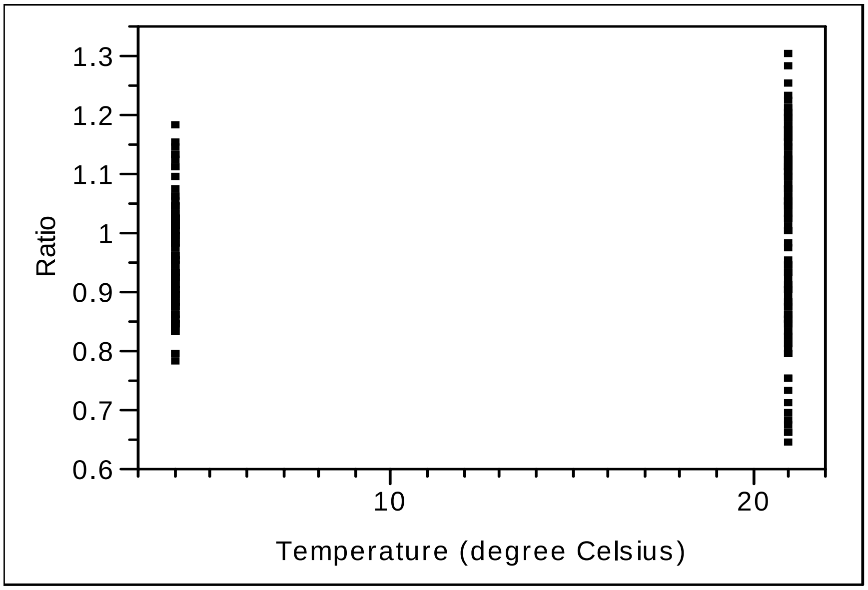


Figure 4-1 Distribution of E* Ratios at Different Temperatures

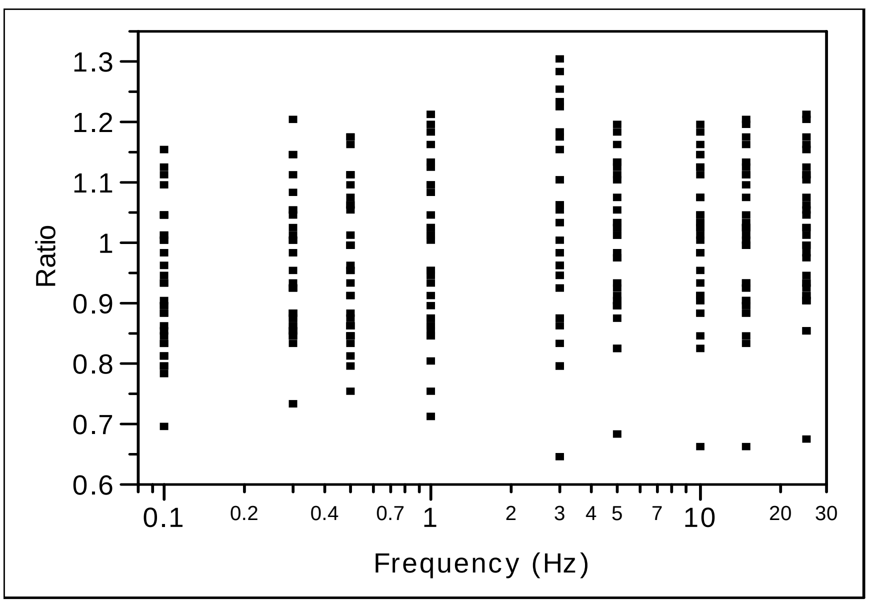


Figure 4-2 Distribution of E* Ratios at Different Frequencies

Table 4-5 All Pair Comparison for E* Ratios*

Mix	Level						Mean
235s	A						1.1633
Jewell	A	B					1.1011
330I	A	B					1.0939
218		B	C				1.0667
ALT		B	C				1.0283
330B		B	C				1.0217
I80B		B	C				1.0128
F52			C	D			0.9867
Ded			C	D			0.9856
NW			C	D			0.9839
6N				D	E		0.9089
330s					E	F	0.8939
I80s					E	F	0.8861
235I					E	F	0.8644
Rose					E	F	0.8239
HW4						F	0.8100

*Levels not connected by same letter are significantly different.

Table 4-6 All Pair Comparison for Phase Angle Ratios*

Mix	Level					Mean
235s	A					0.9733
330B	A	B				1.0350
Ded	A	B				1.0367
I80B	A	B				1.0489
NW	A	B				1.0533
218	A	B				1.0561
Jewell	A	B				1.0589
330I	A	B	C			1.0594
F52		B	C	D		1.1206
235I		B	C	D		1.1206
ALT		B	C	D		1.1733
6N			C	D	E	1.2050
330s				D	E	1.2217
HW4				D	E	1.2233
I80s				D	E	1.2306
Rose					E	1.3433

*Levels not connected by same letter are significantly different.

Table 4-7 Ranking of Mixes Based on E* Ratio

Mix Name	Temp	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
6N	4	9	9	7	13	15	15	16	16	16
218	4	4	4	4	3	3	3	2	3	4
235I	4	16	16	16	16	16	16	14	14	13
235s	4	1	1	1	1	1	1	1	1	1
330B	4	12	10	10	9	7	9	9	7	7
330I	4	2	2	3	2	4	2	5	2	2
330s	4	8	7	8	7	8	8	8	8	9
ALT	4	7	8	9	8	9	7	7	6	8
Ded	4	15	12	12	10	10	13	10	12	6
F52	4	5	5	5	4	6	6	6	9	12
HW4	4	13	11	13	14	14	11	13	13	10
I80B	4	6	6	6	5	5	4	3	5	3
I80s	4	11	15	11	11	12	12	12	11	14
Jewell	4	3	3	2	6	2	5	4	4	5
NW	4	14	13	14	12	11	10	11	10	11
Rose	4	10	14	15	15	13	14	15	15	15
6N	21	10	11	11	11	12	11	11	11	14
218	21	4	4	4	4	4	5	6	5	8
235I	21	13	13	13	13	13	13	13	14	12
235s	21	1	1	1	1	1	1	1	1	3
330B	21	8	7	5	5	5	4	4	7	6
330I	21	3	3	3	3	7	3	3	3	1
330s	21	15	15	15	15	14	14	14	10	10
ALT	21	6	5	7	7	8	6	5	4	4
Ded	21	5	6	6	6	3	8	9	9	11
F52	21	7	8	8	9	9	10	10	13	13
HW4	21	16	16	16	16	16	16	15	12	9
I80B	21	11	10	10	10	10	9	8	8	7
I80s	21	12	12	12	12	11	12	12	15	15
Jewell	21	2	2	2	2	2	2	2	2	2
NW	21	9	9	9	8	6	7	7	6	5
Rose	21	14	14	14	14	15	15	16	16	16

Table 4-8 Ranking of Mixes Based on Phase Angle Ratio

Mix Name	Temp	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
6N	4	15	13	15	13	14	14	10	11	11
218	4	5	2	4	4	3	9	7	5	6
235I	4	11	8	11	11	12	11	14	12	5
235s	4	1	1	1	1	1	2	1	1	1
330B	4	2	4	3	3	2	3	5	10	9
330I	4	9	7	6	7	4	5	6	8	10
330s	4	6	9	13	15	15	15	15	15	14
ALT	4	16	14	12	10	8	12	12	13	12
Ded	4	3	3	2	2	5	1	2	3	7
F52	4	12	6	5	6	9	4	8	6	15
HW4	4	7	12	10	12	13	10	11	7	3
I80B	4	8	11	8	5	7	8	4	2	2
I80s	4	14	15	16	14	11	13	13	14	13
Jewell	4	4	5	7	8	10	6	3	4	8
NW	4	10	10	9	9	6	7	9	9	4
Rose	4	13	16	14	16	16	16	16	16	16
6N	21	13	13	12	12	13	12	13	12	11
218	21	6	7	8	7	5	6	9	6	4
235I	21	11	11	11	11	11	11	8	10	7
235s	21	3	4	5	5	1	5	3	5	3
330B	21	10	5	3	4	2	4	1	7	6
330I	21	4	6	4	3	3	2	2	3	5
330s	21	12	12	13	14	12	14	12	14	15
ALT	21	13	13	12	12	13	12	13	12	11
Ded	21	8	9	7	8	9	9	10	9	9
F52	21	5	2	1	2	6	7	6	8	12
HW4	21	9	10	10	10	8	10	11	11	10
I80B	21	15	15	15	16	15	16	16	16	16
I80s	21	2	1	6	6	10	3	4	4	8
Jewell	21	14	14	14	13	14	13	14	13	13
NW	21	7	8	9	9	7	8	7	1	2
Rose	21	1	3	2	1	4	1	5	2	1

4.4 Master curves

The data from the dynamic modulus test was used to plot master curves for the different mixes. For each mix, the master curve for the control and moisture conditioned results are plotted together at a reference temperature of 21°C. Figures 4-3 through 4-18 present the master curves for the 16 mixes. It can be seen from the master curves that at low temperature and/or high frequencies, the moduli for the control and moisture conditioned samples are very close for all the mixtures with a possible increase in the dynamic modulus values for the moisture conditioned group. The values of the moduli start to be different when the temperature is increased and/or the frequency is decreased. The magnitude of the difference changes from one mixture to the other depending on the moisture susceptibility of the mixes. This means that developing the master curves provides a good means to visualize the effect of moisture on the mixes over the full range of the operating frequencies and temperatures. Only one of the sixteen mixtures (330S) did not follow this trend, the moisture conditioned samples modulus increased at higher temperatures and/or lower frequencies.

For the mixes studied under this project, the area under the master curve was calculated to quantify the difference caused by moisture conditioning. Based on the previous discussion, the area under the master curve had to be split into two zones. The first zone is for frequencies lower than 10Hz at the reference temperature, which represents the high temperature-low frequency zone. The second zone is for frequencies higher than 10Hz, which represents the low temperature-high frequency zone. The results are shown in Table 4-9. The results show that splitting the area under the master curve can be used to provide a good distinction between the different mixes when it comes to moisture susceptibility. The distinction is very clear at the high temperature-low frequency zone.

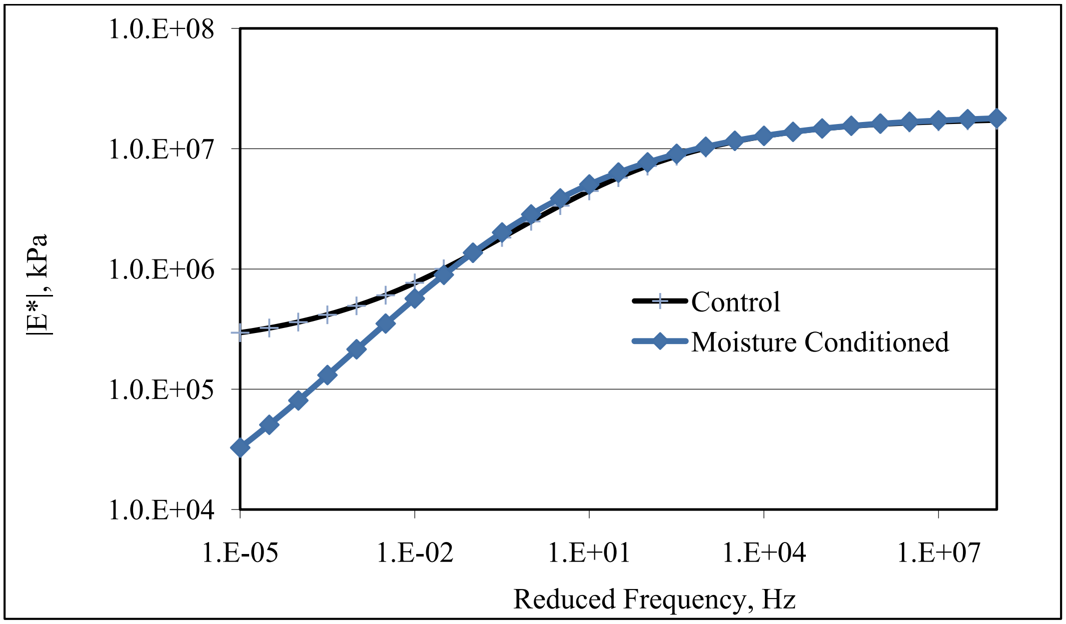


Figure 4-3 Master Curve for Mix 6N

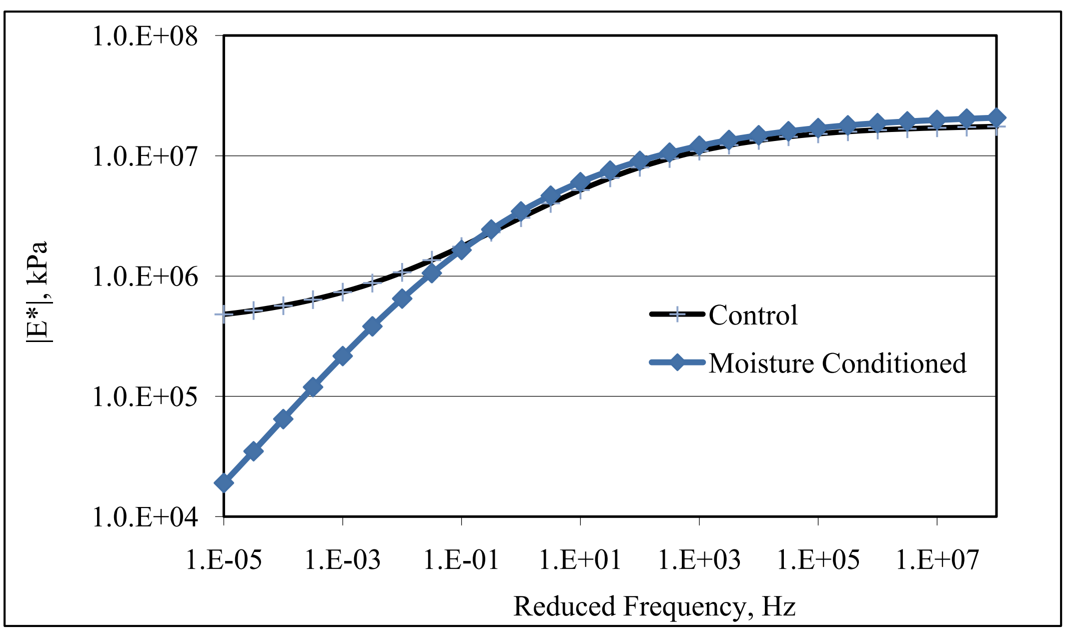


Figure 4-4 Master Curve for Mix 218

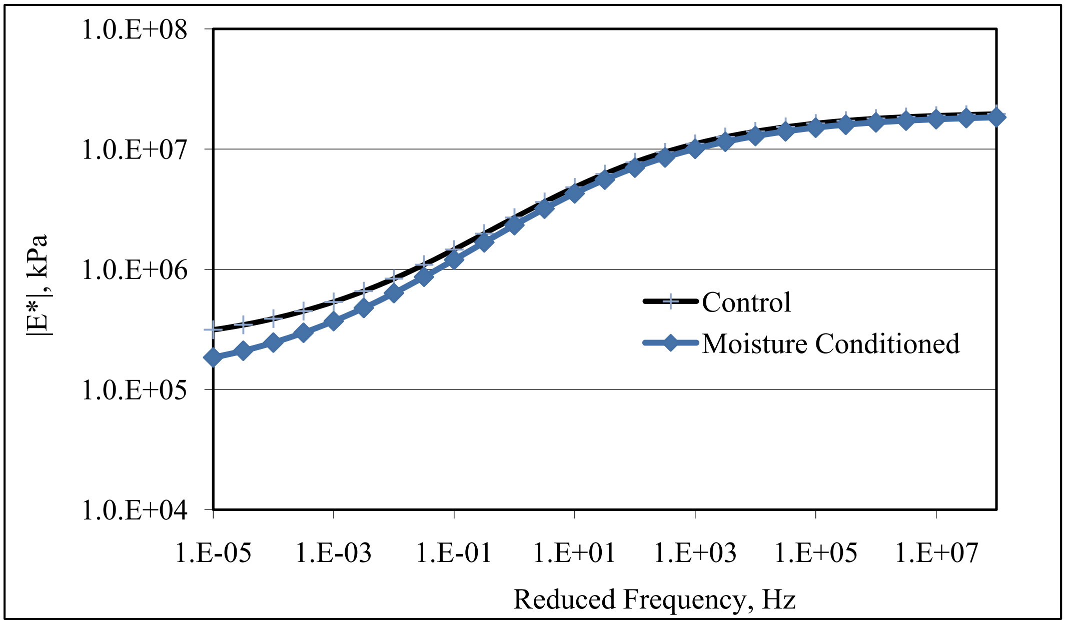


Figure 4-5 Master Curve for Mix 235I

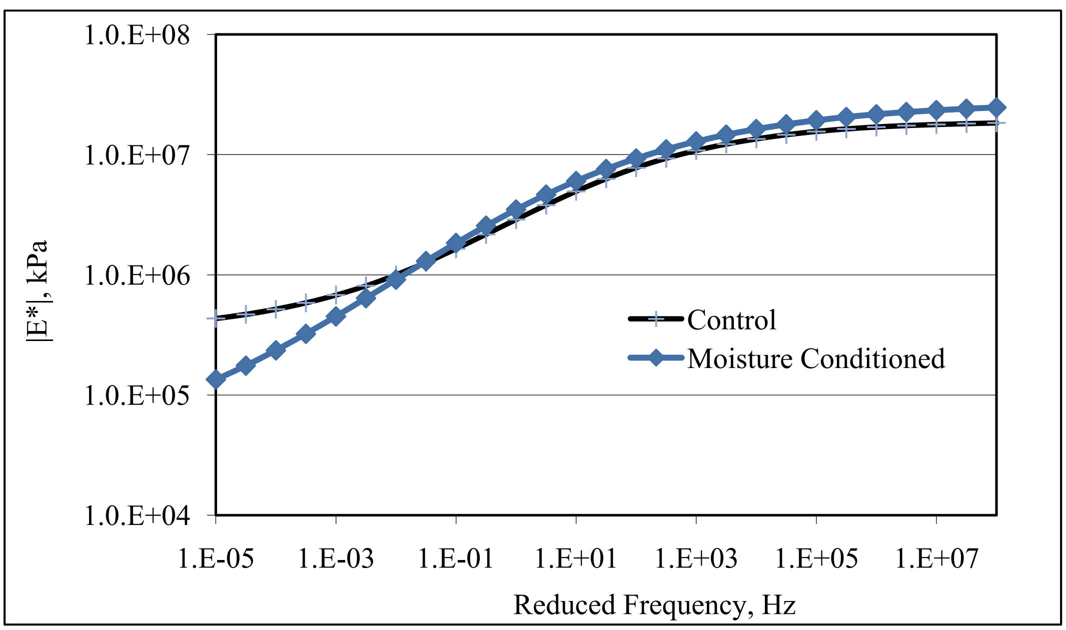


Figure 4-6 Master Curve for Mix 235S

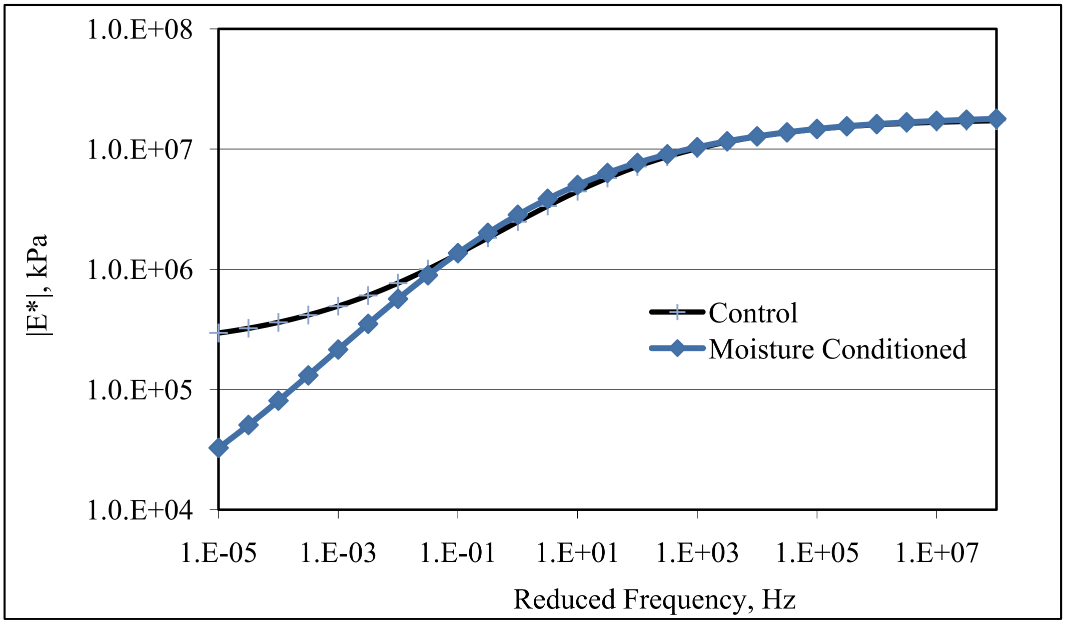


Figure 4-7 Master Curve for Mix 330B

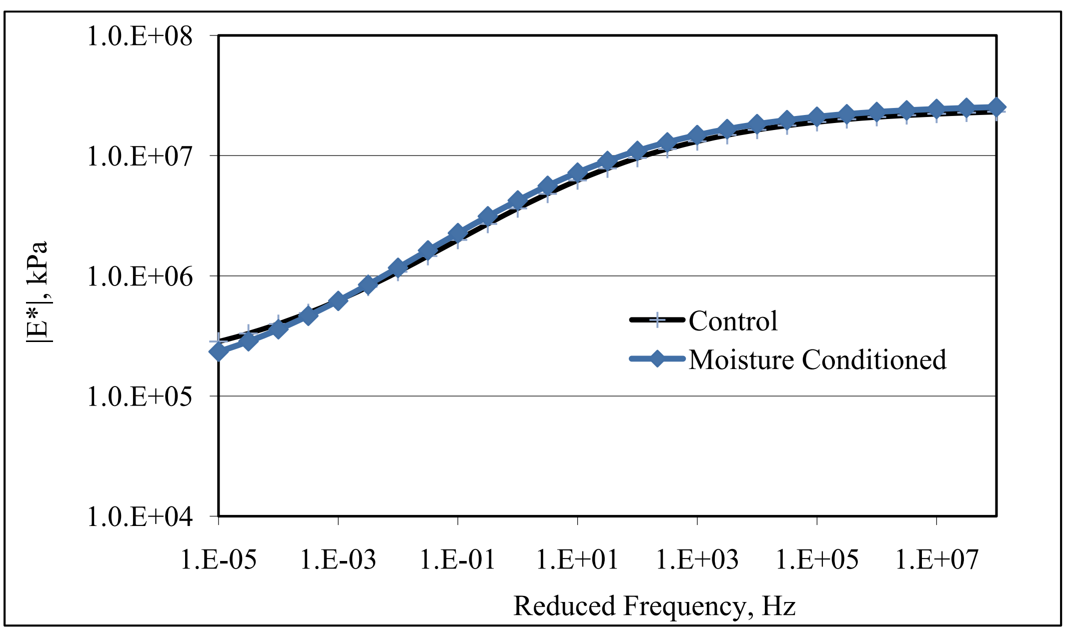


Figure 4-8 Master Curve for Mix 330I

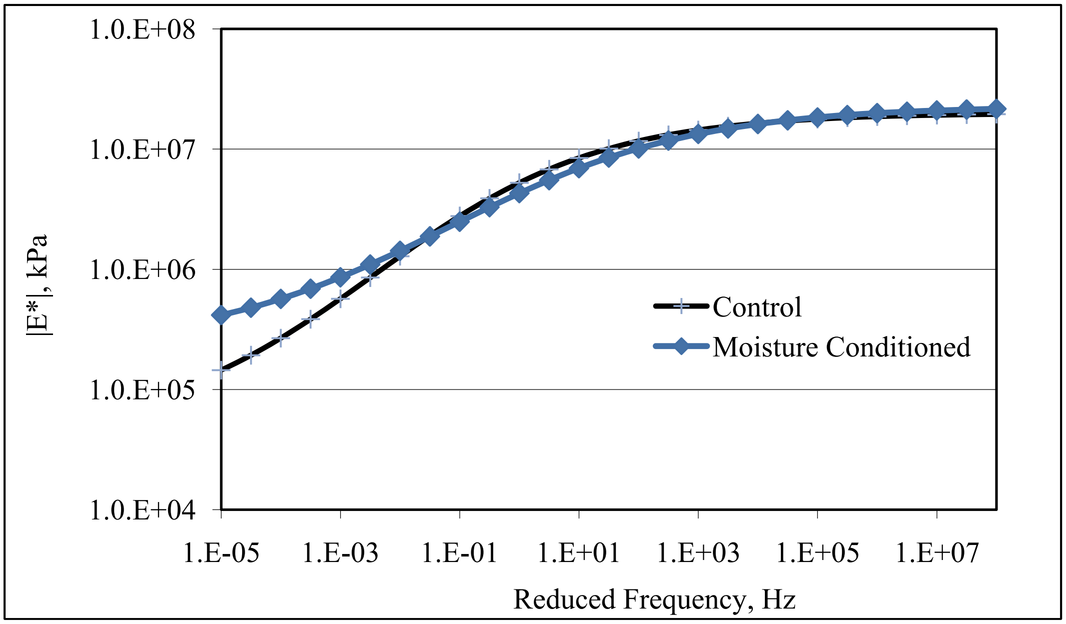


Figure 4-9 Master Curve for Mix 330S

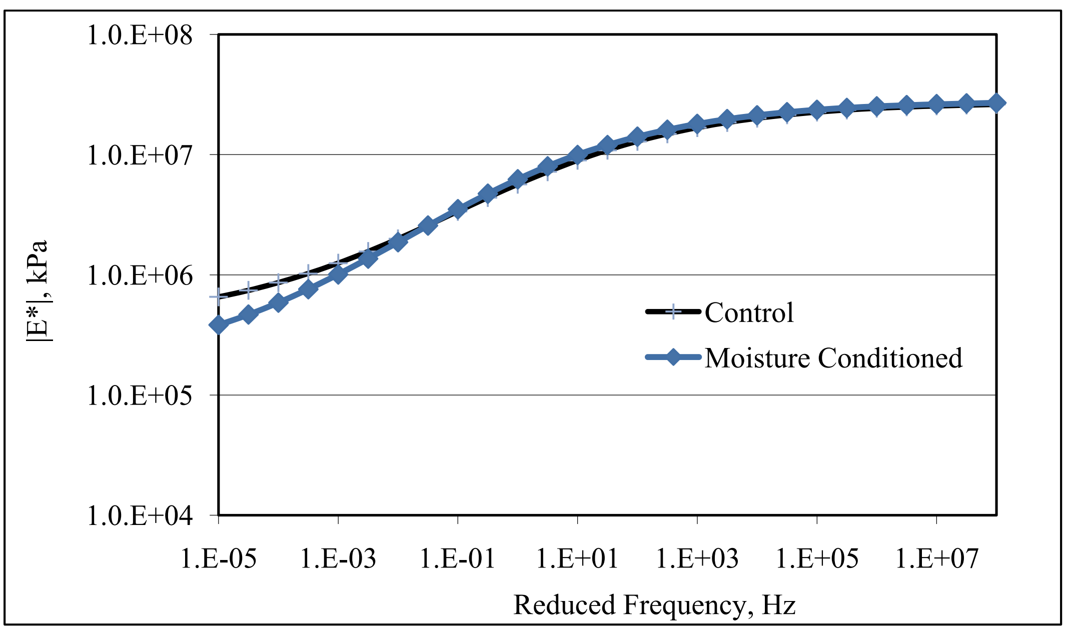


Figure 4-10 Master Curve for Mix ALT

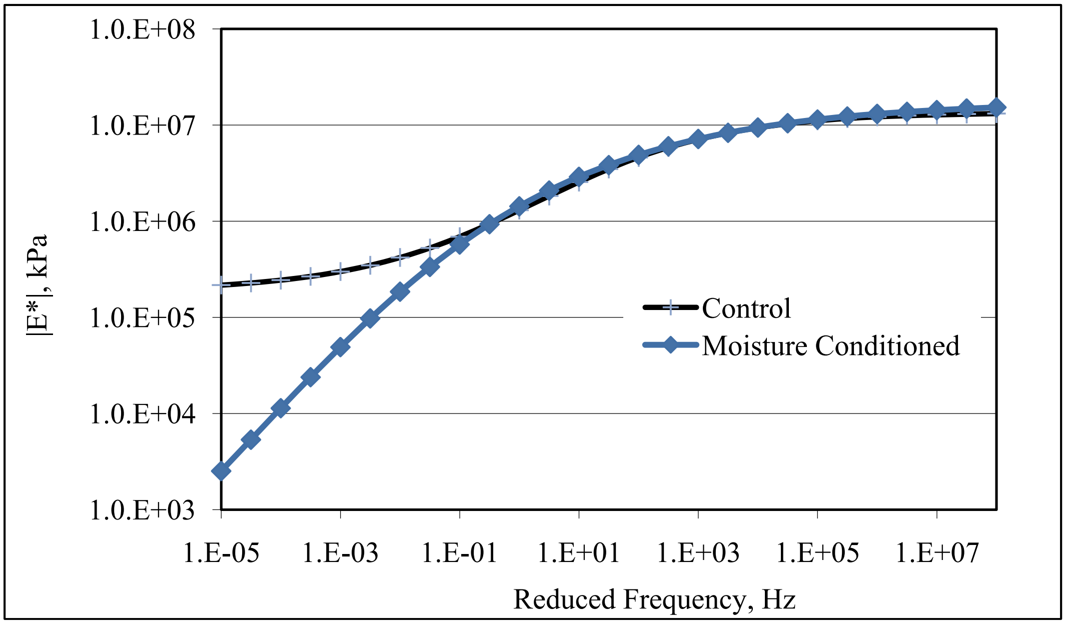


Figure 4-11 Master Curve for Mix Ded

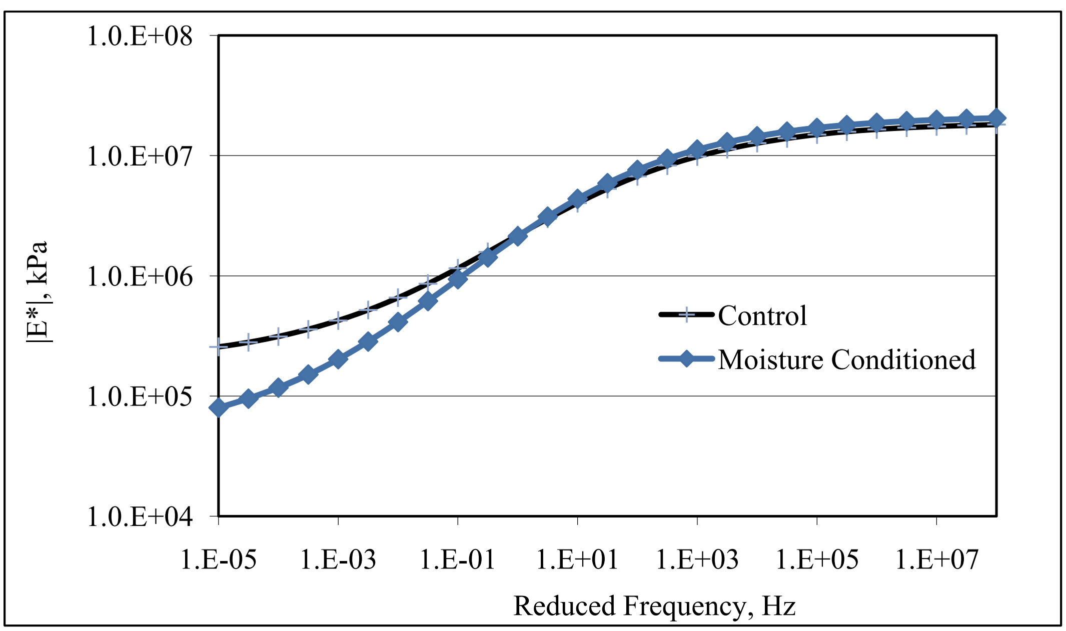


Figure 4-12 Master Curve for Mix F52

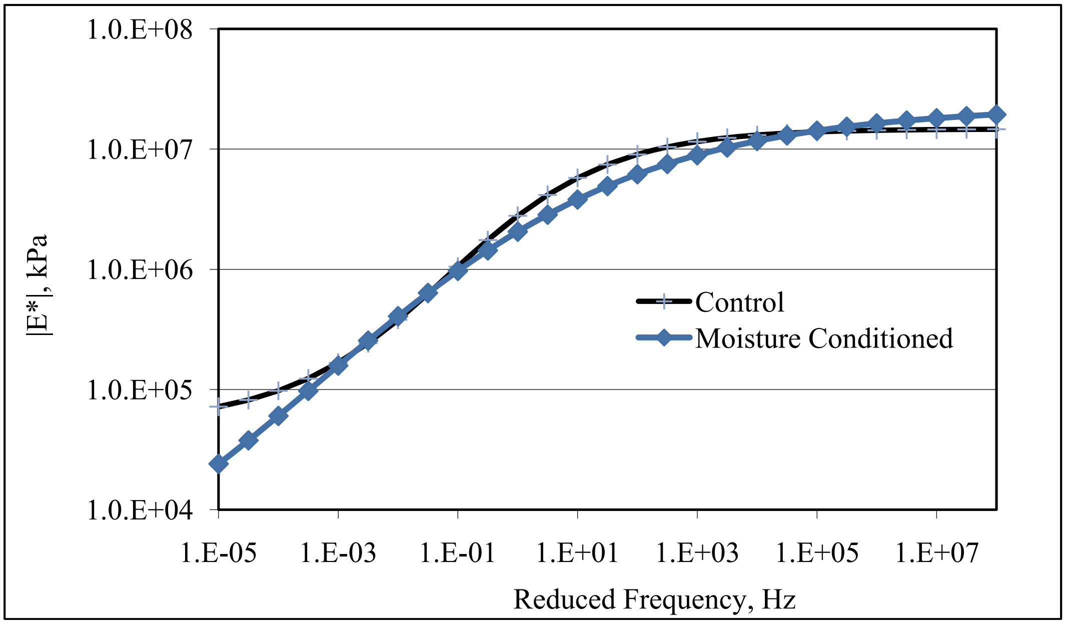


Figure 4-13 Master Curve for Mix HW4

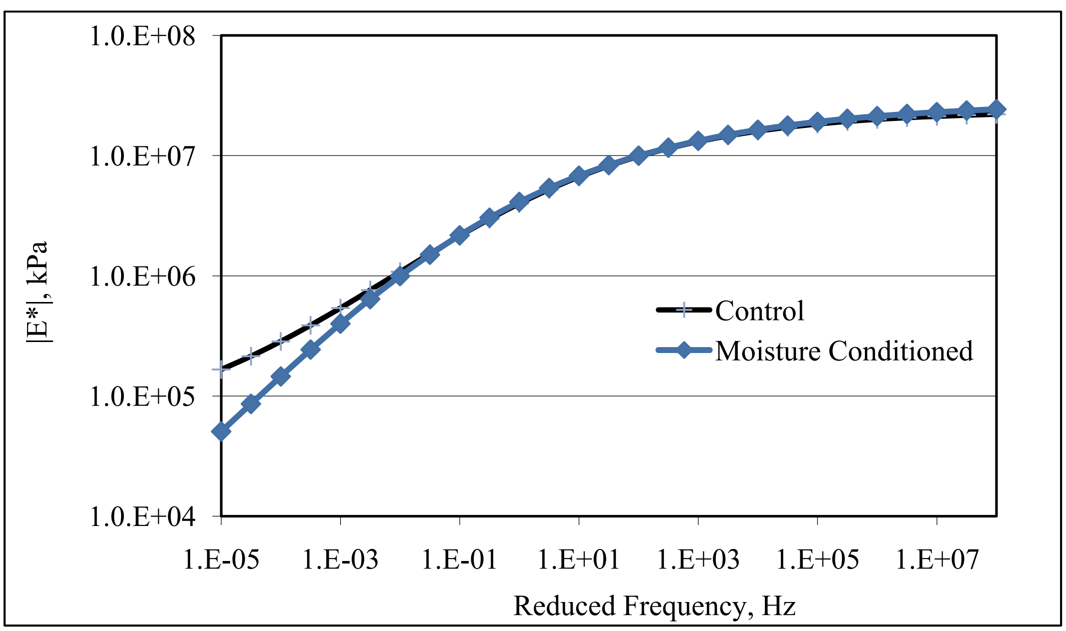


Figure 4-14 Master Curve for Mix I80B

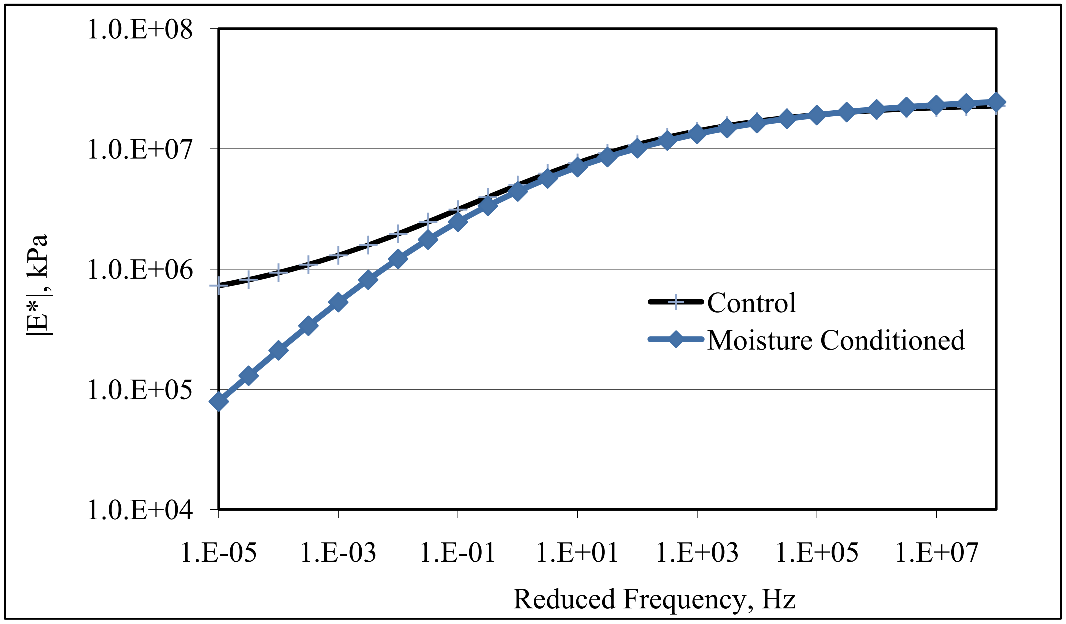


Figure 4-15 Master Curve for Mix I80S

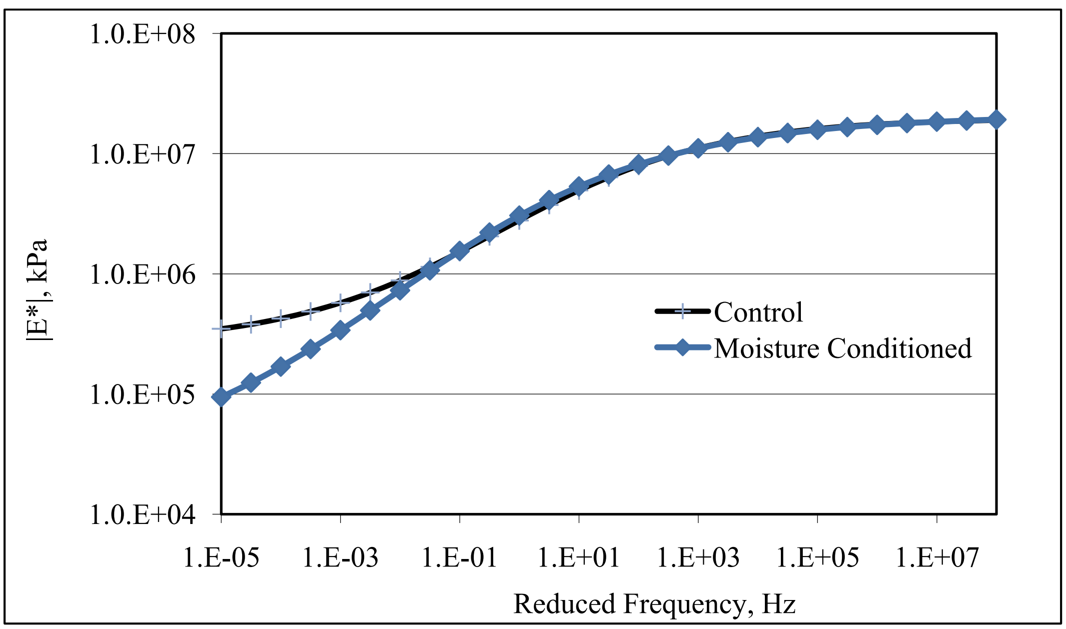


Figure 4-16 Master Curve for Mix NW

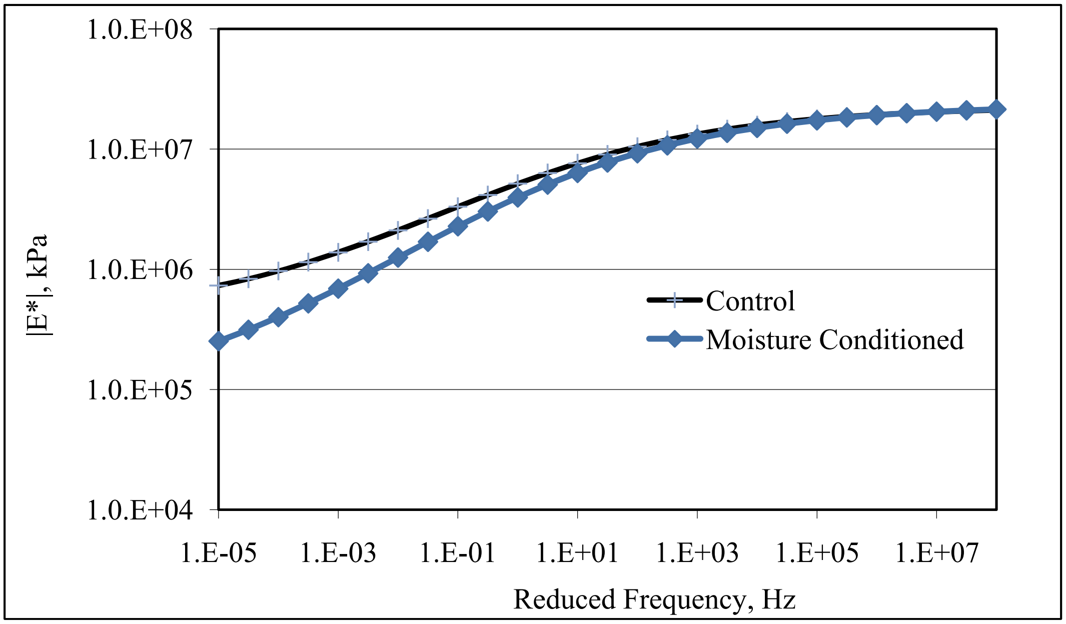


Figure 4-17 Master Curve for Mix Rose

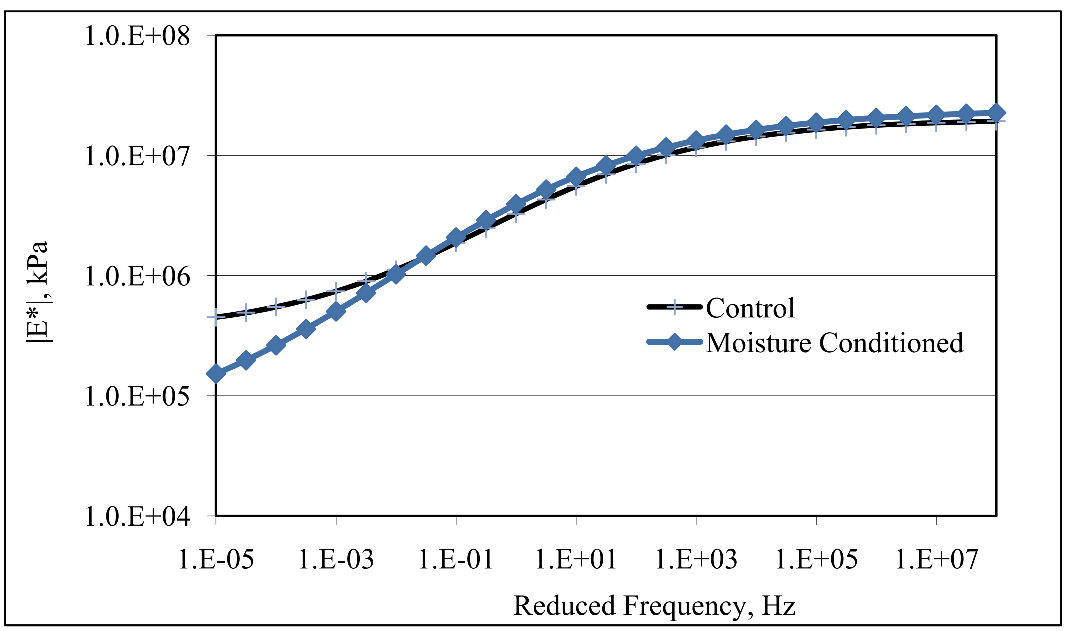


Figure 4-18 Master Curve for Mix Jewell

Table 4-9 Area Under the Master Curve (GPa.s)

Mix Name	High temperature-low frequency				Low temperature-high frequency			
	Control	Conditioned	Diff.	Ratio	Control	Conditioned	Diff.	Ratio
6N	21.36	17.13	4.24	0.80	171.93	203.46	-31.53	1.18
218	22.60	20.79	1.81	0.92	191.39	217.65	-26.25	1.14
235I	19.20	15.97	3.23	0.83	204.55	188.96	15.59	0.92
235s	21.22	22.73	-1.51	1.07	195.33	246.01	-50.69	1.26
330B	17.75	17.43	0.33	0.98	183.17	187.41	-4.25	1.02
330I	24.87	28.08	-3.21	1.13	240.96	267.49	-26.53	1.11
330s	32.76	29.96	2.80	0.91	230.22	234.06	-3.84	1.02
ALT	40.29	41.41	-1.12	1.03	288.35	302.73	-14.37	1.05
Ded	9.87	8.62	1.25	0.87	135.57	145.16	-9.60	1.07
F52	15.60	13.92	1.68	0.89	185.98	211.12	-25.14	1.14
HW4	17.31	12.79	4.52	0.74	178.18	182.19	-4.01	1.02
I80B	25.98	25.59	0.39	0.98	233.98	246.23	-12.25	1.05
I80s	36.84	28.07	8.77	0.76	246.28	247.59	-1.31	1.01
Jewell	23.77	25.41	-1.64	1.07	206.92	238.67	-31.74	1.15
NW	19.99	19.48	0.50	0.97	201.45	200.64	0.81	1.00
Rose	38.12	26.75	11.37	0.70	230.32	222.73	7.59	0.97

4.5 Storage and loss moduli

The dynamic modulus and phase angle were used to calculate the storage and loss moduli for all the mixes the storage modulus ratio is the storage modulus of the control mix divided by that of the moisture conditioned mix. Table 4-10 presents the storage modulus ratios for all the temperature-frequency combinations. The same was done for the loss modulus and the results for the loss modulus ratios are presented in Table 4-11. The results of the storage modulus ratios show that although the ratios have a trend within the same mix, there is no specific trend between the mixes. The ratios are sometimes higher than one and sometimes lower and this makes these values inconclusive when it comes to the effect on the mix performance. For the case of the loss modulus ratios, the results do not have a specific trend within the mixes.

Table 4-10 Storage Modulus Ratios

Mix Name	Temp	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
6N	4	0.96	0.92	1.01	0.89	0.85	0.84	0.78	0.82	0.75
6N	21	1.02	0.99	0.98	0.95	0.92	0.91	0.88	0.84	0.78
218	4	1.04	1.02	1.03	1.02	1.05	1.01	1.01	1.00	0.98
218	21	1.16	1.16	1.13	1.13	1.23	1.13	1.06	1.04	0.94
235I	4	0.90	0.88	0.87	0.86	0.82	0.83	0.83	0.83	0.82
235I	21	0.90	0.89	0.89	0.88	0.86	0.84	0.84	0.84	0.82
235s	4	1.15	1.13	1.14	1.13	1.18	1.13	1.11	1.11	1.09
235s	21	1.21	1.21	1.19	1.19	1.31	1.21	1.19	1.19	1.11
330B	4	0.93	0.92	0.95	0.93	0.96	0.91	0.91	0.92	0.91
330B	21	1.10	1.11	1.12	1.12	1.23	1.16	1.14	1.03	1.04
330I	4	1.07	1.03	1.04	1.03	1.02	1.02	0.99	1.02	0.99
330I	21	1.17	1.17	1.16	1.16	1.15	1.18	1.17	1.14	1.15
330s	4	0.99	0.99	0.98	0.97	0.96	0.93	0.92	0.91	0.87
330s	21	0.84	0.82	0.81	0.81	0.78	0.79	0.83	0.85	0.84
ALT	4	0.99	0.98	0.98	0.97	0.96	0.95	0.95	0.94	0.91
ALT	21	1.11	1.11	1.11	1.10	1.10	1.08	1.08	1.07	1.02
Ded	4	0.90	0.90	0.91	0.92	0.93	0.85	0.88	0.86	0.90
Ded	21	1.12	1.12	1.12	1.11	1.25	1.07	1.05	0.91	0.81
F52	4	1.01	1.01	1.02	1.02	0.97	0.95	0.96	0.91	0.73
F52	21	1.10	1.08	1.06	1.04	1.05	1.01	0.92	0.82	0.80
HW4	4	0.92	0.91	0.90	0.89	0.86	0.86	0.85	0.84	0.87
HW4	21	0.66	0.65	0.65	0.65	0.61	0.67	0.74	0.79	0.79
I80B	4	1.01	1.01	1.02	1.01	1.00	1.00	0.99	0.98	1.00
I80B	21	0.98	1.03	1.03	1.03	1.03	1.04	1.07	1.00	0.99
I80s	4	0.93	0.88	0.91	0.89	0.91	0.86	0.86	0.86	0.81
I80s	21	0.90	0.92	0.92	0.90	0.93	0.86	0.83	0.82	0.75
Jewell	4	0.91	0.89	0.89	0.89	0.92	0.88	0.86	0.87	0.86
Jewell	21	1.06	1.07	1.07	1.07	1.18	1.10	1.07	1.06	1.08
NW	4	0.94	0.88	0.88	0.89	0.86	0.84	0.82	0.83	0.77
NW	21	0.84	0.83	0.83	0.81	0.77	0.73	0.72	0.69	0.65
Rose	4	1.05	1.03	1.04	1.00	1.06	1.00	0.99	1.00	0.96
Rose	21	1.19	1.19	1.17	1.17	1.28	1.19	1.17	1.15	1.16

Table 4-11 Loss Modulus Ratios

Mix Name	Temp	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
6N	4	1.77	1.12	1.26	1.08	1.07	0.98	0.89	0.95	1.05
6N	21	1.16	1.12	1.11	1.08	1.05	1.03	1.02	0.99	0.86
218	4	1.24	1.04	1.12	1.09	1.12	1.11	1.07	1.07	1.22
218	21	1.20	1.18	1.16	1.15	1.20	1.14	1.10	1.07	0.94
235I	4	1.13	1.02	1.01	0.99	1.02	0.93	1.00	1.00	1.00
235I	21	0.98	0.97	0.97	0.95	0.91	0.90	0.86	0.89	0.85
235s	4	1.06	1.05	1.06	1.06	1.13	1.11	1.02	1.08	1.13
235s	21	1.20	1.19	1.20	1.19	1.25	1.22	1.13	1.22	1.10
330B	4	0.91	1.00	1.02	0.97	1.00	0.90	0.95	1.03	1.19
330B	21	1.16	1.11	1.12	1.12	1.19	1.16	1.04	1.06	1.04
330I	4	1.31	1.16	1.14	1.13	1.09	1.07	1.05	1.12	1.36
330I	21	1.18	1.17	1.16	1.16	1.11	1.16	1.10	1.12	1.15
330s	4	1.19	1.15	1.19	1.24	1.27	1.20	1.21	1.25	1.36
330s	21	0.94	0.91	0.92	0.93	0.88	0.93	0.94	1.03	1.09
ALT	4	2.23	1.26	1.14	1.09	1.07	1.07	1.10	1.14	1.27
ALT	21	1.16	1.15	1.14	1.13	1.11	1.14	1.15	1.11	1.08
Ded	4	1.01	0.95	0.96	0.95	1.00	0.82	0.85	0.90	1.17
Ded	21	1.14	1.10	1.10	1.10	1.24	1.09	1.05	0.94	0.92
F52	4	1.40	1.12	1.11	1.12	1.11	1.00	1.03	0.98	1.34
F52	21	1.16	1.14	1.14	1.10	1.06	1.07	1.02	0.93	0.85
HW4	4	1.12	1.10	1.05	1.04	1.08	0.96	0.99	0.93	0.96
HW4	21	0.77	0.77	0.80	0.85	0.79	0.92	1.09	1.18	1.25
I80B	4	1.23	1.20	1.14	1.11	1.12	1.09	1.02	0.97	1.04
I80B	21	0.96	1.01	1.04	1.05	1.04	1.04	1.02	0.99	1.05
I80s	4	1.61	1.14	1.16	1.11	1.10	1.00	1.01	1.09	1.24
I80s	21	1.03	1.06	1.05	1.02	1.08	0.98	0.98	0.97	0.93
Jewell	4	1.14	1.04	1.01	1.00	1.01	0.95	0.95	0.96	1.02
Jewell	21	1.02	1.05	1.05	1.05	1.15	1.06	1.04	1.03	0.97
NW	4	1.36	1.19	1.07	1.19	1.16	1.08	1.16	1.33	1.41
NW	21	1.10	1.07	1.06	1.02	0.97	0.93	0.92	0.95	0.85
Rose	4	1.24	1.13	1.16	1.11	1.22	1.06	1.02	1.06	1.23
Rose	21	1.24	1.22	1.21	1.21	1.28	1.21	1.17	1.11	1.05

4.6 Comparison between E* ratio and master curve

A paired t-test was used to compare the significance of the difference between the dynamic modulus results of the conditioned and the unconditioned group. A similar comparison was done to compare the difference between the master curves of both groups. The results of both comparisons are presented in Table 4-12 with a level of significance (α) = 0.05. The results show that the two methods yield different conclusions for some of the mixes.

Table 4-12 Statistical Comparisons for E* and Master Curves

Mix Name	Dynamic Modulus		Master Curve	
	α	Indication	α	Indication
6N	**0.0009**	**Statistically different**	**0.0075**	**Statistically different**
218	**0.0001**	**Statistically different**	**0.0006**	**Statistically different**
235I	**<0.0001**	**Statistically different**	**<0.0001**	**Statistically different**
235s	**<0.0001**	**Statistically different**	**<0.0001**	**Statistically different**
330B	0.2910	Statistically the Same	0.0225	Statistically the Same
330I	**<0.0001**	**Statistically different**	**<0.0001**	**Statistically different**
330s	**<0.0001**	**Statistically different**	0.8558	Statistically the Same
ALT	0.7355	Statistically the Same	**<0.0001**	**Statistically different**
Ded	0.0618	Statistically the Same	**0.0216**	**Statistically different**
F52	0.8781	Statistically the Same	**0.0003**	**Statistically different**
HW4	**<0.0001**	**Statistically different**	0.9622	Statistically the Same
I80B	0.0124	Statistically the Same	**0.0032**	**Statistically different**
I80s	**<0.0001**	**Statistically different**	0.0666	Statistically the Same
Jewell	**<0.0001**	**Statistically different**	**<0.0001**	**Statistically different**
NW	**0.0208**	**Statistically different**	0.2803	Statistically the Same
Rose	**<0.0001**	**Statistically different**	**<0.0001**	**Statistically different**

4.7 Dynamic modulus test conclusions

The dynamic modulus ratio gives a good evaluation for the moisture susceptibility of the mixes. It provides a distinction between the mixes and the results can be used in modeling the mix performance. The E* ratio results are dependent on the testing conditions (temperature and frequency). This means that the results from the dynamic modulus test need to be coupled with some evaluation tool related to the expected in-situ conditions of the pavement. This implies that simulation is necessary in this case. This can be done either by modeling or by simulating the results in the M-EPDG. Another easy approach that can be used is to plot the master curve of the control and conditioned groups then compare the results to have a visual representation of the effect of moisture on the various working conditions. The area under the master curve can be used to quantify the effect of moisture damage provided that a range of frequencies be selected to reflect the expected aite conditions for the pavement. The phase angle ratios show that the materials tend to be more viscous with moisture conditioning. The storage and loss moduli ratios are not recommended as tools to evaluate moisture damage because of the scatter in the data and the mixed results.

CHAPTER 5 FLOW NUMBER TEST RESULTS AND ANALYSIS

5.1 Test results

In this chapter, the flow number results are presented and discussed. As mentioned earlier in the experimental plan, the test followed the NCHRP report 465 (Witzack et al. 2002) and NCHRP report 513 (Bonaquist et al. 2003) procedure and calculation method. The calculation method was discussed in the literature review. The flow number test is known for its variability. The test is also known to be a good representation of the field's loading conditions. Good simulation of the field loading conditions was the reason for including this test in this study. Several outputs, other than the flow number can be calculated from this test. The number of cycles at which the test stops, the total strain at the end of the test, the flow number, and the strain at the flow number are general outputs that can be calculated from this test. These results are shown in Tables 5-1 through 5-5. By looking at the results, the following can be concluded. The number of cycles at which the test ends is not a reliable measure because it occurs either by the specimen failure or by reaching the machine test limit, which is 40,000 cycles. The strain at failure is constant when the sample reaches failure. The flow number is the main output of this test and it can be seen that it has very high variability, the same goes with the strain at flow number.

The previous discussion leads to the need to have a different analysis method for the test. Two approaches were incorporated in this study. The first approach was to have a designated strain level and to get the corresponding number of cycles. A strain level of 30,000 microstrain was selected for this purpose. The second approach was to apply the Ohio State Model on the test results and see if the parameters "A" and "m" are affected by moisture conditioning or not. Mainly parameter "m" was taken into consideration because this parameter is a function of the material properties as discussed in the literature review.

Table 5-1 Flow Number Results for Control Samples

Mix		Cycles to Failure	Strain at failure (microstrain)	Flow Number (FN)	Strain at FN (microstrain)	Cycles at 30,000 microstrain	A	m
6N	Mean	10482	100158	1761	10109.5	6778	1.96E-04	0.5515
6N	Std	6829	113	1137	662.4	4553	3.40E-05	0.0815
6N	CoV (%)	65.1	0.1	64.6	6.6	67.2	17.4	14.8
218	Mean	2936	100713	534	10046.8	1709	1.62E-04	0.6571
218	Std	620	1086	118	1205.8	376	1.44E-05	0.0182
218	CoV (%)	21.1	1.1	22.1	12.0	22.0	8.9	2.8
235I	Mean	9828	100103	2522	15799.7	5648	2.71E-04	0.5182
235I	Std	1395	43	474	1142.7	882	6.13E-05	0.0158
235I	CoV (%)	14.2	0.0	18.8	7.2	15.6	22.6	3.1
235S	Mean	37063	72736	14840	15164.5	28798	1.58E-04	0.4710
235S	Std	4448	28004	4645	1318.3	6442	1.95E-05	0.0066
235S	CoV (%)	12.0	38.5	31.3	8.7	22.4	12.3	1.4
330B	Mean	1337	102026	248	10413.7	760	2.08E-04	0.7088
330B	Std	157	964	48	1385.3	107	2.05E-05	0.0073
330B	CoV (%)	11.7	0.9	19.2	13.3	14.1	9.8	1.0
330I	Mean	4033	100375	876	10038.9	2719	1.64E-04	0.6037
330I	Std	238	76	104	1276.7	179	1.89E-05	0.0081
330I	CoV (%)	5.9	0.1	11.9	12.7	6.6	11.5	1.3
330S	Mean	31353	53670	19533	12968.3	28392	1.20E-04	0.4918
330S	Std	11892	43193	15275	1840.9	14644	2.05E-05	0.0380
330S	CoV (%)	37.9	80.5	78.2	14.2	51.6	17.1	7.7
Alt	Mean	34361	48319	12990	8988.1	31893	1.58E-04	0.4326
Alt	Std	7922	47323	6881	726.5	11168	3.32E-05	0.0181
Alt	CoV (%)	23.1	97.9	53.0	8.1	35.0	21.0	4.2
Ded	Mean	583	101831	206	30704.3	317	3.24E-04	0.8072
Ded	Std	161	1525	154	38352.8	98	1.50E-04	0.1856
Ded	CoV (%)	27.6	1.5	75.0	124.9	30.8	46.2	23.0
F52	Mean	1191	102520	290	9838.8	855	2.39E-04	0.6593
F52	Std	311	1292	88	847.8	217	1.64E-05	0.0204
F52	CoV (%)	26.1	1.3	30.5	8.6	25.4	6.9	3.1
HW4	Mean	8485	101288	1941	11437.2	6062	2.69E-04	0.6229
HW4	Std	11163	1517	2461	941.8	8134	9.72E-05	0.1248
HW4	CoV (%)	131.6	1.5	126.8	8.2	134.2	36.1	20.0
I80B	Mean	4780	100298	963	9372.0	3191	1.27E-04	0.6248
I80B	Std	599	146	224	1103.6	428	1.24E-05	0.0197
I80B	CoV (%)	12.5	0.1	23.3	11.8	13.4	9.8	3.2

Table 5-1 (continued)

Mix		Cycles to Failure	Strain at failure (microstrain)	Flow Number (FN)	Strain at FN (microstrain)	Cycles at 30,000 microstrain	A	m
I80S	Mean	30645	48972	10912	9866.9	28519	4.17E-04	0.3883
I80S	Std	12830	46700	13892	4183.0	15730	4.43E-04	0.0871
I80S	CoV (%)	41.9	95.4	127.3	42.4	55.2	106.1	22.4
Jewell	Mean	5484	100171	1515	16423.7	3135	3.35E-04	0.5307
Jewell	Std	1048	61	393	2316.0	672	6.93E-05	0.0241
Jewell	CoV (%)	19.1	0.1	25.9	14.1	21.4	20.7	4.5
NW	Mean	3211	100293	701	11935.1	1930	2.26E-04	0.6048
NW	Std	627	131	193	1206.5	422	9.91E-06	0.0202
NW	CoV (%)	19.5	0.1	27.6	10.1	21.9	4.4	3.3
Rose	Mean	34169	45509	5640	6748.6	30984	1.07E-04	0.4629
Rose	Std	7984	52628	3488	5326.6	12334	3.07E-05	0.0734
Rose	CoV (%)	23.4	115.6	61.9	78.9	39.8	28.7	15.9

Table 5-2 Flow Number Results for Water Conditioned Samples Tested Under Water

Mix		Cycles to Failure	Strain at failure (microstrain)	Flow Number (FN)	Strain at FN (microstrain)	Cycles at 30,000 microstrain	A	m
6N	Mean	1733	100601	539	18394.4	971	6.44E-04	0.5348
6N	Std	319	205	289	5026.3	202	1.00E-04	0.0184
6N	CoV (%)	18.4	0.2	53.6	27.3	20.8	15.6	3.4
218	Mean	2893	100225	648	16453.2	1473	5.69E-04	0.5179
218	Std	693	101	109	2110.8	385	6.71E-05	0.0202
218	CoV (%)	24.0	0.1	16.8	12.8	26.1	11.8	3.9
235I	Mean	11120	100114	3398	23700.2	5159	1.09E-03	0.3766
235I	Std	3657	27	1318	4027.8	1962	1.47E-04	0.0204
235I	CoV (%)	32.9	0.0	38.8	17.0	38.0	13.5	5.4
235S	Mean	30867	100091	13245	22644.8	19513	7.36E-04	0.3573
235S	Std	3483	38	6130	6419.6	2450	3.10E-04	0.0562
235S	CoV (%)	11.3	0.0	46.3	28.3	12.6	42.1	15.7
330B	Mean	920	100642	227	17567.4	436	5.35E-04	0.6457
330B	Std	70	62	20	836.0	42	1.15E-04	0.0369
330B	CoV (%)	7.7	0.1	8.8	4.8	9.6	21.5	5.7
330I	Mean	6522	100380	1274	11350.0	4636	7.47E-04	0.3805
330I	Std	1317	223	154	1152.4	841	1.22E-04	0.0171
330I	CoV (%)	20.2	0.2	12.1	10.2	18.1	16.3	4.5

Table 5-2 (continued)

Mix		Cycles to Failure	Strain at failure (microstrain)	Flow Number (FN)	Strain at FN (microstrain)	Cycles at 30,000 microstrain	A	m
330S	Mean	4521	100223	1150	17129.3	2502	7.24E-04	0.4572
330S	Std	642	82	281	3034.7	465	3.26E-04	0.0381
330S	CoV (%)	14.2	0.1	24.4	17.7	18.6	45.1	8.3
Alt	Mean	29370	44178	6085	10011.4	24831	8.58E-04	0.3022
Alt	Std	17337	36708	5257	4873.2	15801	1.81E-04	0.0301
Alt	CoV (%)	59.0	83.1	86.4	48.7	63.6	21.1	10.0
Ded	Mean	272	101854	77	22384.1	115	1.27E-03	0.6711
Ded	Std	40	350	11	1433.8	22	4.73E-04	0.0479
Ded	CoV (%)	14.8	0.3	14.8	6.4	19.5	37.2	7.1
F52	Mean	796	101482	209	13805.9	519	8.26E-04	0.5276
F52	Std	153	308	48	1018.5	118	6.41E-05	0.0227
F52	CoV (%)	19.2	0.3	23.1	7.4	22.8	7.8	4.3
HW4	Mean	742	100792	199	21502.0	315	9.48E-04	0.5919
HW4	Std	94	157	54	3861.2	61	1.52E-04	0.0446
HW4	CoV (%)	12.6	0.2	26.9	18.0	19.4	16.0	7.5
I80B	Mean	11541	100117	3106	17036.8	6928	8.85E-04	0.3759
I80B	Std	1637	46	2248	3093.7	1734	3.02E-04	0.0436
I80B	CoV (%)	14.2	0.0	72.4	18.2	25.0	34.1	11.6
I80S	Mean	12408	100206	1797	16057.6	7059	8.58E-04	0.3934
I80S	Std	11020	248	265	4354.3	6615	2.91E-04	0.0640
I80S	CoV (%)	88.8	0.2	14.7	27.1	93.7	34.0	16.3
Jewell	Mean	7321	100150	1602	15512.0	4275	8.47E-04	0.3956
Jewell	Std	1191	51	300	1793.6	642	2.10E-04	0.0293
Jewell	CoV (%)	16.3	0.1	18.7	11.6	15.0	24.8	7.4
NW	Mean	4863	100206	1135	18815.5	2455	1.09E-03	0.4117
NW	Std	878	92	333	5061.9	626	4.56E-04	0.0438
NW	CoV (%)	18.1	0.1	29.3	26.9	25.5	41.8	10.6
Rose	Mean	9237	100287	2325	16733.8	5462	6.59E-04	0.4153
Rose	Std	2756	157	549	1451.1	1280	4.57E-05	0.0126
Rose	CoV (%)	29.8	0.2	23.6	8.7	23.4	6.9	3.0

Table 5-3 Flow Number Results for Freezer Conditioned Samples Tested in Air

Mix		Cycles to Failure	Strain at failure (microstrain)	Flow Number (FN)	Strain at FN (microstrain)	Cycles at 30,000 microstrain	A	m
6N	Mean	7266	100233	2194	15860.6	4177	4.76E-04	0.5088
6N	Std	9273	124	3234	2481.7	5397	2.19E-04	0.0554
6N	CoV (%)	127.6	0.1	147.4	15.6	129.2	46.1	10.9
218	Mean	2659	100253	494	9715.5	1621	2.14E-04	0.6210
218	Std	534	49	126	1889.8	359	5.97E-05	0.0534
218	CoV (%)	20.1	0.0	25.4	19.5	22.2	27.9	8.6
235I	Mean	14568	100095	4146	18134.5	7964	4.43E-04	0.4512
235I	Std	6431	38	2381	3629.1	3533	1.38E-04	0.0124
235I	CoV (%)	44.1	0.0	57.4	20.0	44.4	31.2	2.8
235S	Mean	31344	68986	16603	16883.5	26316	3.10E-04	0.4289
235S	Std	11434	42610	12112	1605.3	13970	1.51E-04	0.0629
235S	CoV (%)	36.5	61.8	72.9	9.5	53.1	48.8	14.7
330B	Mean	1063	100690	229	13476.8	564	3.18E-04	0.6905
330B	Std	136	62	24	764.6	87	5.18E-05	0.0231
330B	CoV (%)	12.8	0.1	10.4	5.7	15.3	16.3	3.3
330I	Mean	6044	100278	1332	9936.4	4274	2.29E-04	0.5229
330I	Std	619	77	477	3961.1	336	8.37E-05	0.0212
330I	CoV (%)	10.2	0.1	35.8	39.9	7.9	36.6	4.1
330S	Mean	18210	77861	5200	13417.8	12681	4.36E-04	0.4793
330S	Std	19901	33817	6425	2866.0	14246	3.66E-04	0.0955
330S	CoV (%)	109.3	43.4	123.6	21.4	112.3	83.9	19.9
Alt	Mean	27123	43836	8250	10750.5	25081	4.12E-04	0.3748
Alt	Std	8202	34436	5164	3314.9	9531	2.38E-04	0.0624
Alt	CoV (%)	30.2	78.6	62.6	30.8	38.0	57.8	16.7
Ded	Mean	612	101324	170	19808.6	289	7.40E-04	0.6398
Ded	Std	51	151	17	1262.3	19	8.96E-05	0.0273
Ded	CoV (%)	8.4	0.1	10.2	6.4	6.7	12.1	4.3
F52	Mean	956	101948	218	9280.3	689	3.09E-04	0.6364
F52	Std	196	244	74	1632.7	148	5.82E-05	0.0370
F52	CoV (%)	20.5	0.2	34.1	17.6	21.4	18.8	5.8
HW4	Mean	4142	100542	1007	16740.1	2426	5.55E-04	0.5559
HW4	Std	6490	256	1539	588.6	3961	6.68E-05	0.0843
HW4	CoV (%)	156.7	0.3	152.9	3.5	163.3	12.0	15.2
I80B	Mean	10813	100190	2089	9283.4	7658	2.17E-04	0.5276
I80B	Std	5209	68	1310	4097.3	4047	1.49E-04	0.1042
I80B	CoV (%)	48.2	0.1	62.7	44.1	52.8	68.6	19.7

Table 5-3 (continued)

Mix		Cycles to Failure	Strain at failure (microstrain)	Flow Number (FN)	Strain at FN (microstrain)	Cycles at 30,000 microstrain	A	m
I80S	Mean	15532	100140	4849	14312.7	10302	2.32E-04	0.5011
I80S	Std	9485	69	4137	2847.1	6917	7.86E-05	0.0581
I80S	CoV (%)	61.1	0.1	85.3	19.9	67.1	33.8	11.6
Jewell	Mean	4460	82266	1133	10999.1	2941	3.39E-04	0.5291
Jewell	Std	1737	40083	292	2251.2	979	1.99E-04	0.1143
Jewell	CoV (%)	39.0	48.7	25.8	20.5	33.3	58.9	21.6
NW	Mean	5011	100178	1186	13828.5	2981	3.50E-04	0.5192
NW	Std	1040	71	324	1936.1	699	6.08E-05	0.0338
NW	CoV (%)	20.8	0.1	27.3	14.0	23.5	17.4	6.5
Rose	Mean	19326	102306	4348	15918.6	11493	3.50E-04	0.4601
Rose	Std	11810	4954	3013	4389.7	7806	9.78E-05	0.0392
Rose	CoV (%)	61.1	4.8	69.3	27.6	67.9	27.9	8.5

Table 5-4 Flow Number Results for Freezer Conditioned Samples Tested Under Water

Mix		Cycles to Failure	Strain at failure (microstrain)	Flow Number (FN)	Strain at FN (microstrain)	Cycles at 30,000 microstrain	A	M
6N	Mean	5374	100289	1085	13192.7	3414	5.79E-04	0.4536
6N	Std	2570	72	450	2811.4	1819	1.80E-04	0.0247
6N	CoV (%)	47.8	0.1	41.5	21.3	53.3	31.1	5.4
218	Mean	3499	100200	732	12925.8	1991	3.32E-04	0.5585
218	Std	173	52	98	1615.2	81	9.29E-05	0.0397
218	CoV (%)	4.9	0.1	13.3	12.5	4.0	28.0	7.1
235I	Mean	20844	100056	3447	11771.7	12639	5.11E-04	0.4430
235I	Std	9582	289	1828	5942.8	4783	3.91E-04	0.1472
235I	CoV (%)	46.0	0.3	53.0	50.5	37.8	76.6	33.2
235S	Mean	39696	51494	13895	14446.7	31893	5.09E-04	0.3470
235S	Std	680	31811	5853	4838.6	5335	1.70E-04	0.0378
235S	CoV (%)	1.7	61.8	42.1	33.5	16.7	33.3	10.9
330B	Mean	3449	94900	791	16126.5	1663	4.12E-04	0.5750
330B	Std	1016	11876	323	2220.3	641	2.30E-04	0.0981
330B	CoV (%)	29.5	12.5	40.9	13.8	38.5	55.8	17.1
330I	Mean	12863	100184	3992	13671.1	9113	4.05E-04	0.4204
330I	Std	1480	92	1129	2637.5	1037	9.91E-05	0.0328
330I	CoV (%)	11.5	0.1	28.3	19.3	11.4	24.5	7.8

Table 5-4 (continued)

Mix		Cycles to Failure	Strain at failure (microstrain)	Flow Number (FN)	Strain at FN (microstrain)	Cycles at 30,000 microstrain	A	m
330S	Mean	26165	50252	5420	11642.7	25015	8.90E-04	0.3077
330S	Std	17400	45863	3966	4570.3	18959	2.70E-04	0.0788
330S	CoV (%)	66.5	91.3	73.2	39.3	75.8	30.3	25.6
Alt	Mean	40000	15018	35335	11674.3	33927	3.93E-04	0.3634
Alt	Std	0	3311	4366	2745.4	13562	3.49E-04	0.0861
Alt	CoV (%)	0.0	22.0	12.4	23.5	40.0	88.6	23.7
Ded	Mean	994	100736	245	17923.5	484	6.25E-04	0.6274
Ded	Std	176	296	77	4548.7	121	2.99E-04	0.0610
Ded	CoV (%)	17.7	0.3	31.4	25.4	24.9	47.8	9.7
F52	Mean	1496	101070	414	13077.5	998	6.19E-04	0.5267
F52	Std	734	329	298	3155.3	480	1.99E-04	0.0625
F52	CoV (%)	49.1	0.3	72.0	24.1	48.1	32.2	11.9
HW4	Mean	5723	96944	2153	19910.5	3304	6.68E-04	0.5115
HW4	Std	8186	7813	3571	2591.8	5063	1.76E-04	0.0869
HW4	CoV (%)	143.0	8.1	165.9	13.0	153.2	26.4	17.0
I80B	Mean	18615	100103	3167	9518.9	13432	4.71E-04	0.3725
I80B	Std	3885	24	1192	2745.1	3576	1.20E-04	0.0153
I80B	CoV (%)	20.9	0.0	37.6	28.8	26.6	25.4	4.1
I80S	Mean	24347	68181	8990	12669.6	20032	5.40E-04	0.3889
I80S	Std	12389	43780	8766	3521.3	13401	4.45E-04	0.0656
I80S	CoV (%)	50.9	64.2	97.5	27.8	66.9	82.3	16.9
Jewell	Mean	10510	69888	2479	14184.5	7326	8.90E-04	0.3600
Jewell	Std	3520	41818	566	3064.1	1651	3.93E-04	0.0648
Jewell	CoV (%)	33.5	59.8	22.8	21.6	22.5	44.1	18.0
NW	Mean	6707	100120	1973	21244.7	3234	7.76E-04	0.4398
NW	Std	1178	44	696	1776.9	917	2.05E-04	0.0326
NW	CoV (%)	17.6	0.0	35.2	8.4	28.4	26.5	7.4
Rose	Mean	26033	82459	7182	14066.7	18615	5.63E-04	0.3650
Rose	Std	7953	39568	4131	3840.8	12014	1.49E-04	0.0665
Rose	CoV (%)	30.5	48.0	57.5	27.3	64.5	26.4	18.2

Table 5-5 Flow Number Results for Unconditioned Samples Tested Under Water

Mix		Cycles to Failure	Strain at failure (microstrain)	Flow Number (FN)	Strain at FN (microstrain)	Cycles at 30,000 microstrain	A	m
235I	Mean	11976	100104	2700	16116.2	6634	5.36E-04	0.4350
235I	Std	2255	43	1480	5546.5	1445	2.15E-04	0.0422
235I	CoV	18.8	0.0	54.8	34.4	21.8	40.1	9.7
235S	Mean	27012	100126	8640	21260.6	16694	6.89E-04	0.3669
235S	Std	5834	78	1548	4891.6	3858	3.27E-04	0.0554
235S	CoV	21.6	0.1	17.9	23.0	23.1	47.4	15.1
HW4	Mean	3020	100304	646	17657.3	1471	8.49E-04	0.4766
HW4	Std	1126	115	245	5431.2	457	3.31E-04	0.0576
HW4	CoV	37.3	0.1	37.9	30.8	31.1	39.0	12.1
I80S	Mean	20194	69457	5261	15988.6	17487	6.40E-04	0.3745
I80S	Std	16039	42731	3303	7438.2	17445	2.14E-04	0.1016
I80S	CoV	79.4	61.5	62.8	46.5	99.8	33.5	27.1
Jewell	Mean	18192	100152	4662	18086.6	10779	9.63E-04	0.3624
Jewell	Std	12985	50	2810	1978.9	8498	5.80E-04	0.0670
Jewell	CoV	71.4	0.0	60.3	10.9	78.8	60.3	18.5

It can be concluded from Tables 5-1 through 5-5 that for the parameters tested (cycles to failure, flow number, cycles at 30,000 microstrain, and parameter "A") have very high variability. Parameter "m" has lower variability as compared to the other parameters. Tables 5-6 through 5-9 present the ratio of dividing the different parameters at each condition by those of the control samples. It should be noted that the strain at flow number and parameter "A" are expected to increase with moisture conditioning so the ratios are expected to be greater than one.

Table 5-6 Ratio of Flow Number Test Parameters for Water Conditioned Samples Tested Under Water to Control Samples

Mix	Cycles to Failure	Flow Number	Strain at Flow Number	Cycles at 30,000 microstrain	A	m
6N	0.17	0.31	1.82	0.14	3.29	0.97
218	0.99	1.21	1.64	0.86	3.52	0.79
235I	1.13	1.35	1.50	0.91	4.02	0.73
235S	0.83	0.89	1.49	0.68	4.65	0.76
330B	0.69	0.92	1.69	0.57	2.57	0.91
330I	1.62	1.45	1.13	1.70	4.55	0.63
330S	0.14	0.06	1.32	0.09	6.03	0.93
Alt	0.85	0.47	1.11	0.78	5.42	0.70
Ded	0.47	0.37	0.73	0.36	3.92	0.83
F52	0.67	0.72	1.40	0.61	3.45	0.80
HW4	0.09	0.10	1.88	0.05	3.52	0.95
I80B	2.41	3.23	1.82	2.17	6.97	0.60
I80S	0.40	0.16	1.63	0.25	2.06	1.01
Jewell	1.33	1.06	0.94	1.36	2.52	0.75
NW	1.51	1.62	1.58	1.27	4.82	0.68
Rose	0.27	0.41	2.48	0.18	6.18	0.90

Table 5-7 Ratio of Flow Number Test Parameters for Freezer Conditioned Samples Tested in Air to Control Samples

Mix	Cycles to Failure	Flow Number	Strain at Flow Number	Cycles at 30,000 microstrain	A	m
6N	0.69	1.25	1.57	0.62	2.43	0.92
218	0.91	0.93	0.97	0.95	1.32	0.95
235I	1.48	1.64	1.15	1.41	1.64	0.87
235S	0.85	1.12	1.11	0.91	1.96	0.91
330B	0.80	0.92	1.29	0.74	1.53	0.97
330I	1.50	1.52	0.99	1.57	1.39	0.87
330S	0.58	0.27	1.03	0.45	3.63	0.97
Alt	0.79	0.64	1.20	0.79	2.60	0.87
Ded	1.05	0.83	0.65	0.91	2.28	0.79
F52	0.80	0.75	0.94	0.81	1.29	0.97
HW4	0.49	0.52	1.46	0.40	2.06	0.89
I80B	2.26	2.17	0.99	2.40	1.71	0.84
I80S	0.51	0.44	1.45	0.36	0.56	1.29
Jewell	0.81	0.75	0.67	0.94	1.01	1.00
NW	1.56	1.69	1.16	1.54	1.55	0.86
Rose	0.57	0.77	2.36	0.37	3.28	0.99

Table 5-8 Ratio of Flow Number Test Parameters for Freezer Conditioned Samples Tested Under Water to Control Samples

Mix	Cycles to Failure	Flow Number	Strain at Flow Number	Cycles at 30,000 microstrain	A	m
6N	0.51	0.62	1.30	0.50	2.96	0.82
218	1.19	1.37	1.29	1.16	2.05	0.85
235I	2.12	1.37	0.75	2.24	1.89	0.85
235S	1.07	0.94	0.95	1.11	3.22	0.74
330B	2.58	3.19	1.55	2.19	1.98	0.81
330I	3.19	4.56	1.36	3.35	2.47	0.70
330S	0.83	0.28	0.90	0.88	7.41	0.63
Alt	1.16	2.72	1.30	1.06	2.48	0.84
Ded	1.70	1.19	0.58	1.52	1.93	0.78
F52	1.26	1.43	1.33	1.17	2.59	0.80
HW4	0.67	1.11	1.74	0.55	2.48	0.82
I80B	3.89	3.29	1.02	4.21	3.71	0.60
I80S	0.79	0.82	1.28	0.70	1.29	1.00
Jewell	1.92	1.64	0.86	2.34	2.65	0.68
NW	2.09	2.82	1.78	1.68	3.43	0.73
Rose	0.76	1.27	2.08	0.60	5.28	0.79

Table 5-9 Ratio of Flow Number Test Parameters for Unconditioned Samples Tested Under Water to Control Samples

Mix	Cycles to Failure	Flow Number	Strain at Flow Number	Cycles at 30,000 microstrains	A	m
235I	1.22	1.07	1.03	1.17	1.98	0.84
235S	0.73	0.58	1.23	0.58	4.36	0.78
HW4	0.36	0.33	1.41	0.24	3.16	0.77
I80S	0.66	0.48	1.63	0.61	1.53	0.96
Jewell	3.32	3.08	1.10	3.44	2.87	0.68

The mixes were then ranked to study based on the ratios for each of the parameters studied. Ranks of the water conditioned mixes tested under water are presented in Table 5-10. Ranks for freezer conditioned mixes tested in air are presented in Table 5-11. Ranks for freezer conditioned samples tested under water are presented in Table 5-12.

Table 5-10 Ranking of Mixes Performance Based on the Ratio of Flow Number Test Parameters for Water Conditioned Samples Tested Under Water to Control Samples

Mix	Cycles to Failure	Flow Number	Strain at Flow Number	Cycles at 30,000 microstrain	A	m
6N	14	13	14	14	4	2
218	6	5	11	6	6	9
235I	5	4	8	5	9	12
235S	8	8	7	8	11	10
330B	9	7	12	10	3	5
330I	2	3	4	2	10	15
330S	15	16	5	15	14	4
Alt	7	10	3	7	13	13
Ded	11	12	1	11	8	7
F52	10	9	6	9	5	8
HW4	16	15	15	16	7	3
I80B	1	1	13	1	16	16
I80S	12	14	10	12	1	1
Jewell	4	6	2	3	2	11
NW	3	2	9	4	12	14
Rose	13	11	16	13	15	6

Table 5-11 Ranking of Mixes Performance Based on the Ratio of Flow Number Test Parameters for Freezer Conditioned Samples Tested in Air to Control Samples

Mix	Cycles to Failure	Flow Number	Strain at Flow Number	Cycles at 30,000 microstrain	A	m
6N	12	5	15	12	13	8
218	6	7	4	5	4	7
235I	4	3	9	4	8	12
235S	7	6	8	7	10	9
330B	9	8	12	11	6	5
330I	3	4	5	2	5	11
330S	13	16	7	13	16	6
Alt	11	13	11	10	14	13
Ded	5	9	1	8	12	16
F52	10	12	3	9	3	4
HW4	16	14	14	14	11	10
I80B	1	1	6	1	9	15
I80S	15	15	13	16	1	1
Jewell	8	11	2	6	2	2
NW	2	2	10	3	7	14
Rose	14	10	16	15	15	3

Table 5-12 Ranking of Mixes Performance Based on the Ratio of Flow Number Test Parameters for Freezer Conditioned Samples Tested Under Water to Control Samples

Mix	Cycles to Failure	Flow Number	Strain at Flow Number	Cycles at 30,000 microstrain	A	m
6N	16	15	10	16	11	6
218	9	9	8	9	5	3
235I	4	8	2	4	2	2
235S	11	13	5	10	12	11
330B	3	3	13	5	4	7
330I	2	1	12	2	6	13
330S	12	16	4	12	16	15
Alt	10	5	9	11	7	4
Ded	7	11	1	7	3	10
F52	8	7	11	8	9	8
HW4	15	12	14	15	8	5
I80B	1	2	6	1	14	16
I80S	13	14	7	13	1	1
Jewell	6	6	3	3	10	14
NW	5	4	15	6	13	12
Rose	14	10	16	14	15	9

5.2 Statistical analysis

The parameters studied in the flow number test showed very high variability represented in the coefficient of variation. The parameter that showed the least variability in most of the cases is the parameter “m”. Cycles to failure will not be included in the statistical analysis because it is based on two different failure conditions caused by the machine limit and this introduced extra variability to this parameter. The flow number ratios are scattered around one, which provides inconclusive results. The variability in the flow number ratios is shown in Figure 5-1 for one of the conditions, which is the freezer conditioned samples tested in air. This variability is similar to what was found by Solimanian et al. (2007). Strain at flow number followed a similar trend as shown in Figure 5-2. Both parameters “A” and “m” offer promising results, but only parameter "m" will be considered because it depends mainly on the material properties and the ratios achieved using this parameter are very consistent in being less than one except for one reading that was 1.29.

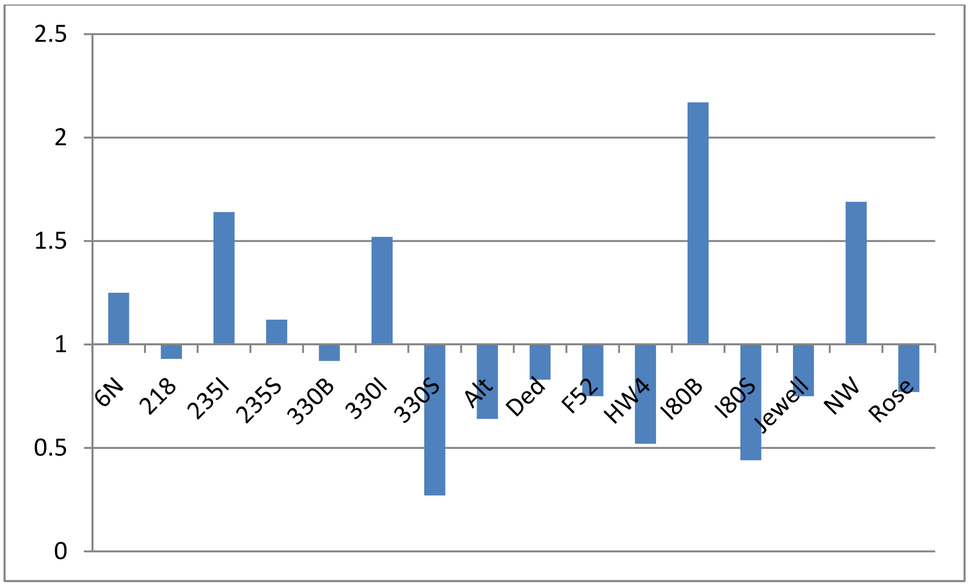


Figure 5-1 Variability of FN ratios for Freezer Conditioned Samples Tested in Air

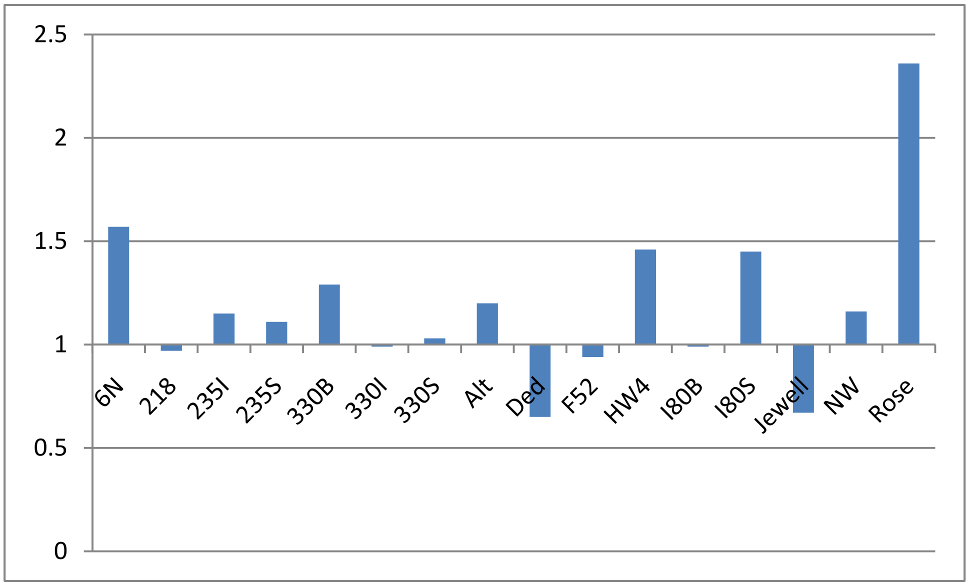


Figure 5-2 Variability of Strain at Flow Number ratios for Freezer Conditioned Samples Tested in Air

CHAPTER 6 AASHTO T283 TEST RESULTS

Performing the AASHTO T283 test is important to compare the results achieved using the other methods to those achieved using the AASHTO T283 test. The main reason behind the comparison is that AASHTO T283 is what practitioners are used to performing and thus provides a good reference to the test that is currently being performed in practice. The test followed the methodology described in Chapter 3. Two groups of samples were tested: a control group and a moisture conditioned group, which was subjected to one freeze/thaw cycle. Five samples were tested in each group. Table 6-1 presents the tensile strength for both groups for the mixes tested. The individual sample results are presented in Appendix C. The results were then use to calculate the tensile strength ratio (TSR), which is presented in Table 6-2. The TSR was used to rank the mixes, where 1 represents the least moisture susceptible mix. The ranking of the mixes is presented in Table 6-2. The next step was to perform a statistical analysis on the results. A statistical analysis software (JMP) was used in the analysis. The first hypothesis that was tested was that the mean of the two tested groups for all the mixes was equal. This hypothesis was tested by a pair wise comparison t-test. This resulted in a p-value less than 0.0001, which means that the hypothesis is rejected at a level of significance $\alpha=0.05$ and that the two groups are statistically different. The second hypothesis that was tested was that the mean of the two groups for each mix is equal for the five samples tested for this mix. The results of this analysis are presented in Table 6-2. The results are presented as a p-value and whether the two means are statistically different or not. It can be seen from the results of this analysis that the means of the good performing mixes are not statistically different (p-value less than 0.05). It appears that the transition between the statistically similar and the statistically different groups occurs somewhere between TSR values of 0.93 and 0.86.

Table 6-1 Tensile Strength for Both Groups

Mix	Sample	Tensile strength, control (kPa)	Tensile Strength, moisture (kPa)
6N	Mean	994.8	854.9
6N	Stdev	25.6	69.7
6N	COV	2.6	8.2
218	Mean	1206.3	859.2
218	Stdev	69.3	80.2
218	COV	5.7	9.3
235I	Mean	1204.3	1170.5
235I	Stdev	31.8	36.5
235I	COV	2.6	3.1
235S	Mean	1174.7	1206.8
235S	Stdev	45.8	73.4
235S	COV	3.9	6.1
330B	Mean	1014.5	777.8
330B	Stdev	67.7	34.4
330B	COV	6.7	4.4
330I	Mean	1202.9	1145.7
330I	Stdev	56.1	22.2
330I	COV	4.7	1.9
330S	Mean	1266.6	1248.8
330S	Stdev	13.9	7.3
330S	COV	1.1	0.6
ALT	Mean	1343.3	1339.6
ALT	Stdev	5.3	5.2
ALT	COV	0.4	0.4
DED	Mean	1171.8	873.0
DED	Stdev	50.1	30.3
DED	COV	4.3	3.5
F52	Mean	839.3	781.4
F52	Stdev	111.6	57.5
F52	COV	13.3	7.4
HW4	Mean	1135.9	910.3
HW4	Stdev	164.5	180.8
HW4	COV	14.5	19.9
I80B	Mean	1290.9	1247.4
I80B	Stdev	10.3	18.5
I80B	COV	0.8	1.5

Table 6-1 (continued)

Mix	Sample	Tensile strength, control (kPa)	Tensile Strength, moisture (kPa)
I80S	Mean	1243.0	981.1
I80S	Stdev	13.3	42.5
I80S	COV	1.1	4.3
Jewell	Mean	1177.5	1107.0
Jewell	Stdev	24.0	93.1
Jewell	COV	2.0	8.4
NW	Mean	914.3	789.3
NW	Stdev	19.1	79.5
NW	COV	2.1	10.1
Rose	Mean	1220.8	1221.6
Rose	Stdev	30.8	15.1
Rose	COV	2.5	1.2

Table 6-2 TSR and Mixture Ranking

Mix	Tensile Strength Ratio (TSR)	p-value	Statistical Variation	Rank
6N	**0.86**	**0.0109**	**Statistically different**	11
218	**0.71**	**0.0042**	**Statistically different**	16
235I	0.97	0.2596	Statistically the same	5
235S	1.03	0.4716	Statistically the same	1
330B	**0.77**	**0.0006**	**Statistically different**	14
330I	0.95	0.1198	Statistically the same	7
330S	0.99	0.0563	Statistically the same	4
ALT	1.00	0.3577	Statistically the same	3
DED	**0.75**	**<0.0001**	**Statistically different**	15
F52	0.93	0.4566	Statistically the same	9
HW4	**0.80**	**0.0385**	**Statistically different**	12
I80B	0.97	**0.0220**	Statistically the same	6
I80S	**0.79**	**0.0004**	**Statistically different**	13
Jewell	0.94	0.2292	Statistically the same	8
NW	**0.86**	**0.0376**	**Statistically different**	10
Rose	1.00	0.9672	Statistically the same	2

CHAPTER 7 COMPARISON BETWEEN THE DIFFERENT TEST METHODS

In order to investigate the difference in results between the three tests investigated, a comparison was conducted between the results achieved using the different tests. The results from the three tests were compared together. The comparisons were done between samples with the same conditions. This means that only samples tested under condition 4 (moisture conditioned with one freeze/thaw cycle) and condition 1 (control) are included in this comparison. Based on the discussion presented earlier about the dependence of the E* ratio on temperature and frequency, a situation corresponding to that of the flow number was considered. The master curves were used to calculate the dynamic modulus at 37^{o}C and a loading frequency of 10Hz. These dynamic modulus values were then used to calculate the ratios used in the statistical analysis. The average of the E* ratios of all the tested temperature-frequency combinations was also used in the comparison. A statistical analysis software (JMP) was used to run a pairwise comparison to show statistically different groups. The comparison was done for the ratio between the conditioned and unconditioned group results. The results of the different tests are presented in Table 7-1. A paired t-test comparison was performed on these results. The results of the comparison are presented in Table 7-2. The results showed that there is no statistical difference between the parameter "m" and the TSR ratio and the average E* ratio. All the other comparisons are statistically different. Figures 7-1 through 7-6 show a graphical representation for the tested pairs. The ranking of the mixes based on the different methods is presented in Table 7-3.

Table 7-1 Ratios from Different Tests

Mix	TSR ratio	E* ratio (average)	E* ratio (37°C-10Hz)	Parameter "m" ratio
6N	0.86	0.92	1.10	0.92
218	0.71	1.08	1.19	0.95
235I	0.97	0.87	0.91	0.87
235s	1.03	1.17	1.27	0.91
330B	0.77	1.03	1.28	0.97
330I	0.95	1.09	1.31	0.87
330s	0.99	0.90	0.78	0.97
ALT	1.00	1.03	1.26	0.87
Ded	0.75	1.00	1.21	0.79
F52	0.93	1.01	1.10	0.97
HW4	0.80	0.80	0.59	0.89
I80B	0.97	1.01	1.04	0.84
I80s	0.79	0.90	0.92	1.29
Jewell	0.94	1.11	1.37	1.00
NW	0.86	0.99	1.25	0.86
Rose	1.00	0.83	0.78	0.99

Table 7-2 Statistical Comparison Between the Different Methods*

	E* ratio (average)	E* ratio (37°C-10Hz)	Parameter "m" ratio
TSR ratio	**0.0235**	**0.0090**	0.3460
E* ratio (average)		**0.0125**	0.2612
E* ratio (37°C-10Hz)			**0.0453**

* Values in bold are statistically significant at α=0.05

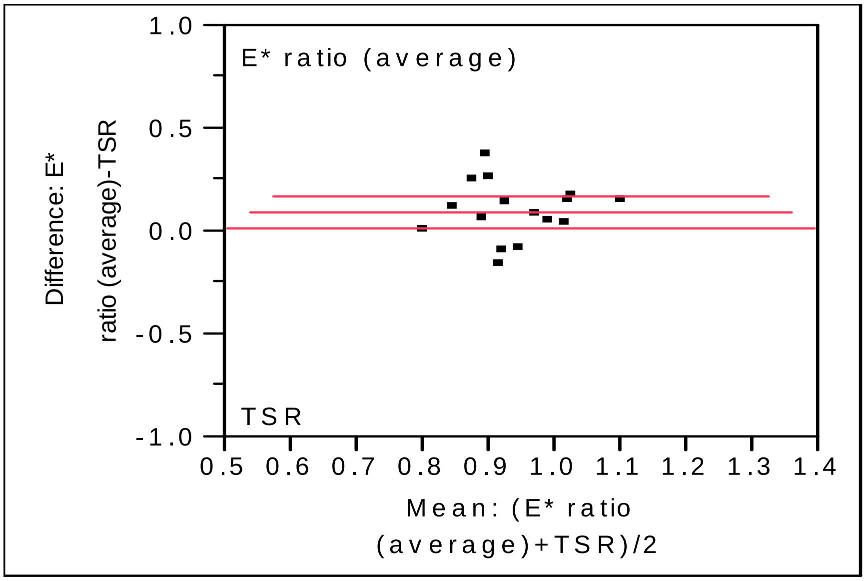


Figure 7-1 Comparison between Average E* Ratio and TSR

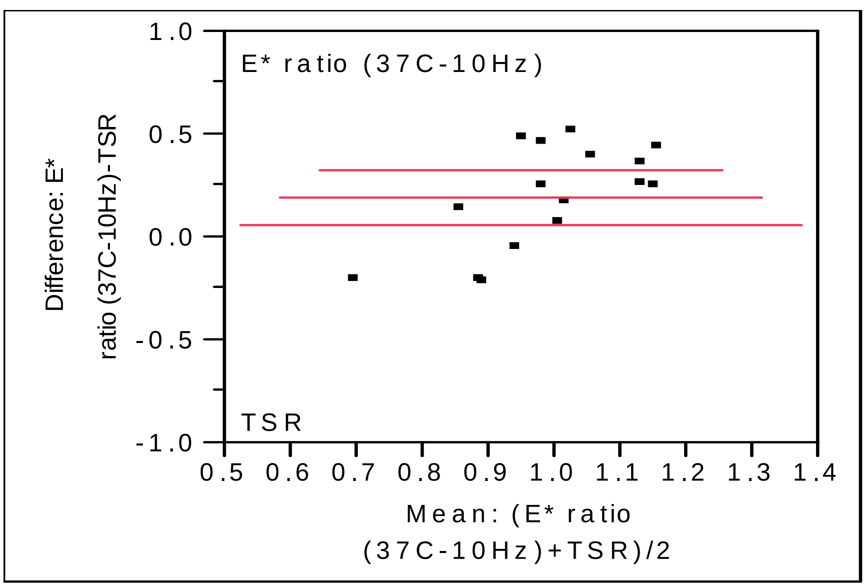


Figure 7-2 Comparison between E* (37^{o}C-10Hz) Ratio and TSR

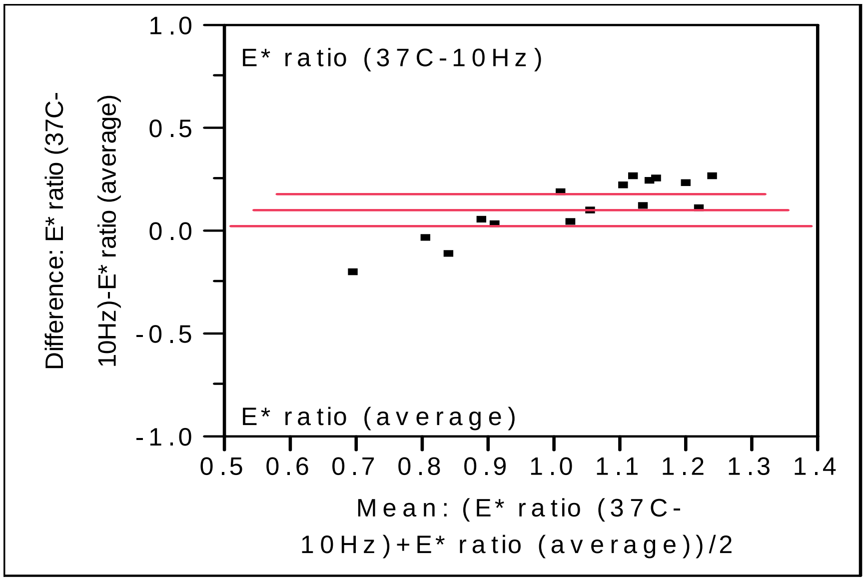


Figure 7-3 Comparison between E* (37^{o}C-10Hz) and Average E* Ratios

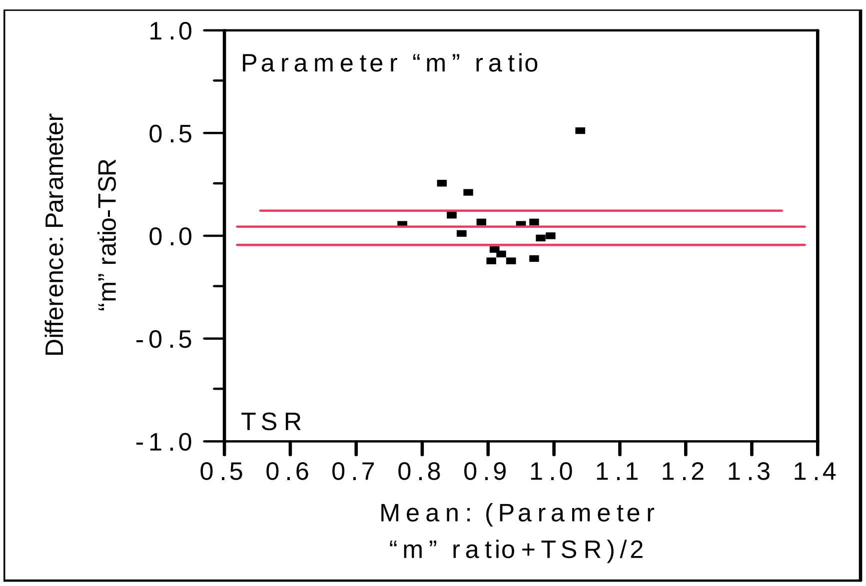


Figure 7-4 Comparison between Parameter "m" Ratio and TSR

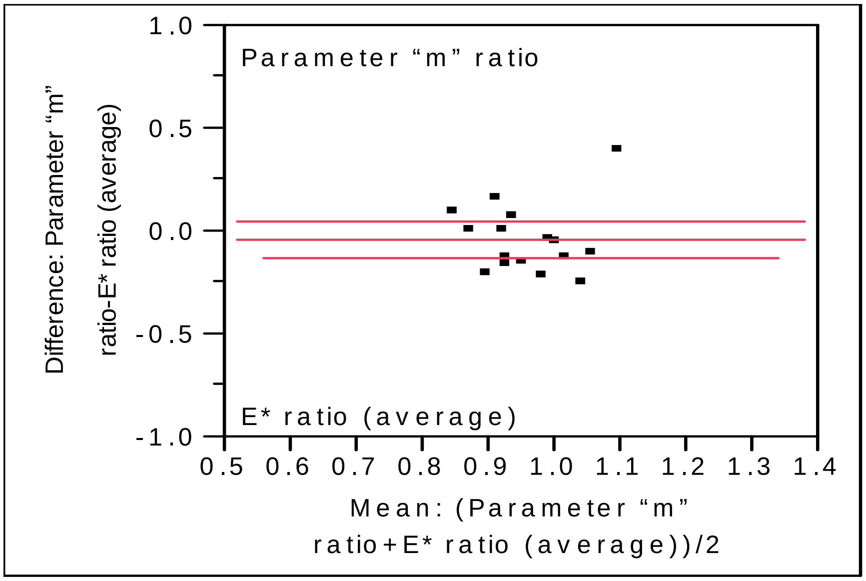


Figure 7-5 Comparison between Average E* and Parameter "m" Ratios

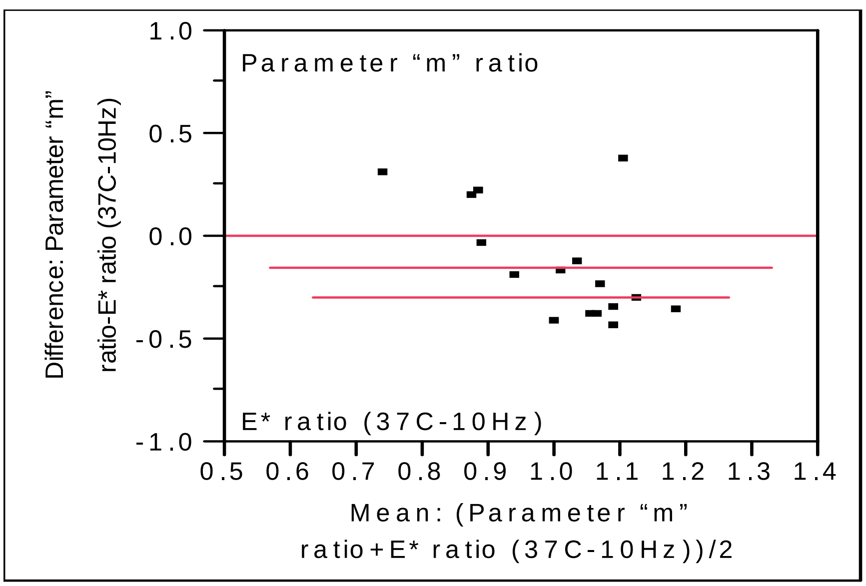


Figure 7-6 Comparison between E* (37°C-10Hz) and Parameter "m" Ratios

Table 7-3 Ranking of the Mixes Using the Different Methods

Mix	TSR ratio	E* ratio (average)	E* ratio (37^{o}C-10Hz)	Parameter "m" ratio
6N	10	11	10	8
218	16	4	8	7
235I	5	14	13	13
235s	1	1	4	9
330B	14	6	3	4
330I	7	3	2	11
330s	4	12	14	6
ALT	2	5	5	12
Ded	15	9	7	16
F52	9	8	9	5
HW4	12	16	16	10
I80B	6	7	11	15
I80s	13	13	12	1
Jewell	8	2	1	2
NW	11	10	6	14
Rose	3	15	15	3

CHAPTER 8 FINITE ELEMENT MODEL

8.1 Introduction

Finite element analysis was performed using a multi-purpose finite element software, ABAQUS™ version 6.9.1 (2009). The reason for choosing this software is that it includes a module for viscoelastic materials and that it has pre- and post-processors that can be used in the stochastic part of the analysis. Two different models with two different geometries were used in this study. The first model is the validation model and has a cylindrical geometry having the same dimensions as the flow number sample. This model was used to validate and calibrate the data transformation that was done to transform the dynamic complex modulus results to the shear complex modulus results. The reason for the selection of this validation method is that the same samples were used in the dynamic modulus and the flow number tests, so if the flow number test can be simulated and the results are comparable then this demonstrates that the transformation is correct and can be used to in the main model. The second model is the stochastic finite element analysis model. The stochastic finite element analysis was conducted using a non-intrusive technique. In this technique, the test results were analyzed to develop a variable set of data for each material based on the experimental results. The developed data sets were used as inputs for the model that was subdivided into sections that varied in material properties in which the details and results of this model is discussed in detail in this chapter.

8.2 Statistical approach

The purpose of the stochastic finite element analysis is to model the variability of the results based on variability of the input. In the case of this study, the variability consisted of three types: material variability, construction variability and loading/testing variability. To be able to incorporate these three types of variability in the input data, results from different samples and loading cycles were used. This was achieved by using the dynamic modulus results of five samples for each of the control and moisture conditioned groups, which represents the material and construction variability. The loading/testing variability was incorporated by taking the results from two different cycles. This resulted in 10 different sets of data for each group. A random number generator that generates numbers between one and ten was used to pick two data sets from each sample to be used in the model. The random number generation concept was used to avoid developing data sets because the mixture behavior depends on the relation between the numbers within the set, which cannot be maintained in randomly generated data.

8.3 Material characterization

ABAQUS has a viscoelastic module that can be used in modeling asphalt concrete. There are several alternatives that can be used for defining the material properties. The one used in this analysis was to use the complex shear modulus, which can be obtained by converting the dynamic modulus test results. The conversion was done using an approximation technique developed by Schapery and Park (1999), details about the transportation technique will be presented later in this section. Temperature dependency of the material needs to be entered in the model. Temperature dependency is calculated using the WLF equation presented in section 2.7, the inputs are the constants c_1 and c_2. Finally the elastic properties of the materials were assumed. The modulus of elasticity was assumed to be 500MPa, the selection of this value was based on the high temperature used in modeling (37°C) and a sensitivity analysis was done on the value of the modulus of elasticity and showed that the results are not affected by the modulus value. The Poison's ratio was assumed to be 0.35.

The approximation method proposed by Schapery and Park (1999) for interconversion between the linear viscoelastic material properties was used. In the case of dynamic modulus conversion to shear modulus, the following steps apply (Schapery and Park 1999):

The dynamic modulus is converted into the storage modulus:

$E' = E^{*} cos\varphi$ (8-1)

Where:

E' is the storage modulus,

E* is the dynamic modulus, and

φ is the phase angle.

The next step is to calculate the adjustment factor that is used to transform the storage modulus into relaxation modulus

$\lambda' = \Gamma(1-n)\cos\left(\frac{n\pi}{2}\right)$ (8-2)

Where:

λ' is the adjustment factor,

Γ( ) is the gamma function, and

n is the local log-log slope of the source function (in this case the storage modulus.

the relaxation modulus is calculated as follows:

$E(t) = E'(\varpi)/\lambda'$ (8-3)

Where:

E(t) is the relaxation modulus at time t,

$E'(\varpi)$ is the storage modulus at frequency ϖ,

λ' is the adjustment factor, and

t = $1/\varpi$.

A sigmoidal function can be fitted to the relaxation modulus to get the relaxation modulus at a reference temperature. The sigmoidal function presented in section 2.7 was used.

The shear modulus is then calculated from the relaxation modulus using the relationship:

$G(t) = \frac{E(t)}{2(1+\upsilon)}$ (8-4)

G(t) is the shear modulus at time t,

E(t) is the relaxation modulus at time t, and

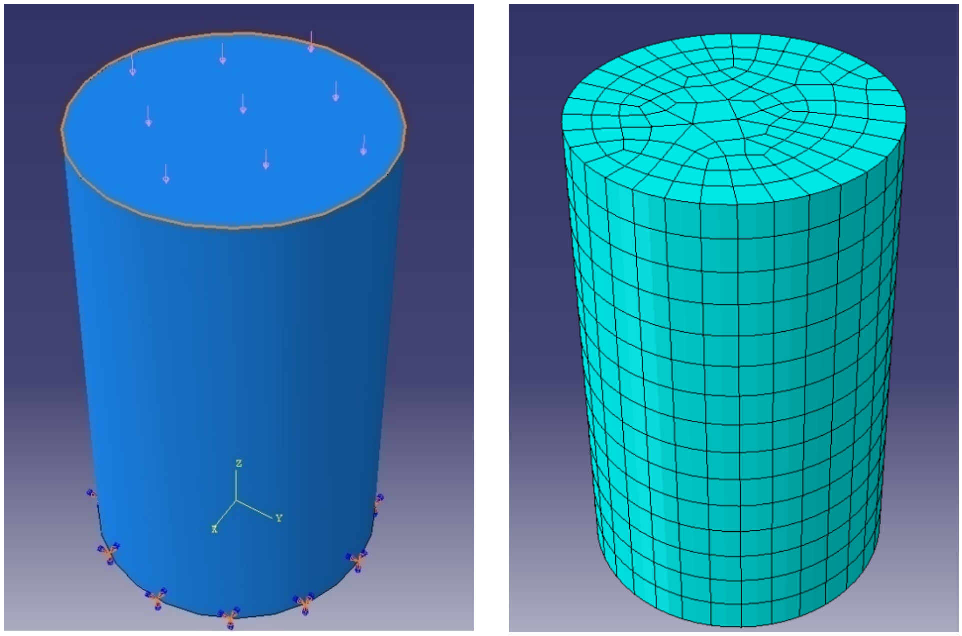
υ is Poison's ratio.

ABAQUS has a built in function that transforms the shear modulus into a Prony series. The data is entered as the long term modulus and then the ratio of the modulus at specific times to the long term modulus. The reference temperature that was used in the sigmoidal function fitting was selected to be 21°C. The simulation temperature was 37°C. All the data was shifted to 37°C before entering them into the model using the shift factors calculated from the WLF equation.

8.4 Validation model

8.4.1 Model geometry and meshing

The validation model has a cylindrical geometry having the same dimensions as the flow number sample. This model was used to test the validity of the data conversion by simulating the flow number test and comparing the results. This model is presented in Figure 8-1. The mesh used for this model was a structured a 20-node quadratic brick, with reduced integration (C3D20R).



a. Loads and Boundary Conditions b. The Meshed Part

Figure 8-1 Finite Element Validation Model

8.4.2 Loads and boundary conditions

To resemble the laboratory test, the model was restrained at the bottom from movement and rotation in all directions. The load applied to the model was the same as the load applied in the lab. The load was defined as a 0.1 sec loading cycle at 630kPa followed by arrest period of 0.9 sec. During the rest period, the load was not completely removed, a load of 30kPa was maintained. The simulation represented a low volume traffic level of 0.5 million ESALs, so the load was applied 0.5 million times on each wheel location.

8.4.3 Model results

The results of the validation model are presented in Figures 8-2 through 8-17. The results shown in the figures are a comparison between the flow number results and the modeling results. The model results needed to be multiplied by scaling factors to obtain strain values close to the actual strain, these scaling factors were carried over to the full model to be used in scaling the deformations. Since the model used is a viscoelastic model, it does not simulate the plastic deformation portion of the material. This is why the model was calibrated up to 1 percent strain, which ensures that the material is still in the linear viscoelastic region of its behavior (before the flow number). The results show that the model was capable of capturing the trend followed by the material.

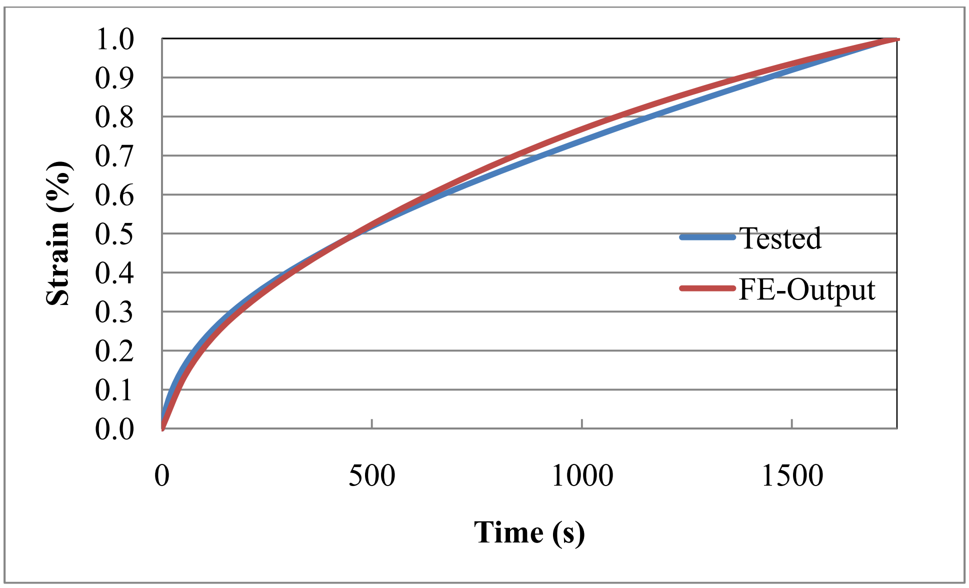


Figure 8-2 Validation Model Results for Mix 6N

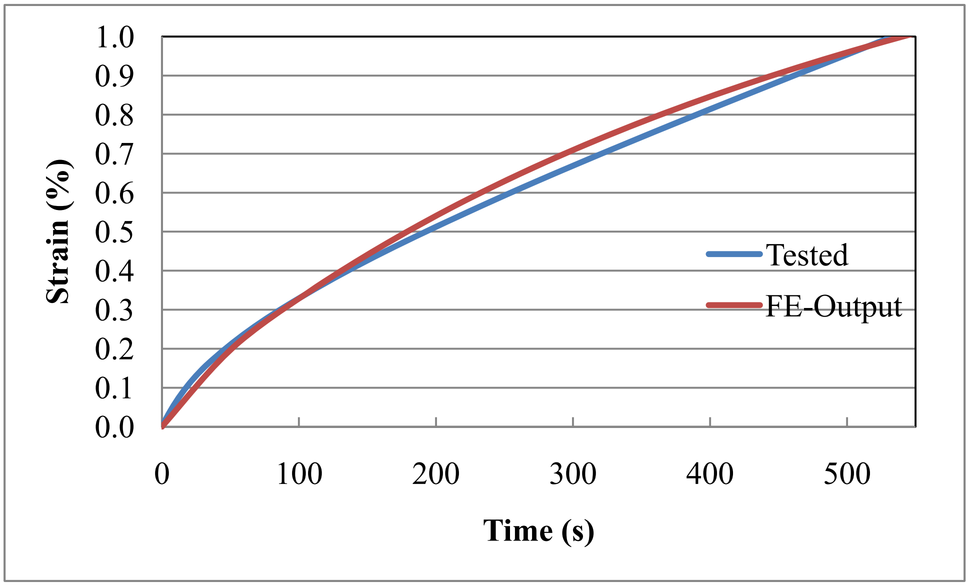


Figure 8-3 Validation Model Results for Mix 218

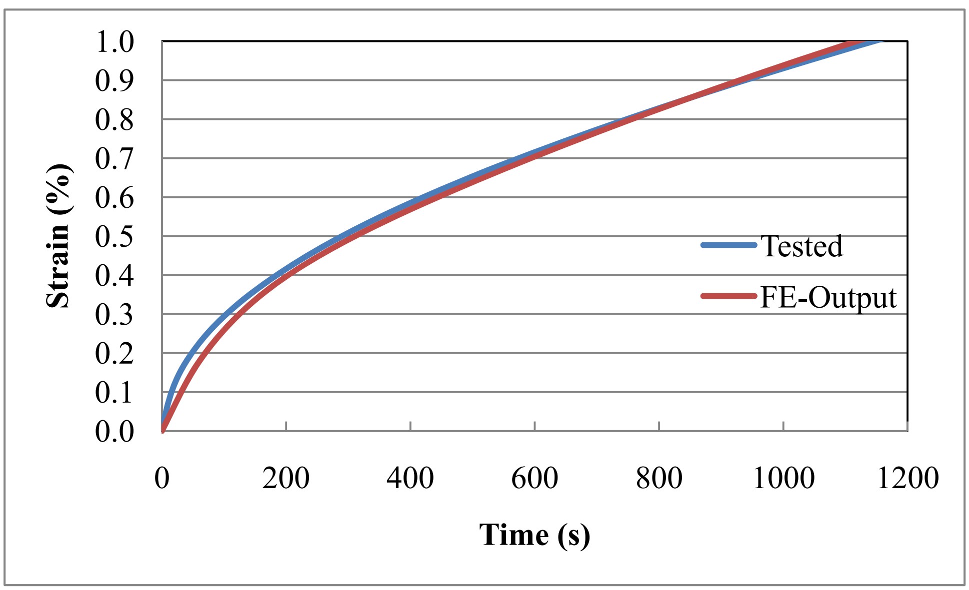


Figure 8-4 Validation Model Results for Mix 235I

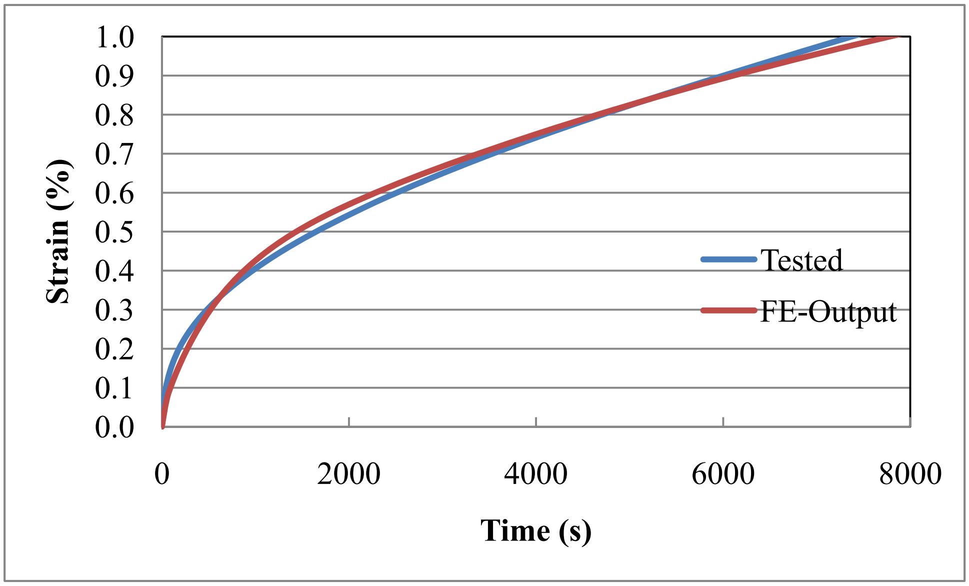


Figure 8-5 Validation Model Results for Mix 235S

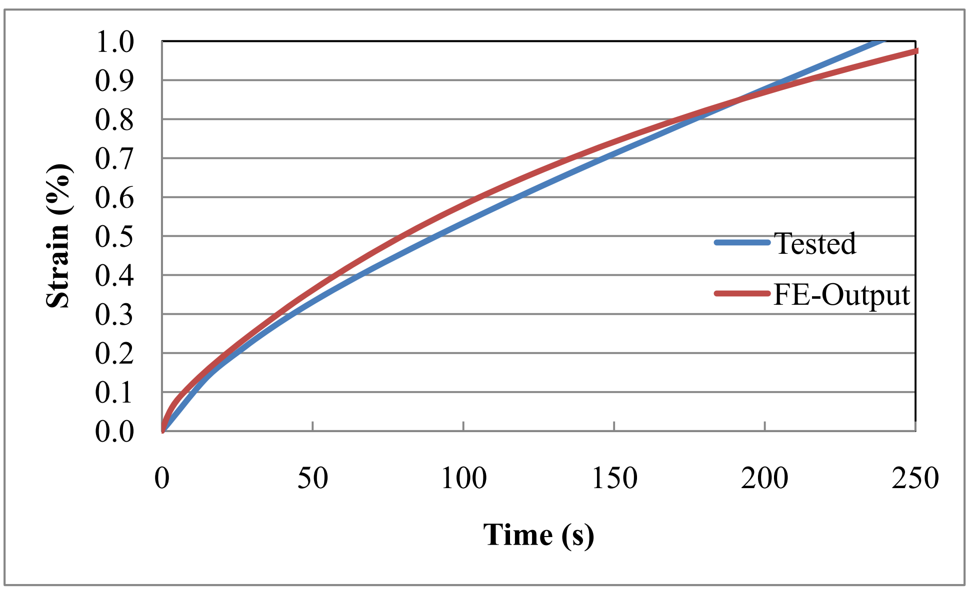


Figure 8-6 Validation Model Results for Mix 330B

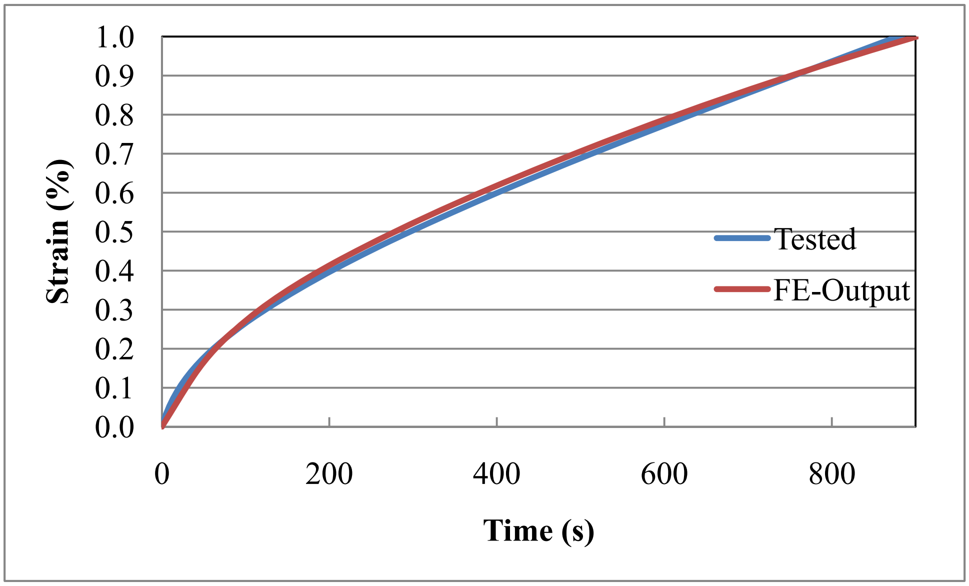


Figure 8-7 Validation Model Results for Mix 330I

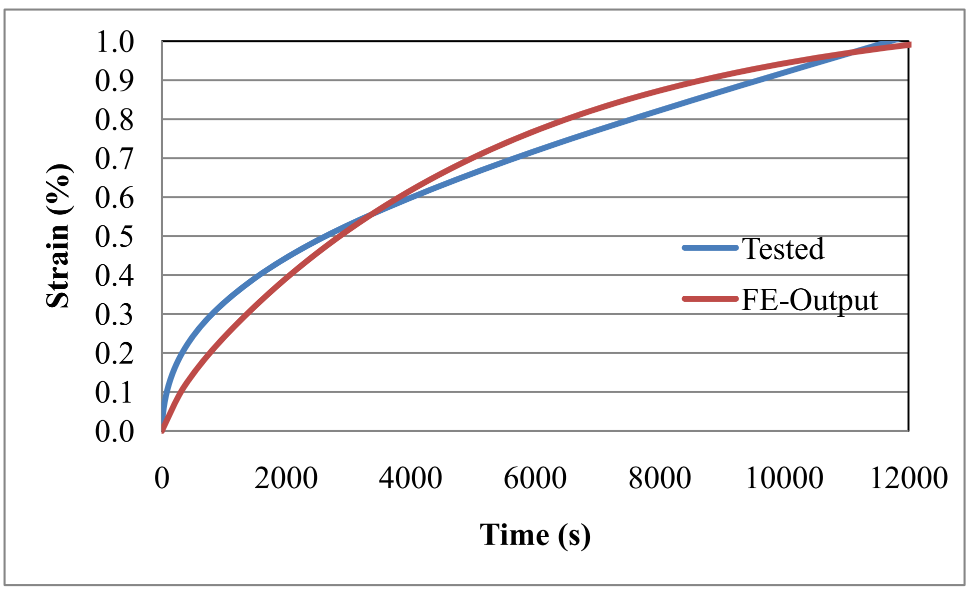


Figure 8-8 Validation Model Results for Mix 330S

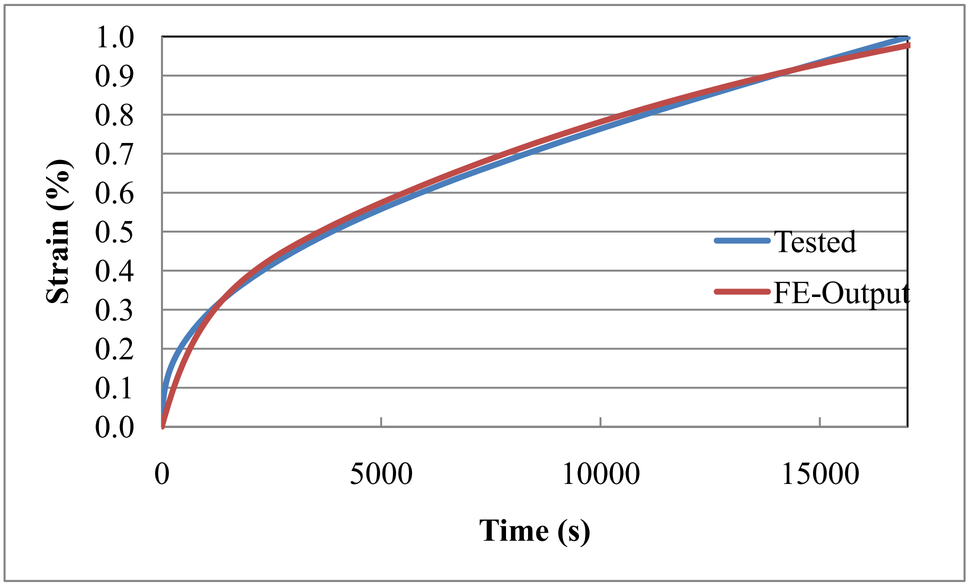


Figure 8-9 Validation Model Results for Mix ALT

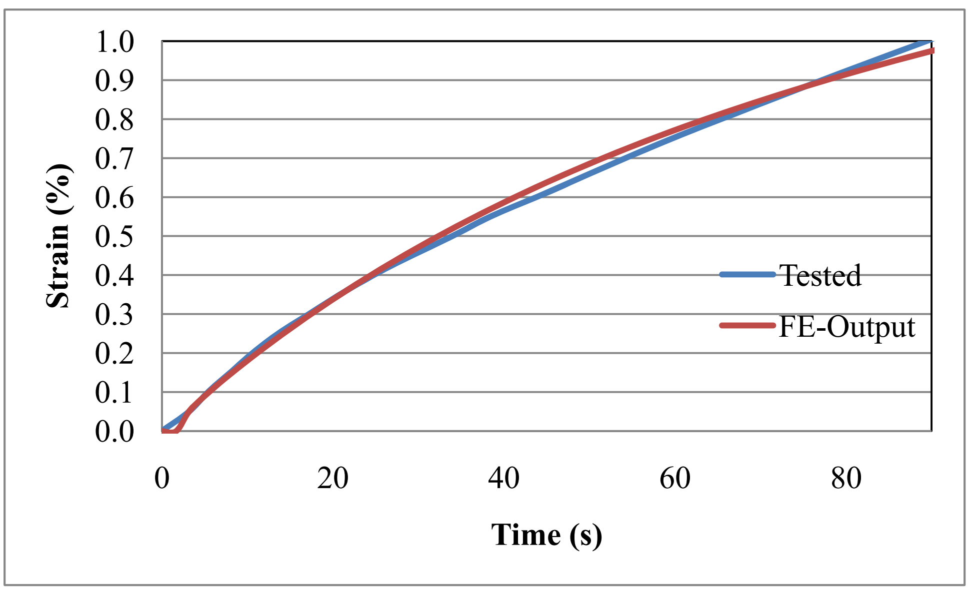


Figure 8-10 Validation Model Results for Mix DED

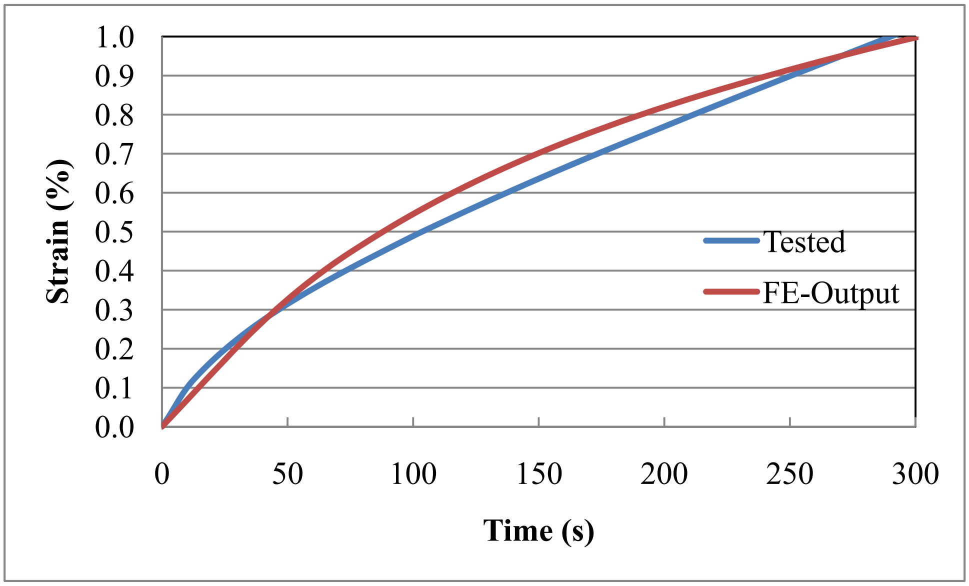


Figure 8-11Validation Model Results for Mix F52

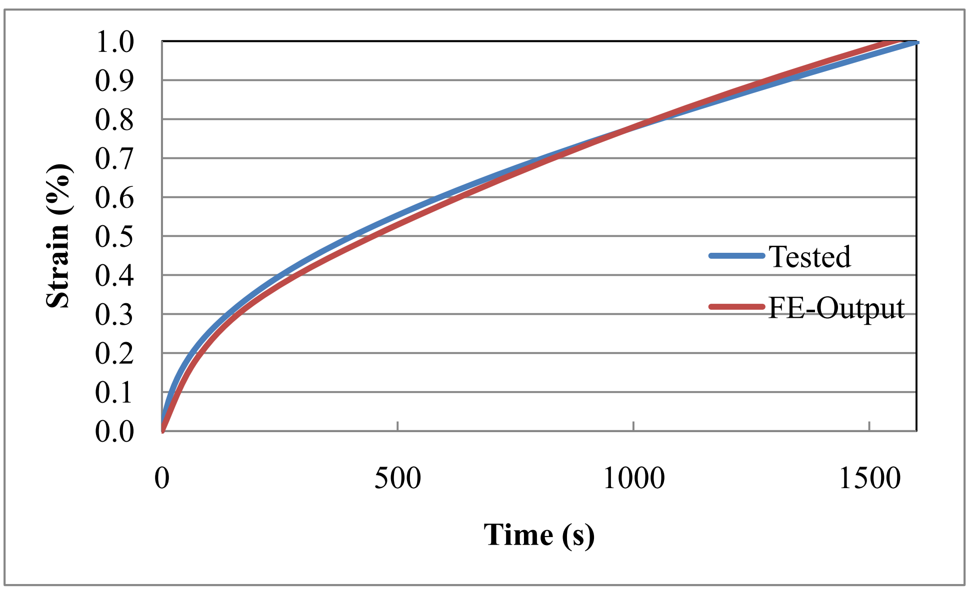


Figure 8-12 Validation Model Results for Mix HW4

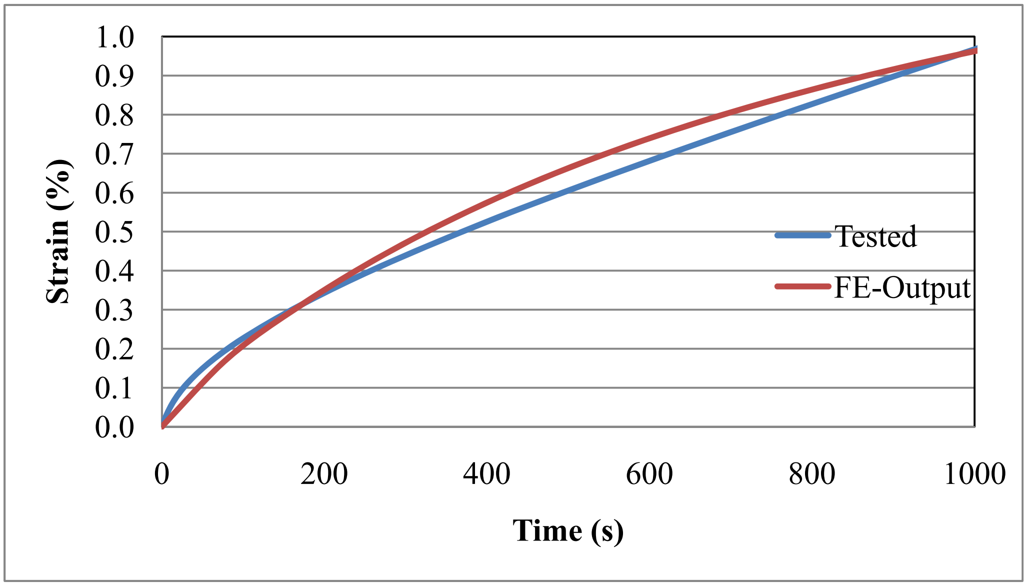


Figure 8-13 Validation Model Results for Mix I80B

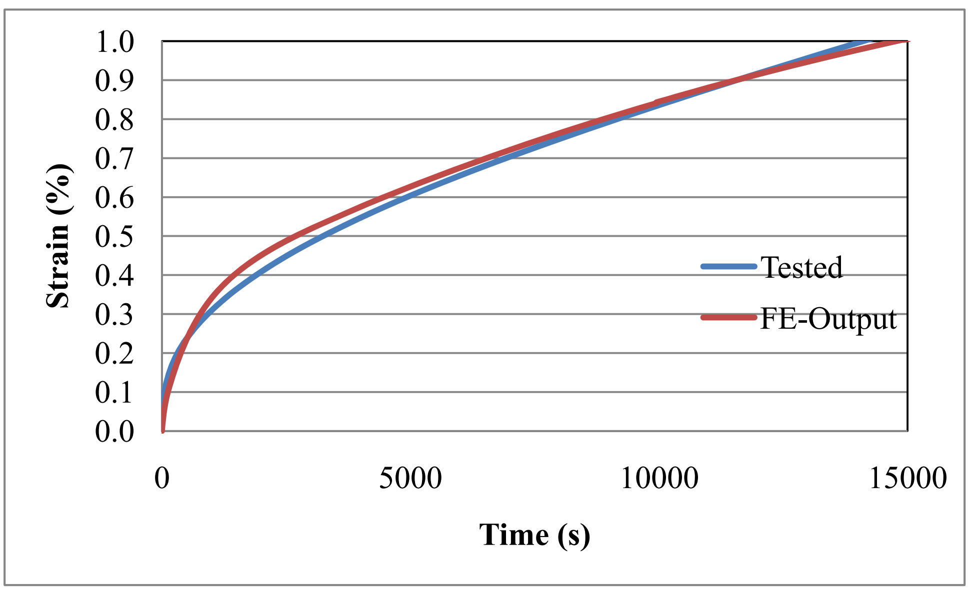


Figure 8-14 Validation Model Results for Mix I80S

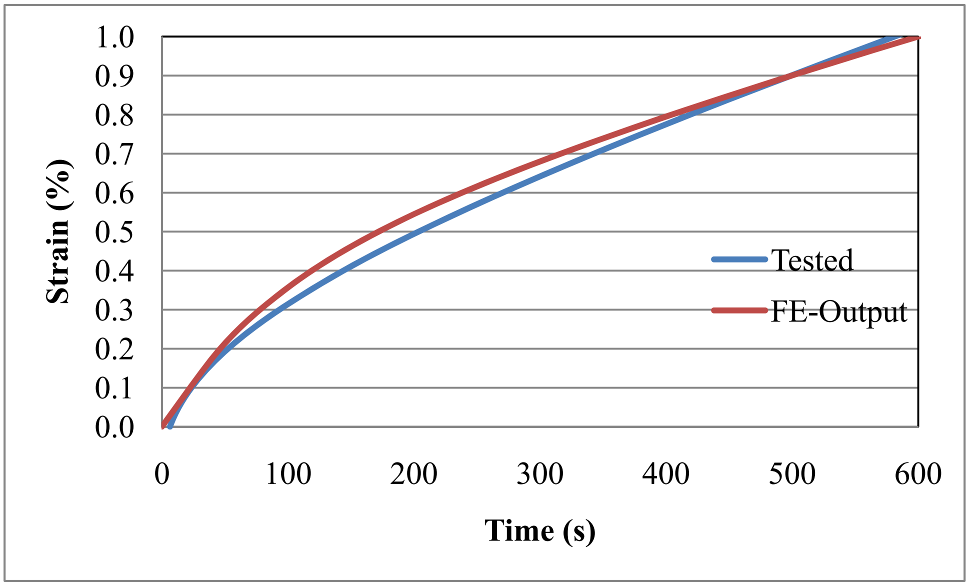


Figure 8-15 Validation Model Results for Mix NW

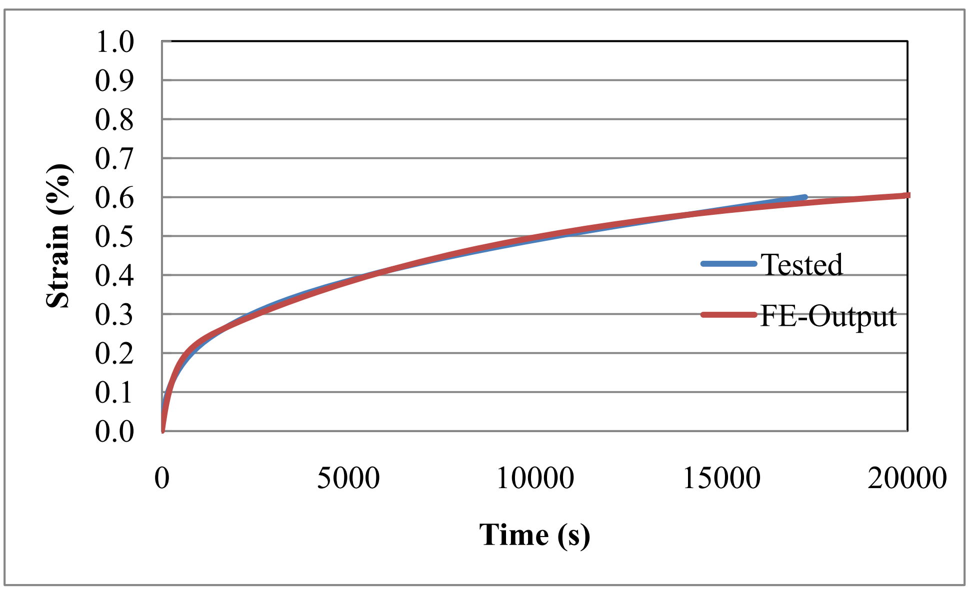


Figure 8-16 Validation Model Results for Mix Rose

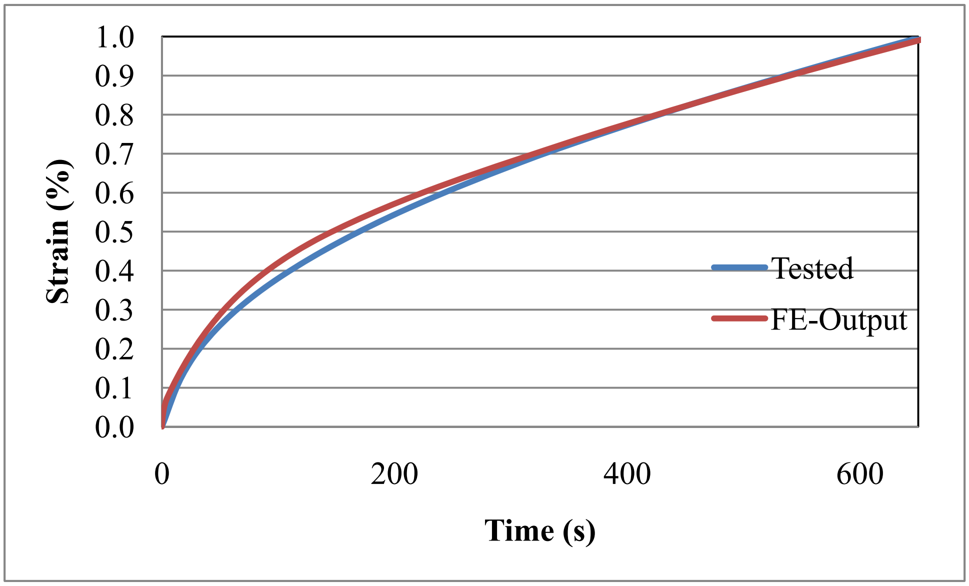


Figure 8-17 Validation Model Results for Mix Jewell

8.5 The stochastic model

8.5.1 Model geometry and meshing

The stochastic finite element model represents a three dimensional (3D) pavement structure that consists of a 15cm (6in) thick asphalt pavement on top of a 30cm (12in) granular base with an assumed modulus of 30MPa (4.35ksi) on top of a subgrade with a modulus of 10MPa (1.45ksi). The bedrock was assumed to be at a depth of 2m from the surface of the subgrade. The model was subdivided along the traffic direction (Y-direction) into 12 sections. The first and last sections were 3 meters (10ft) in length and were not included in the analysis, the only function of these two segments was to eliminate the edge effects. The remaining 10 sections were 1 meter in length and each one was assigned material properties based on the variability of the material. Figure 8-18 presents the data input used in modeling unconditioned mix 6N as a sample for the input data. On the transverse direction (X-direction), the pavement was assumed to be 3.6 meters (12ft) wide, which is the normal width of a traffic lane. The lane marking was assumed to be 50cm (20in) feet from the edge of the pavement and the traffic was assumed to be 30cm (1ft) from the lane marking. This model is presented in Figure 8-19. The mesh used for this model was a structured a 20-node quadratic brick, with reduced integration (C3D20R). The global mesh size used for the asphalt pavement layer was 0.1m. A wider mesh was used for the base and subgrade (0.6m). the meshed model is presented in Figure 8-20.

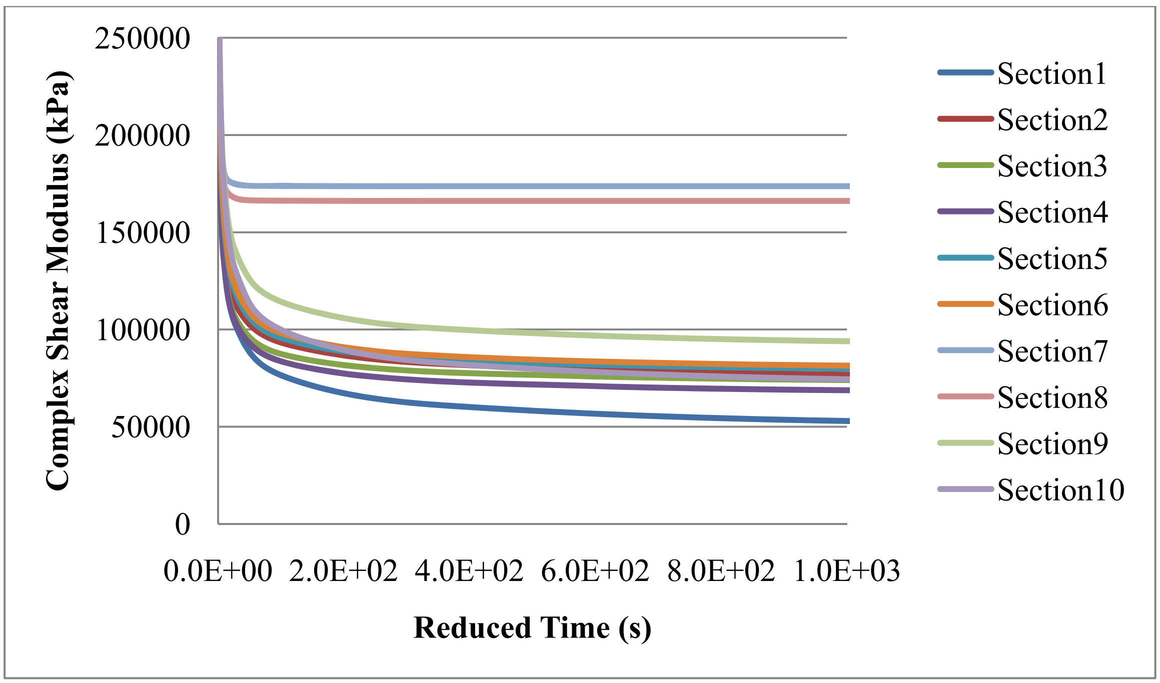


Figure 8-18 Input Data for Mix 6N (Unconditioned)

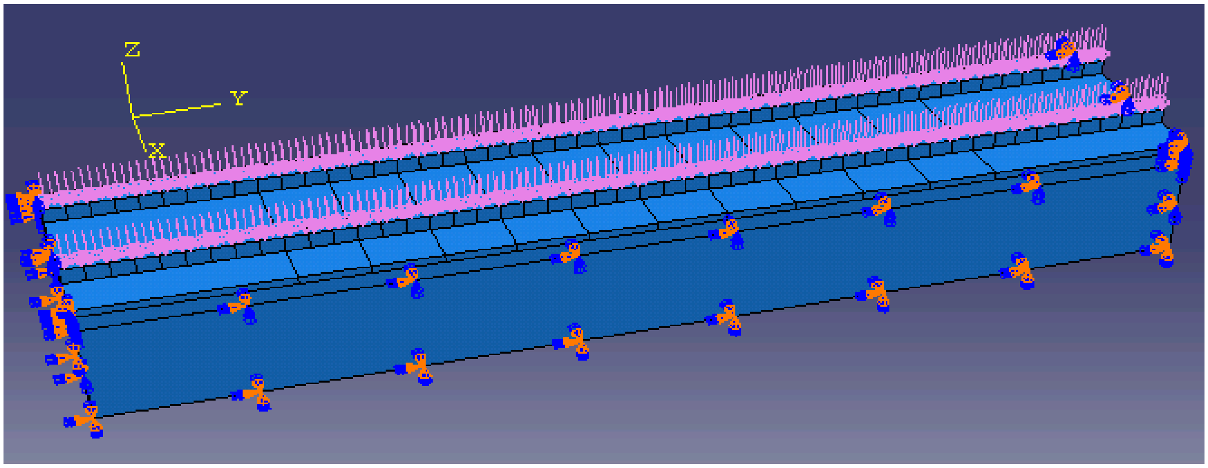


Figure 8-19 The Stochastic Model with Loads and Boundary Conditions

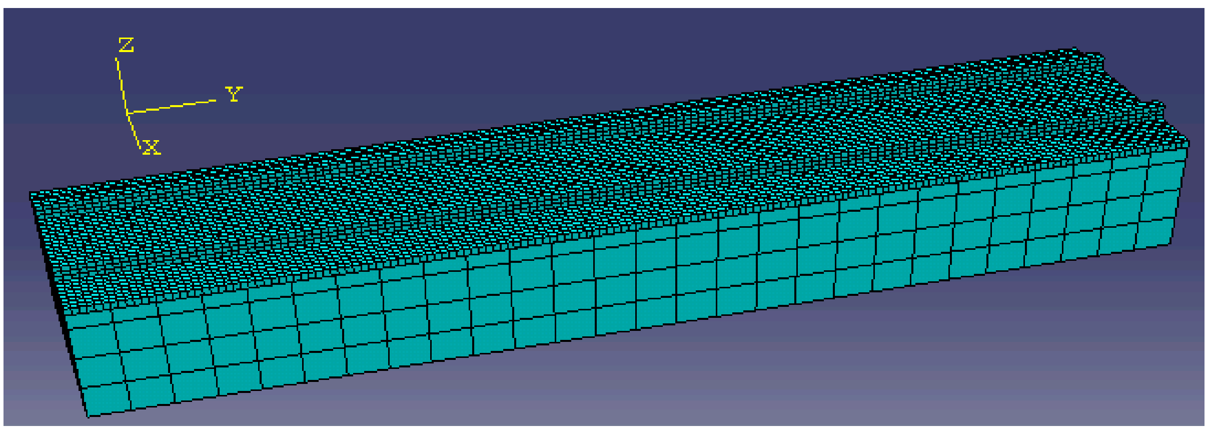


Figure 8-20 The Meshed Stochastic Model

8.5.2 Loads and boundary conditions

As mentioned earlier, the load was applied 0.8m from the right edge of the pavement and the traffic was assumed to move in the positive Y-direction. The load was simulated using a wheel with a contact dimension of 0.2m in width and 0.33m in length. The applied load was assumed to be one equivalent single axle load (ESAL). The applied load was 620kPa per wheel, which is equivalent to the ESAL load. Blocks that simulate the wheels were placed in two parallel lines. To simulate the movement of the load, the load was shifted from one block to the adjacent one every 0.15s, which corresponds to a traffic speed of 80km/hr (50mph). The load was repeated every 1s.

8.5.3 Model results

The results of the finite element model are presented in this section. The deformation along the transverse direction (X-axis) is presented for all the mixes. The results for the different sections of the mix are presented on the same chart to show the variability. The results in general followed the expected trend and deformation pattern in which the deformation is highest under the wheel paths. Figures 8-21 through 8-36 show the deformation in the transverse direction for the unconditioned mixes and Figures 8-37 through 8-53 are for the conditioned mixes.

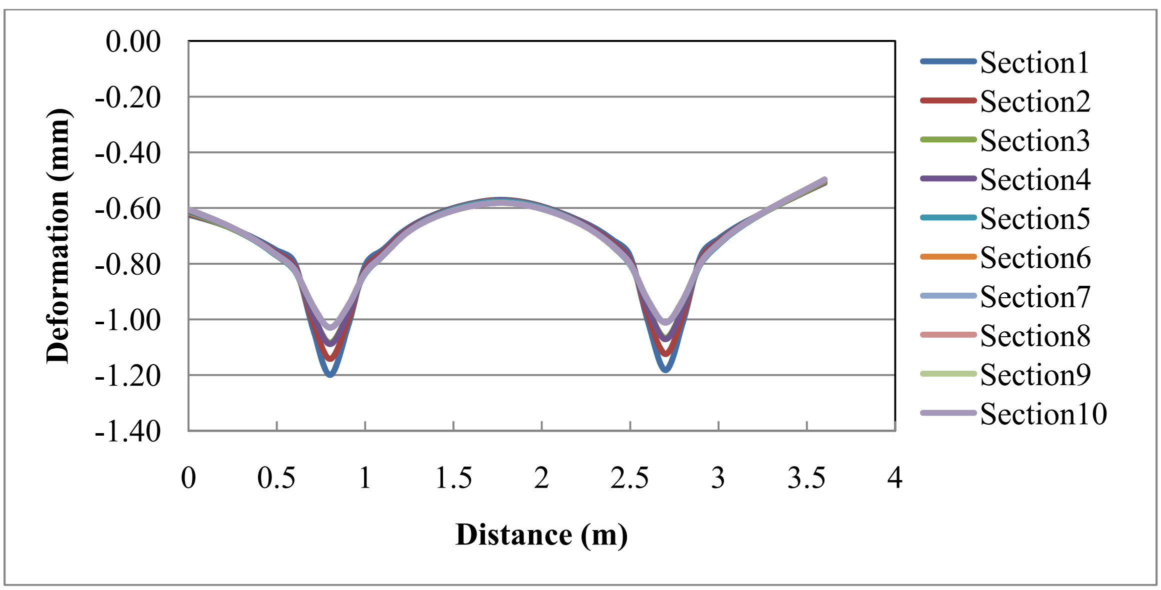


Figure 8-21 Transverse Deformation Profile for Mix 6N (Unconditioned)

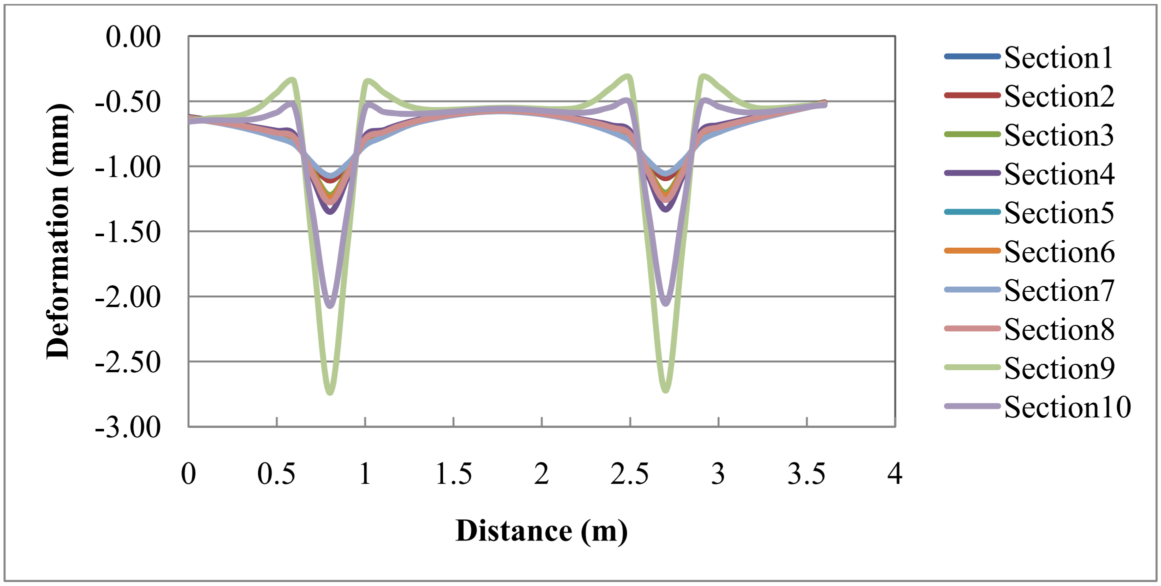


Figure 8-22 Transverse Deformation Profile for Mix 218 (Unconditioned)

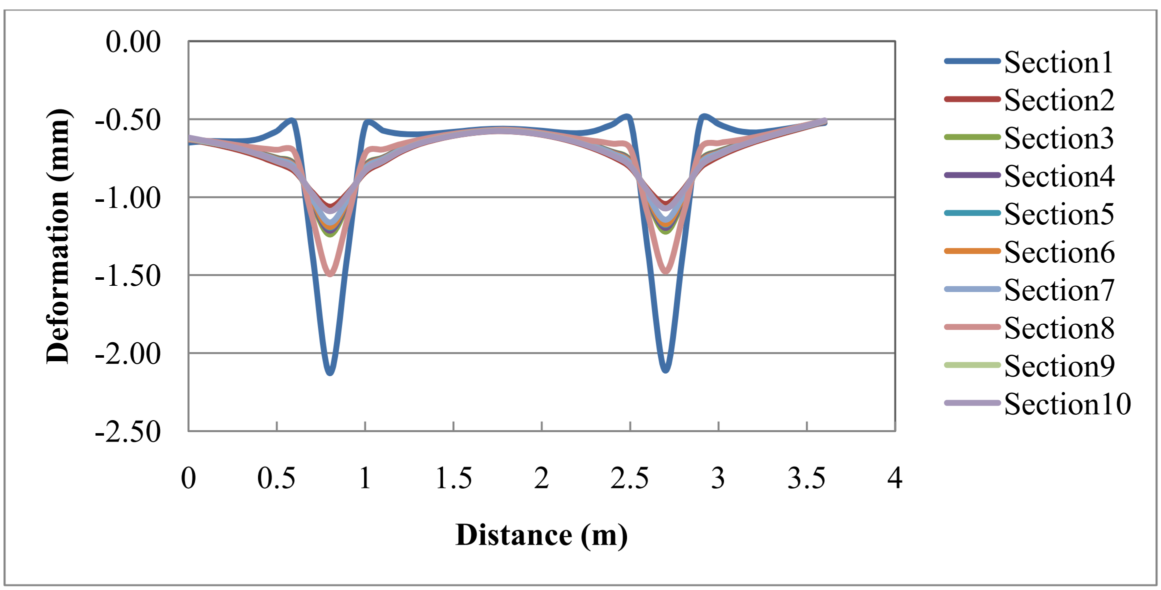


Figure 8-23 Transverse Deformation Profile for Mix 235I (Unconditioned)

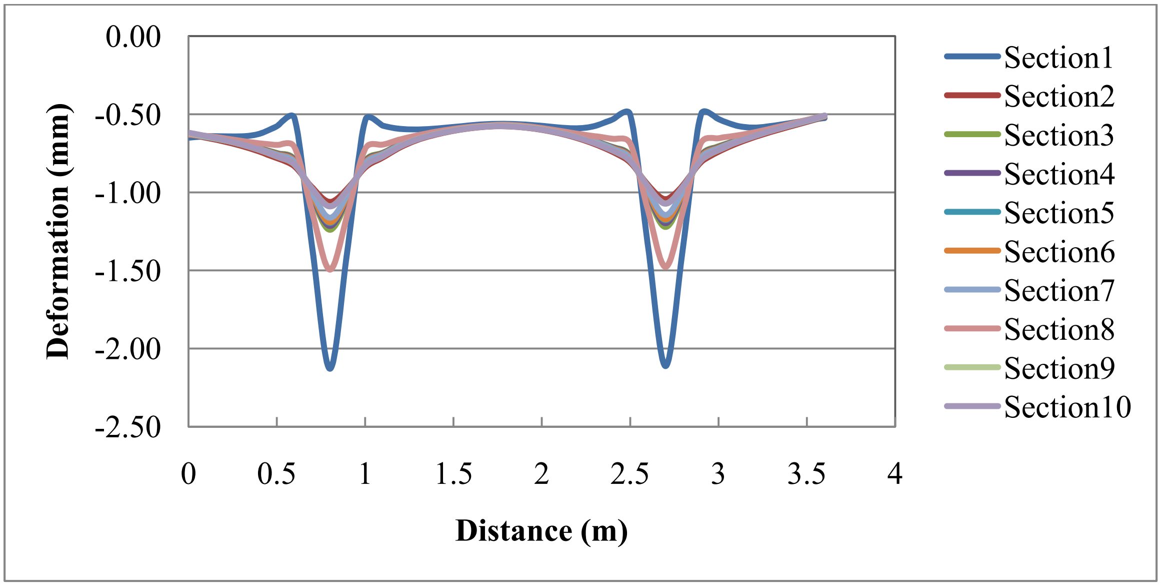


Figure 8-24 Transverse Deformation Profile for Mix 235S (Unconditioned)

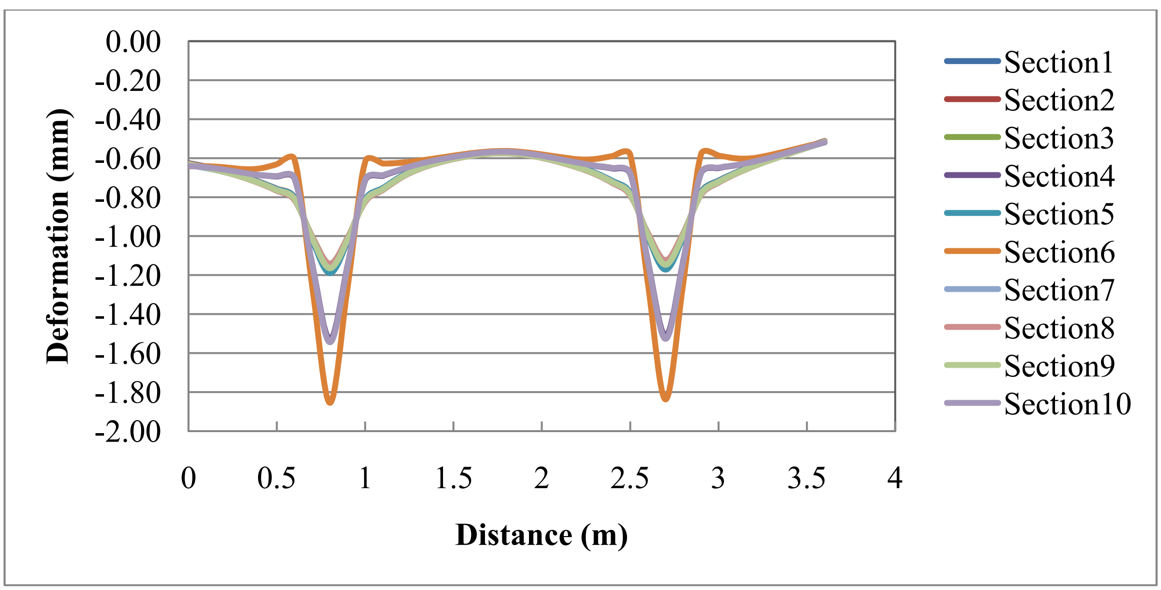


Figure 8-25 Transverse Deformation Profile for Mix 330B (Unconditioned)

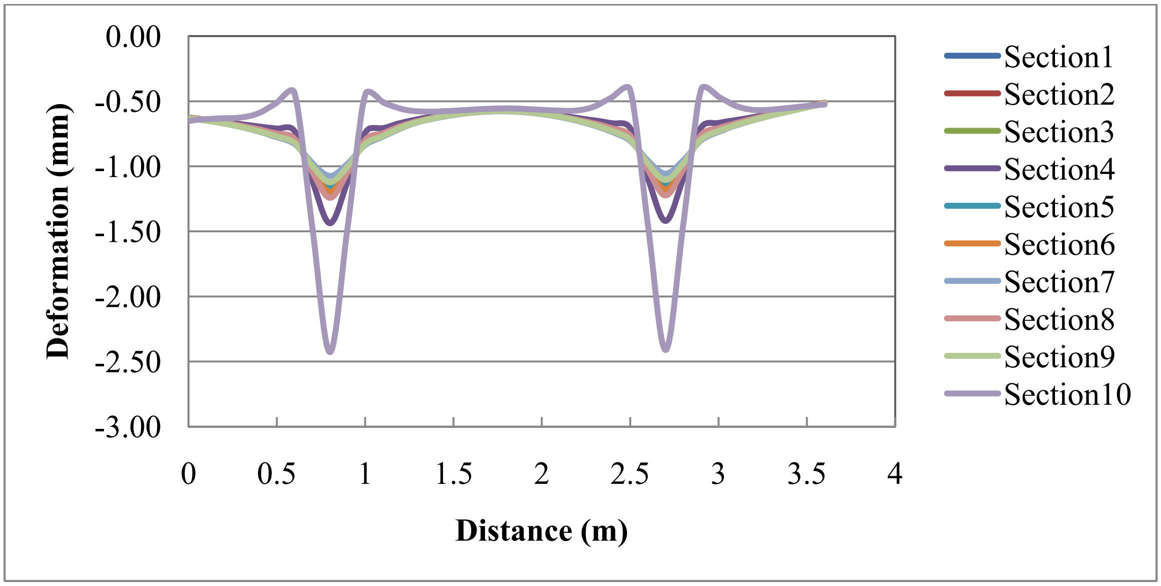


Figure 8-26 Transverse Deformation Profile for Mix 330I (Unconditioned)

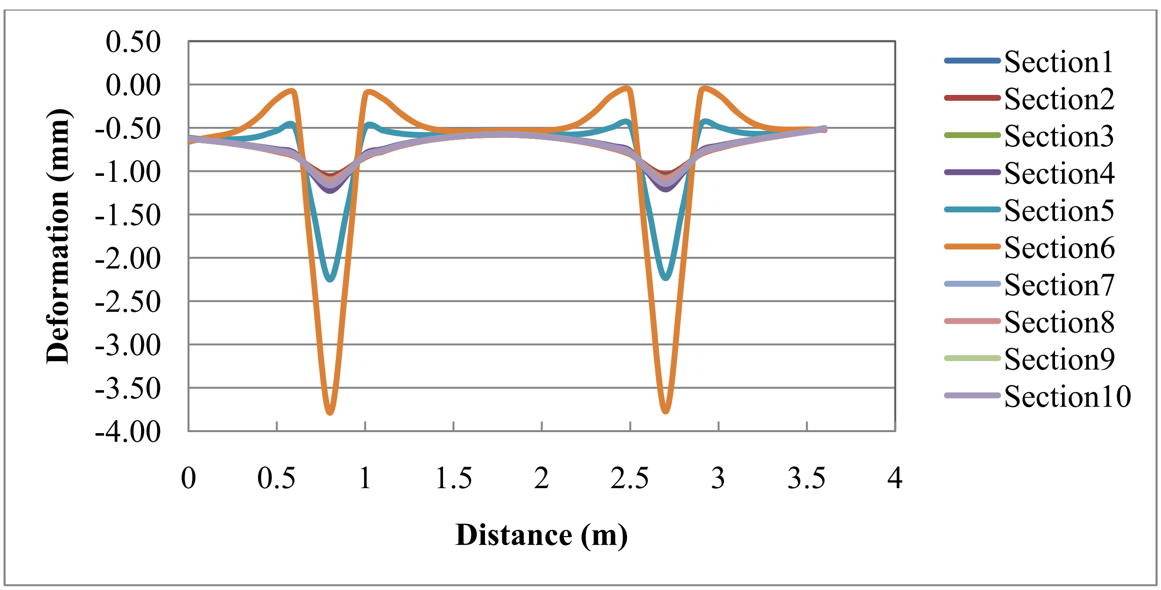


Figure 8-27 Transverse Deformation Profile for Mix 330S (Unconditioned)

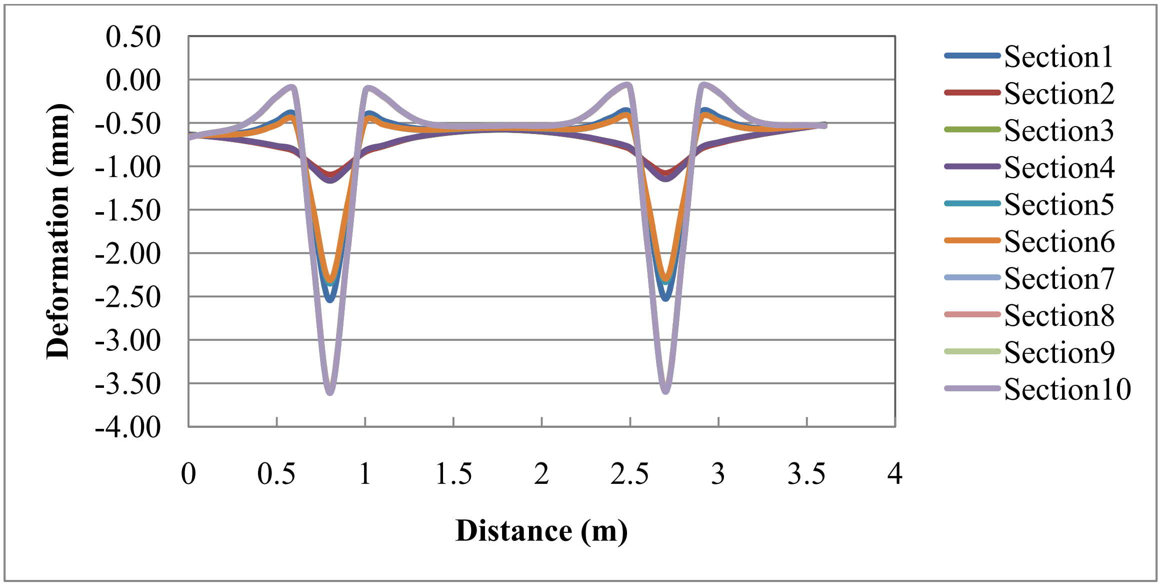


Figure 8-28 Transverse Deformation Profile for Mix ALT (Unconditioned)

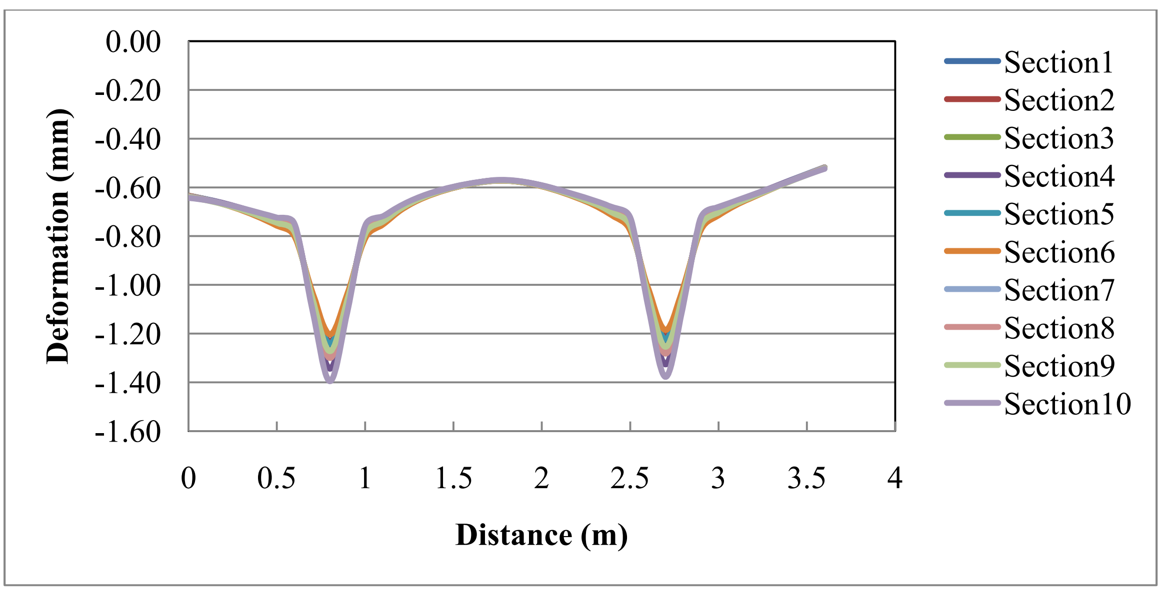


Figure 8-29 Transverse Deformation Profile for Mix DED (Unconditioned)

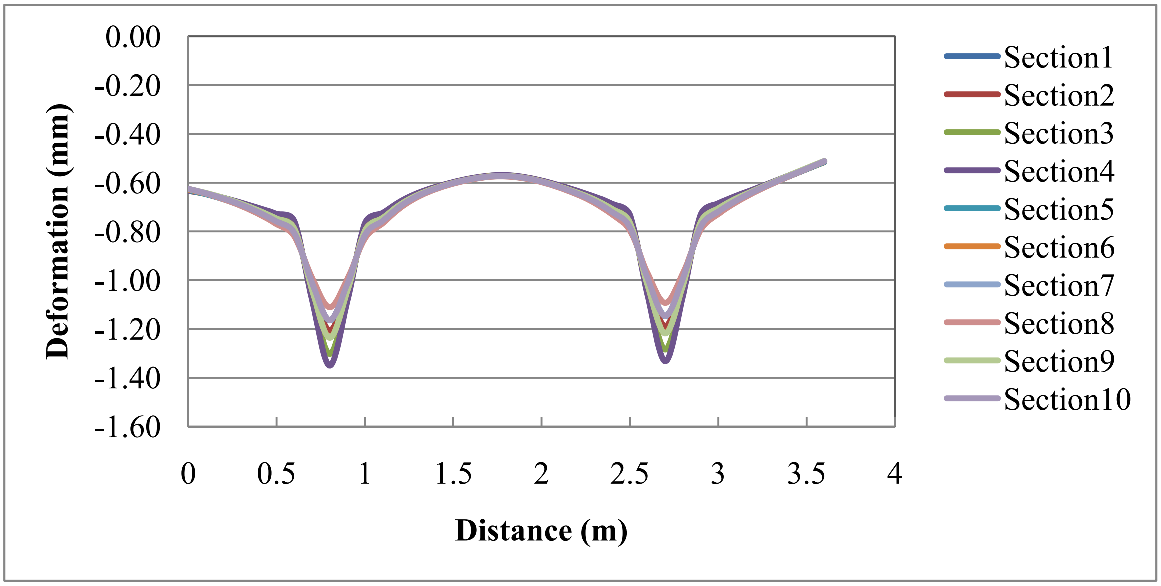


Figure 8-30 Transverse Deformation Profile for Mix F52 (Unconditioned)

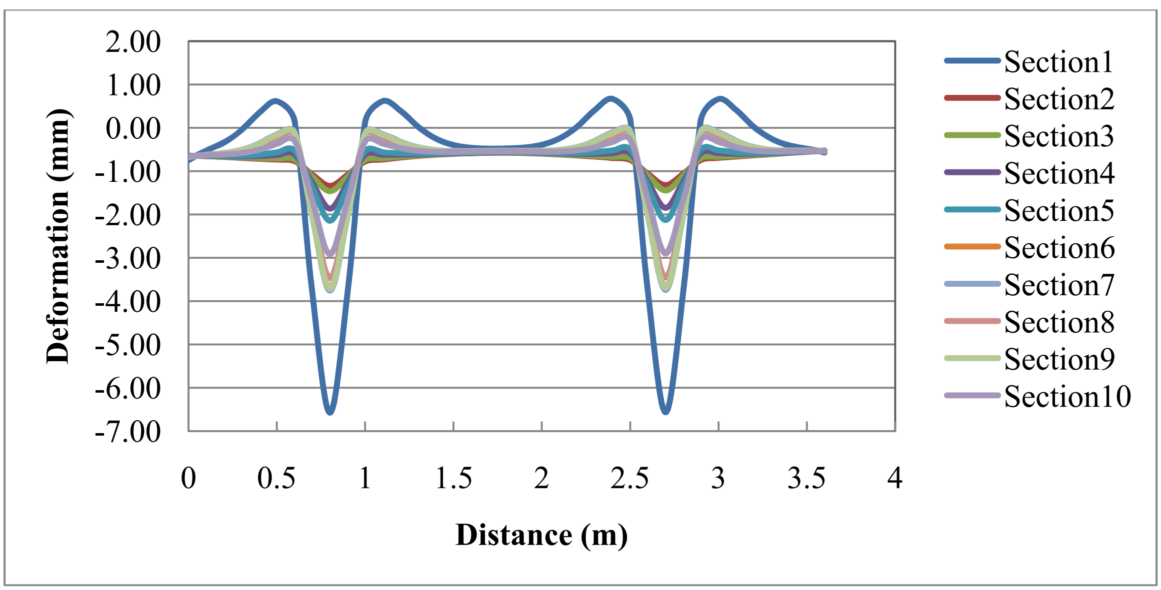


Figure 8-31 Transverse Deformation Profile for Mix HW4 (Unconditioned)

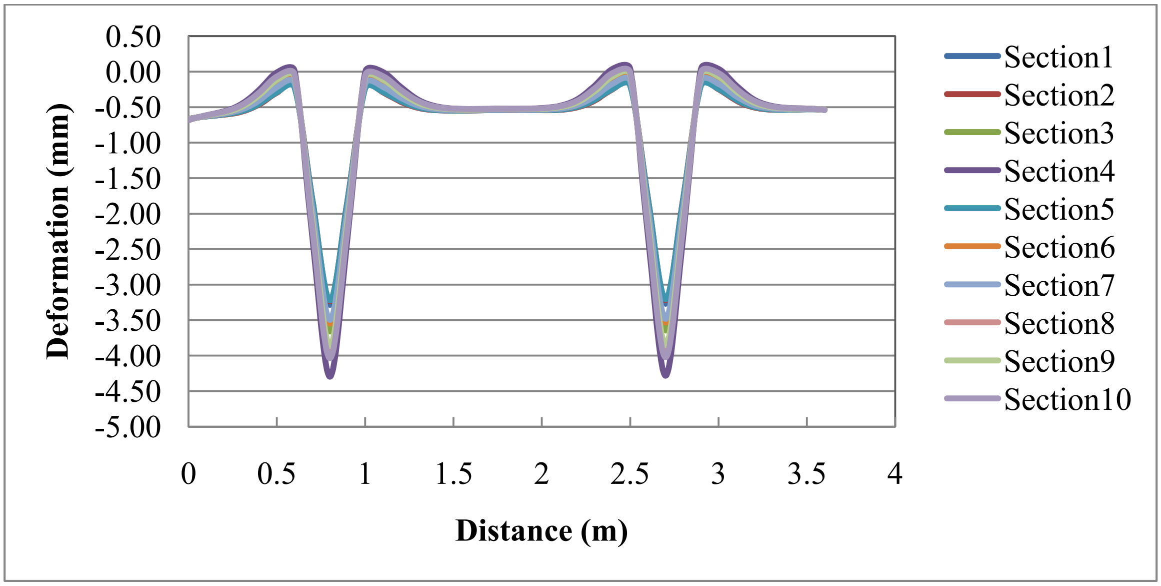


Figure 8-32 Transverse Deformation Profile for Mix I80B (Unconditioned)

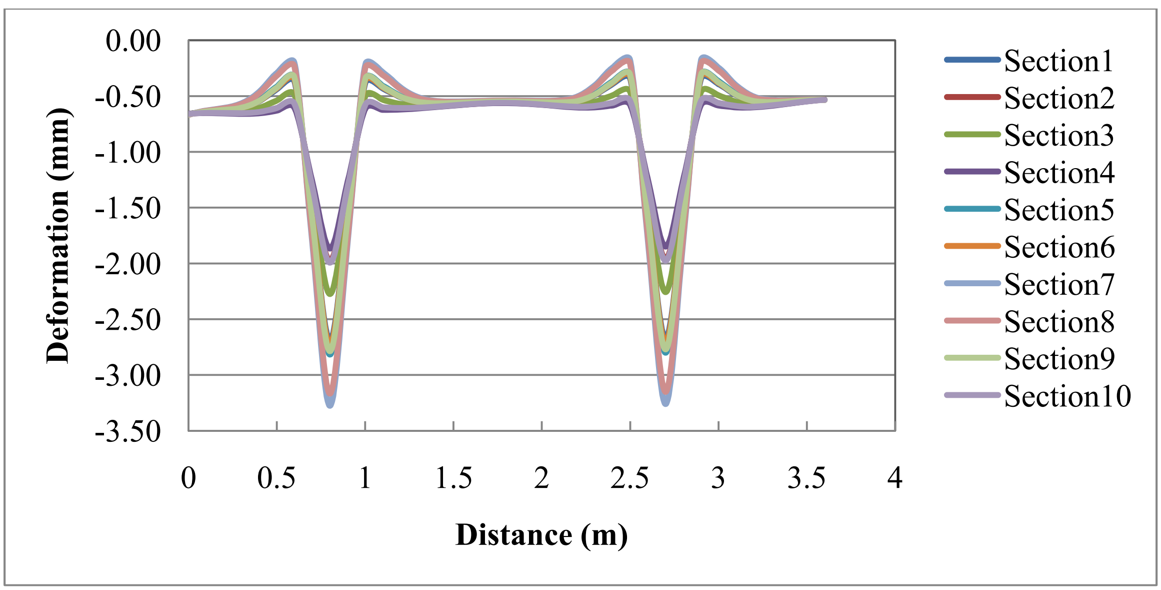


Figure 8-33 Transverse Deformation Profile for Mix I80S (Unconditioned)

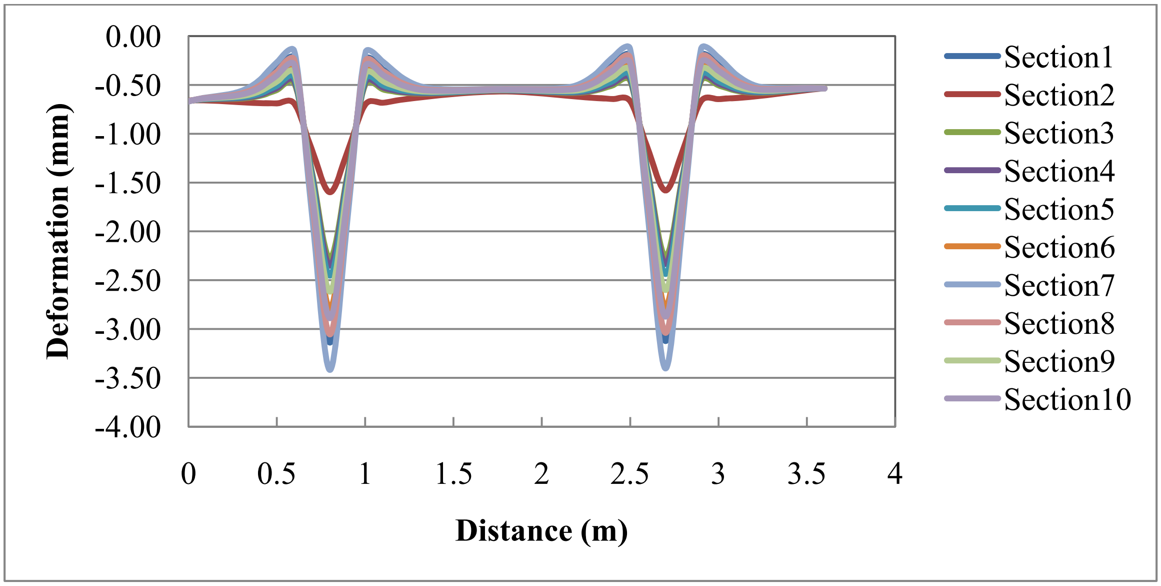


Figure 8-34 Transverse Deformation Profile for Mix NW (Unconditioned)

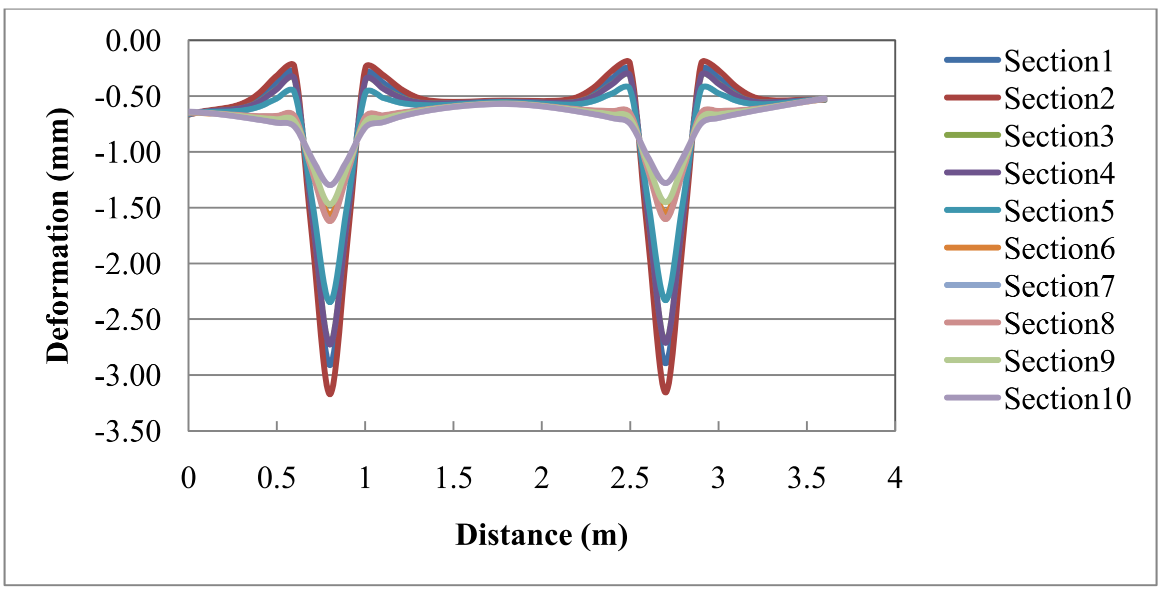


Figure 8-35 Transverse Deformation Profile for Mix Rose (Unconditioned)

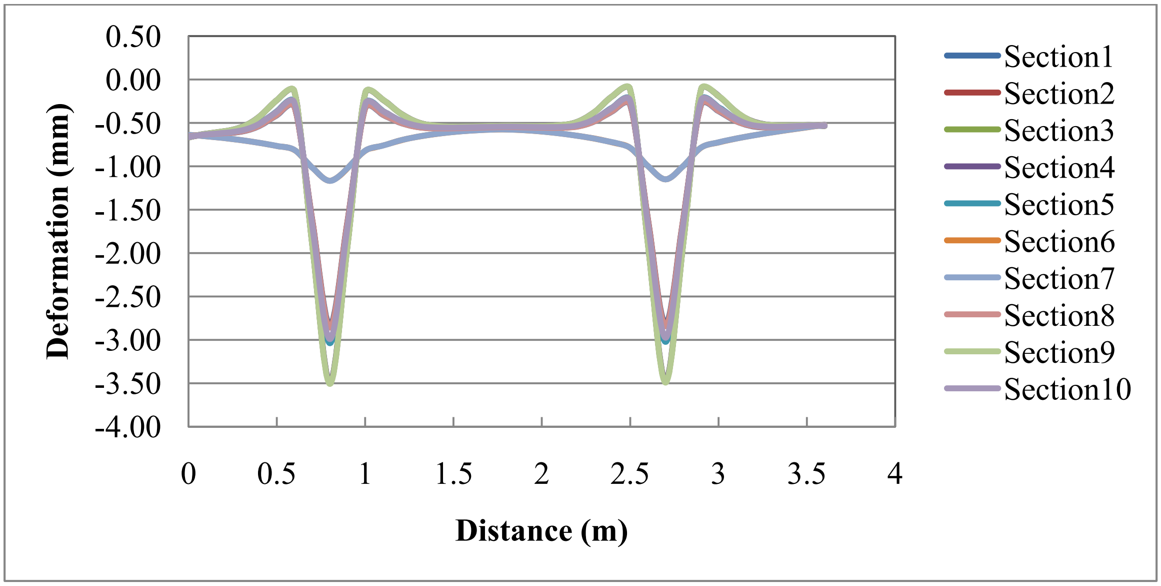


Figure 8-36 Transverse Deformation Profile for Mix Jewell (Unconditioned)

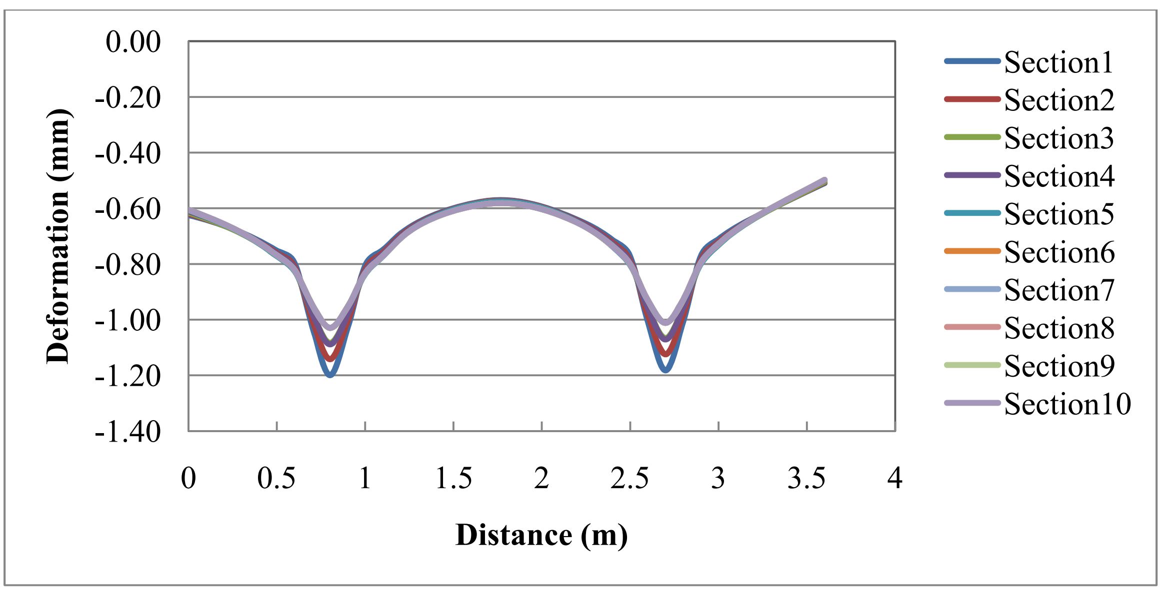


Figure 8-37 Transverse Deformation Profile for Mix 6N (Moisture-Conditioned)

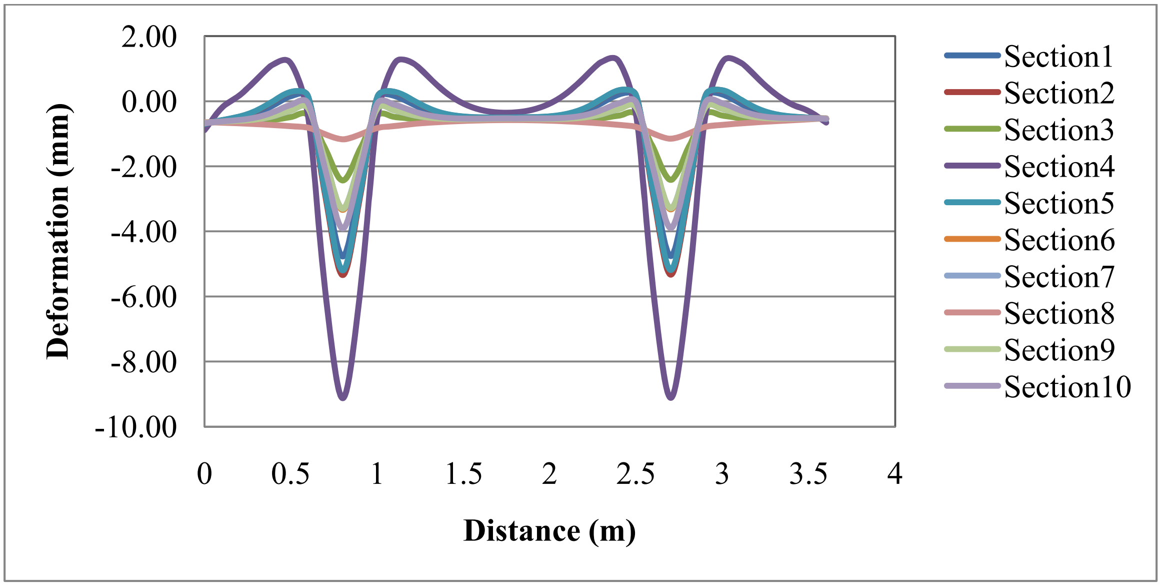


Figure 8-38 Transverse Deformation Profile for Mix 218 (Moisture-Conditioned)

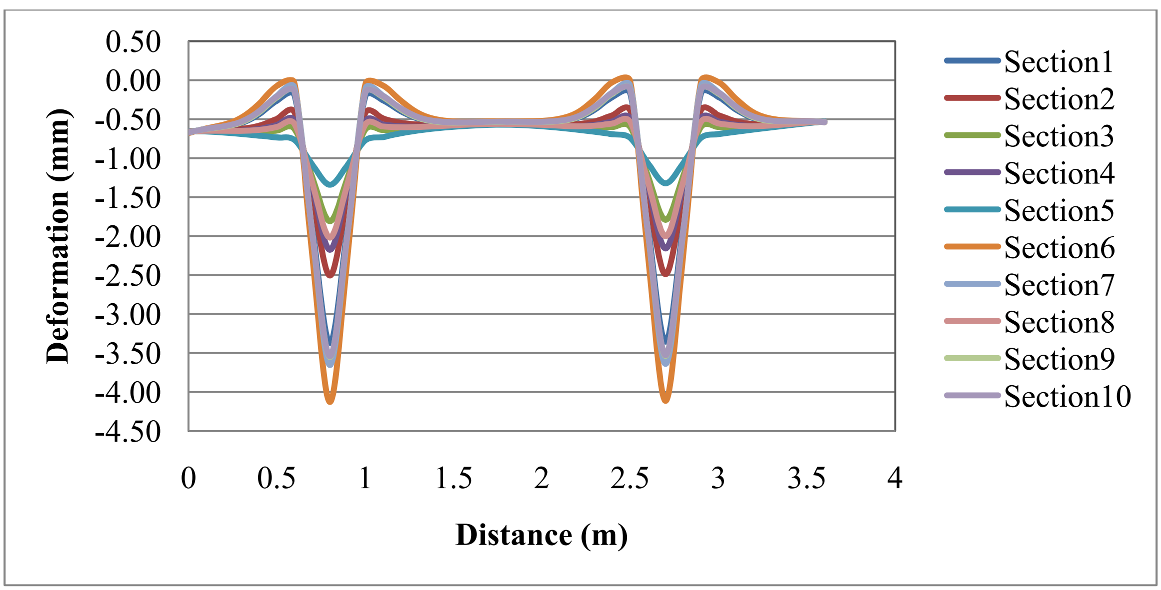


Figure 8-39 Transverse Deformation Profile for Mix 235I (Moisture-Conditioned)

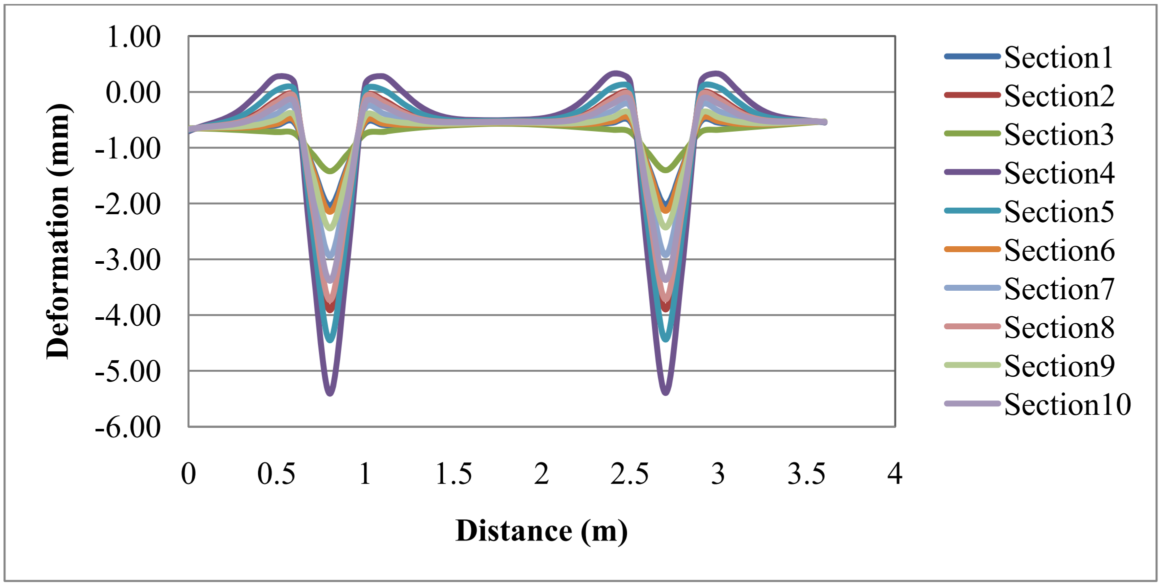


Figure 8-40 Transverse Deformation Profile for Mix 235S (Moisture-Conditioned)

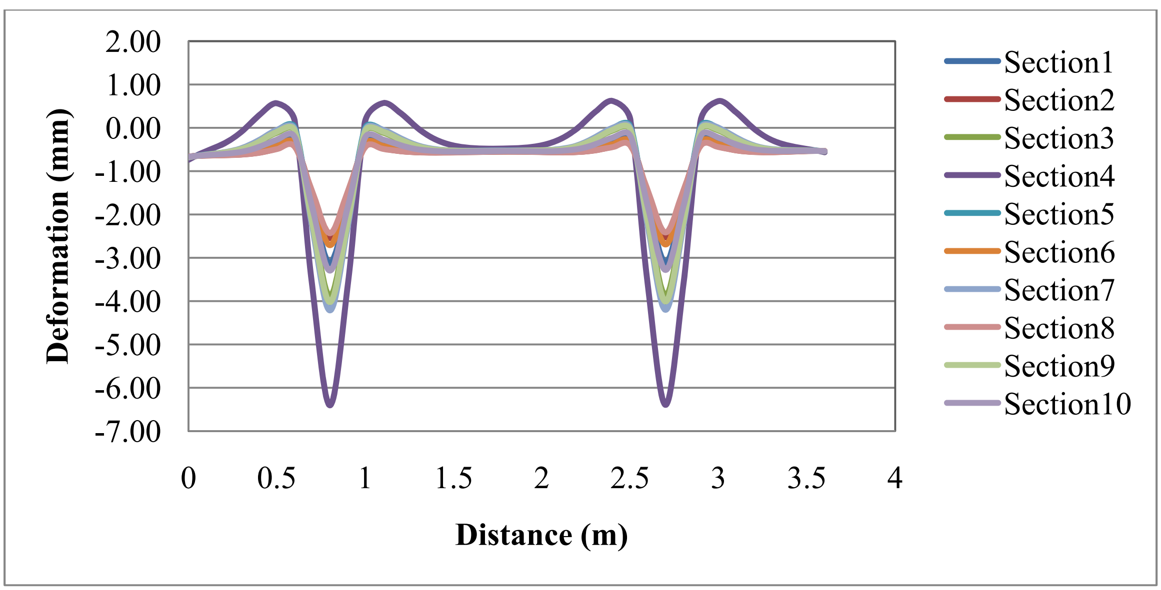


Figure 8-41 Transverse Deformation Profile for Mix 330B (Moisture-Conditioned)

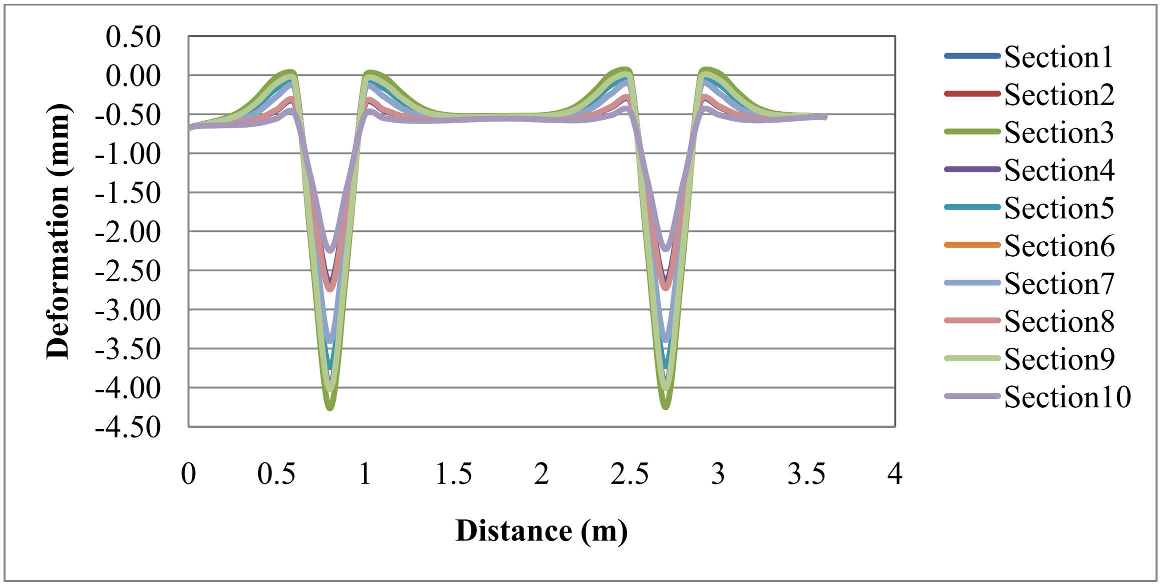


Figure 8-42 Transverse Deformation Profile for Mix 330I (Moisture-Conditioned)

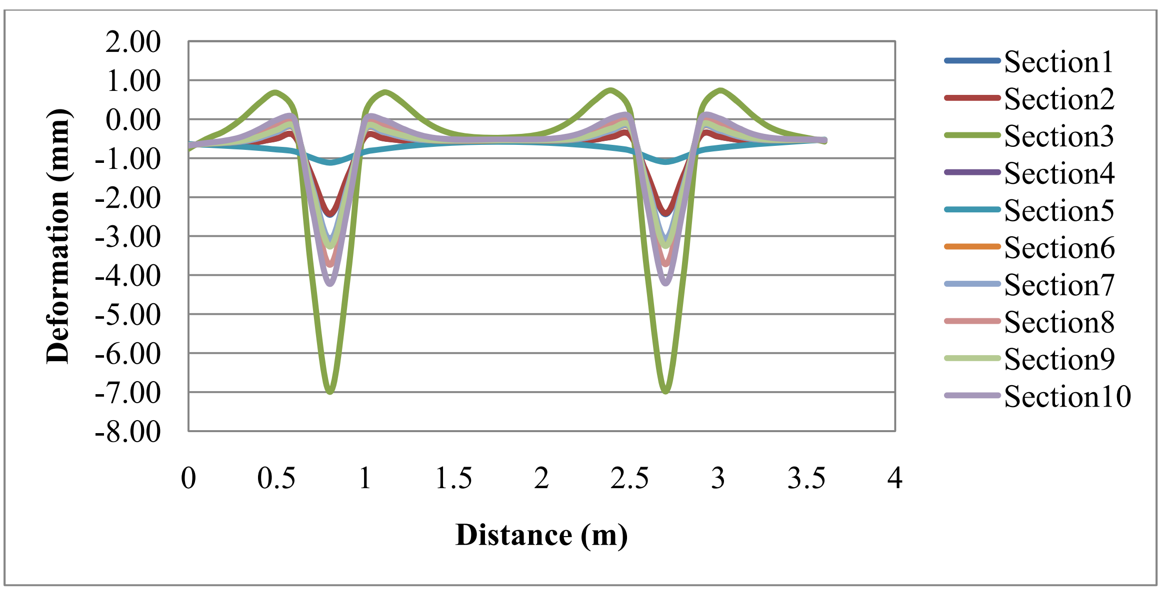


Figure 8-43 Transverse Deformation Profile for Mix 330S (Moisture-Conditioned)

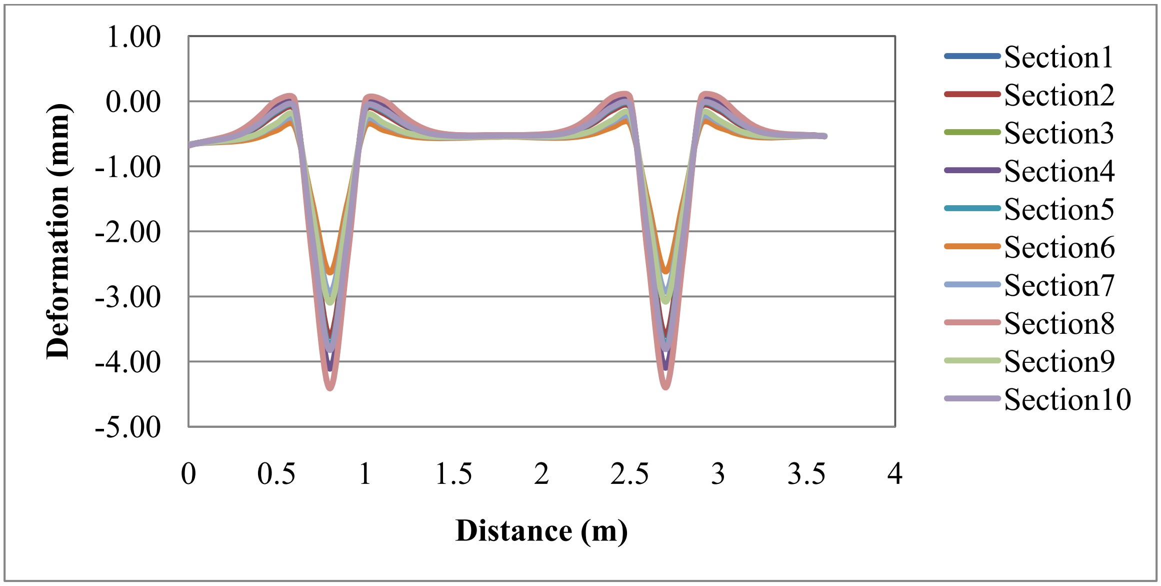


Figure 8-44 Transverse Deformation Profile for Mix ALT (Moisture-Conditioned)

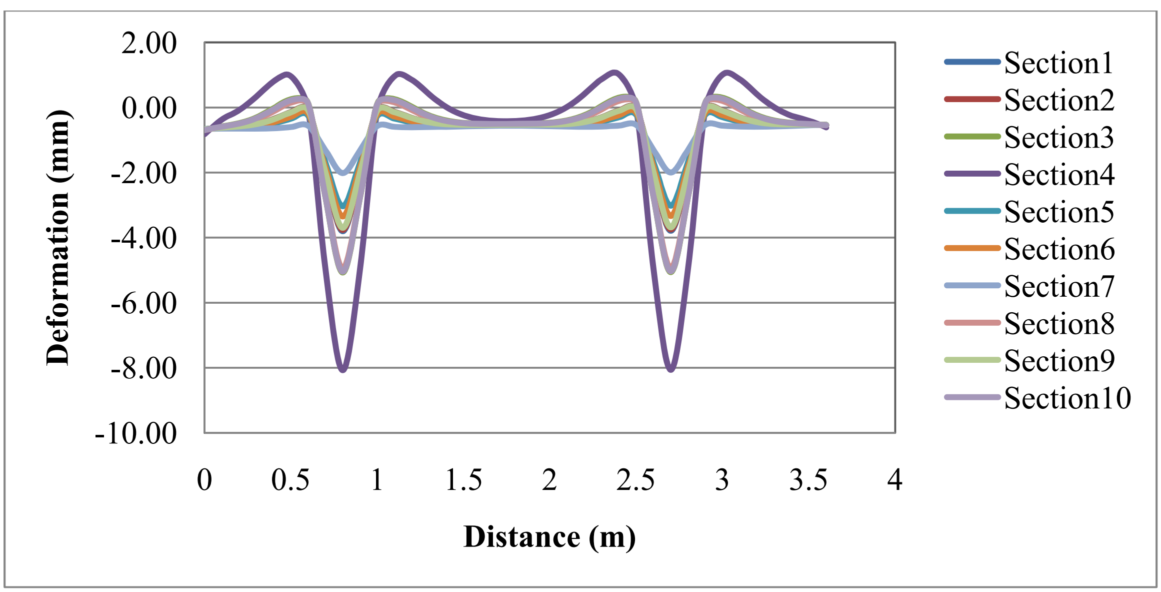


Figure 8-45 Transverse Deformation Profile for Mix DED (Moisture-Conditioned)

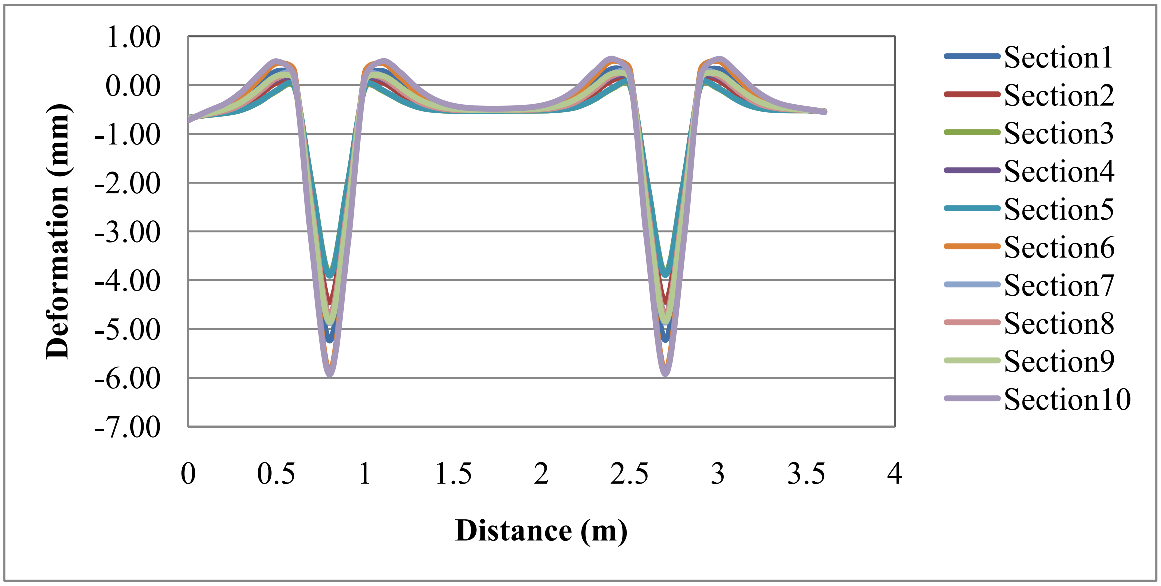


Figure 8-46 Transverse Deformation Profile for Mix F52 (Moisture-Conditioned)

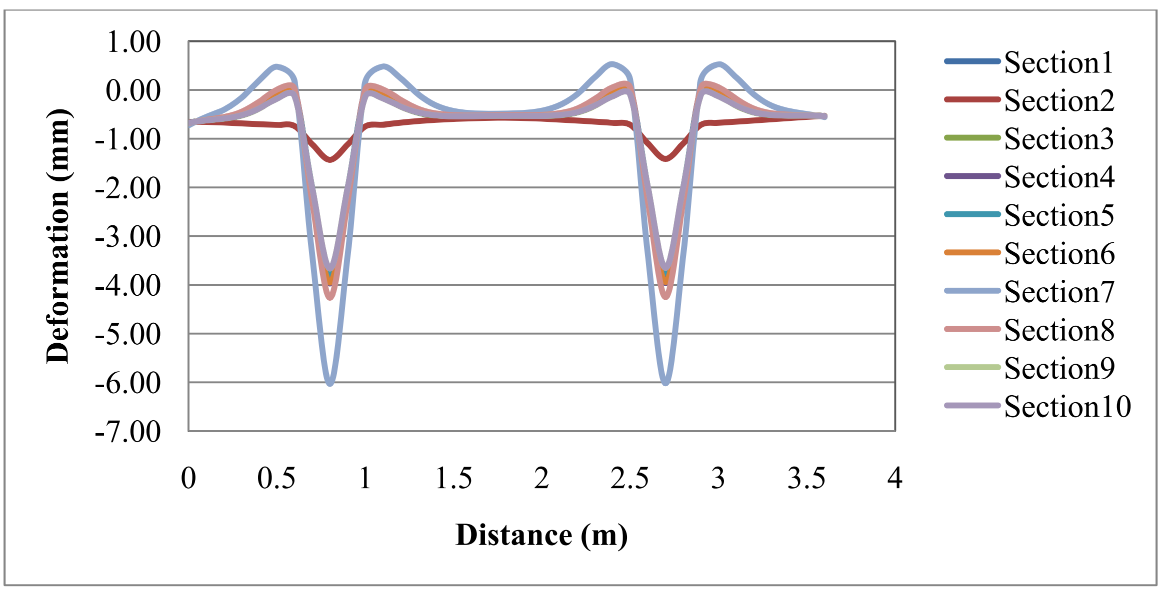


Figure 8-47 Transverse Deformation Profile for Mix HW4 (Moisture-Conditioned)

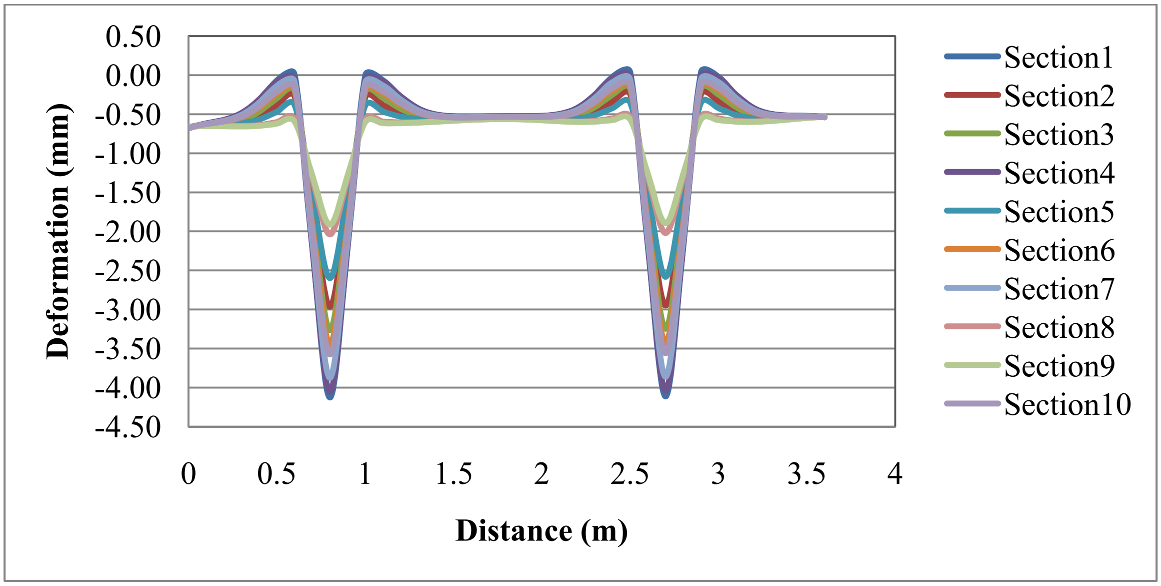


Figure 8-48 Transverse Deformation Profile for Mix I80B (Moisture-Conditioned)

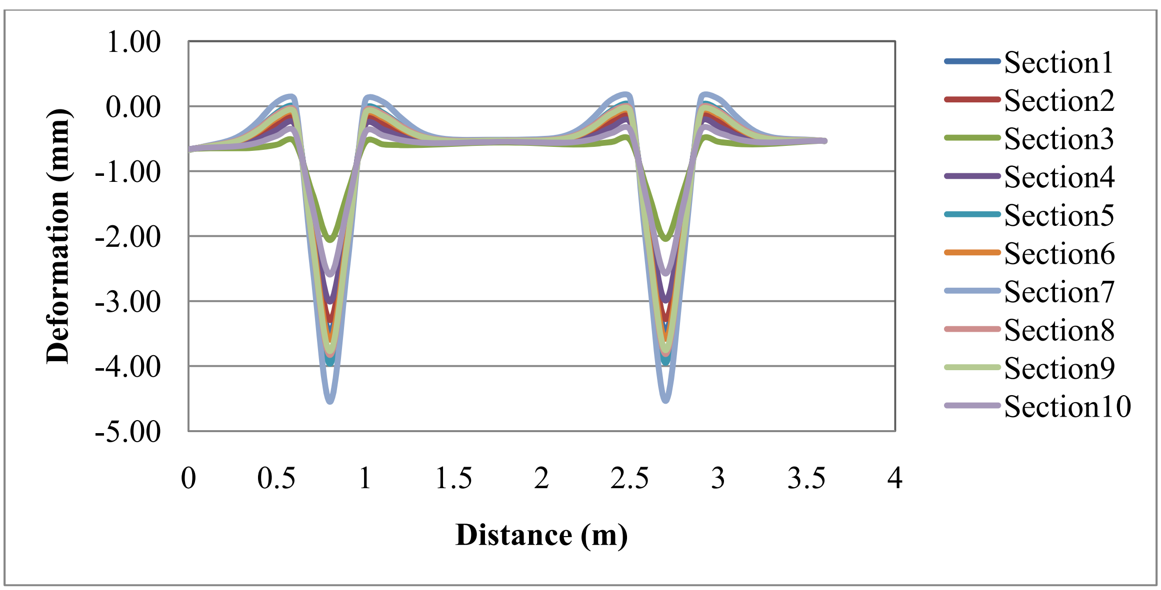


Figure 8-49 Transverse Deformation Profile for Mix I80S (Moisture-Conditioned)

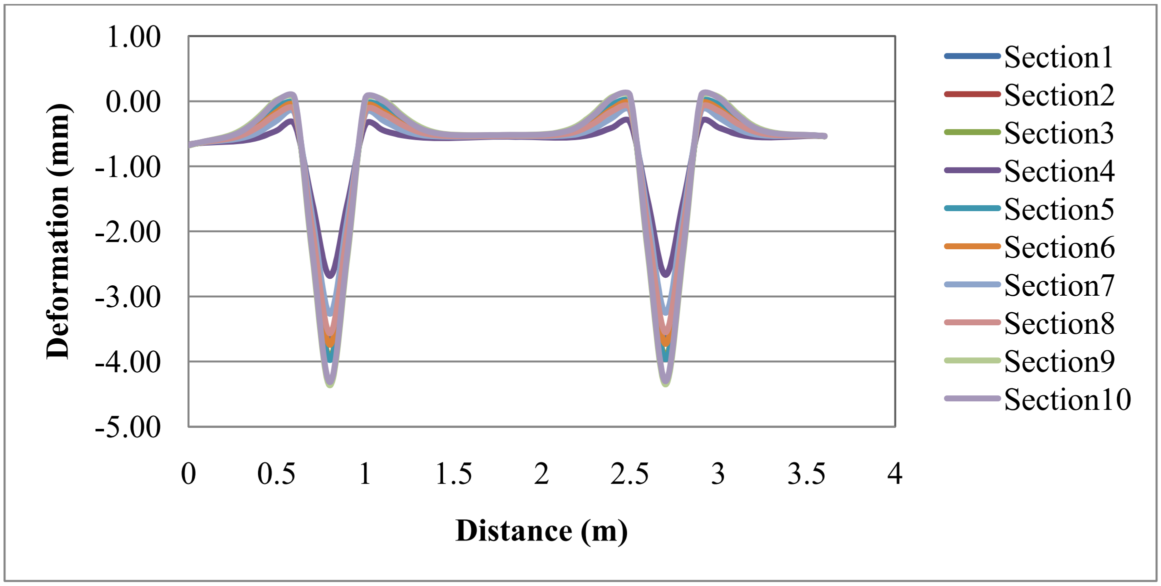


Figure 8-50 Transverse Deformation Profile for Mix NW (Moisture-Conditioned)

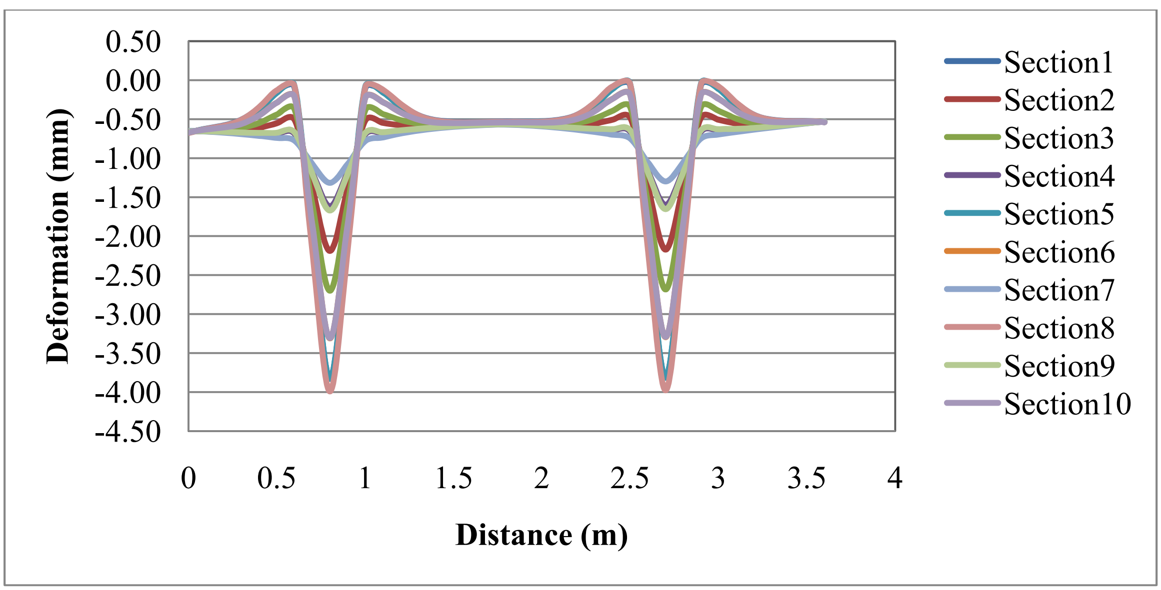


Figure 8-51 Transverse Deformation Profile for Mix Rose (Moisture-Conditioned)

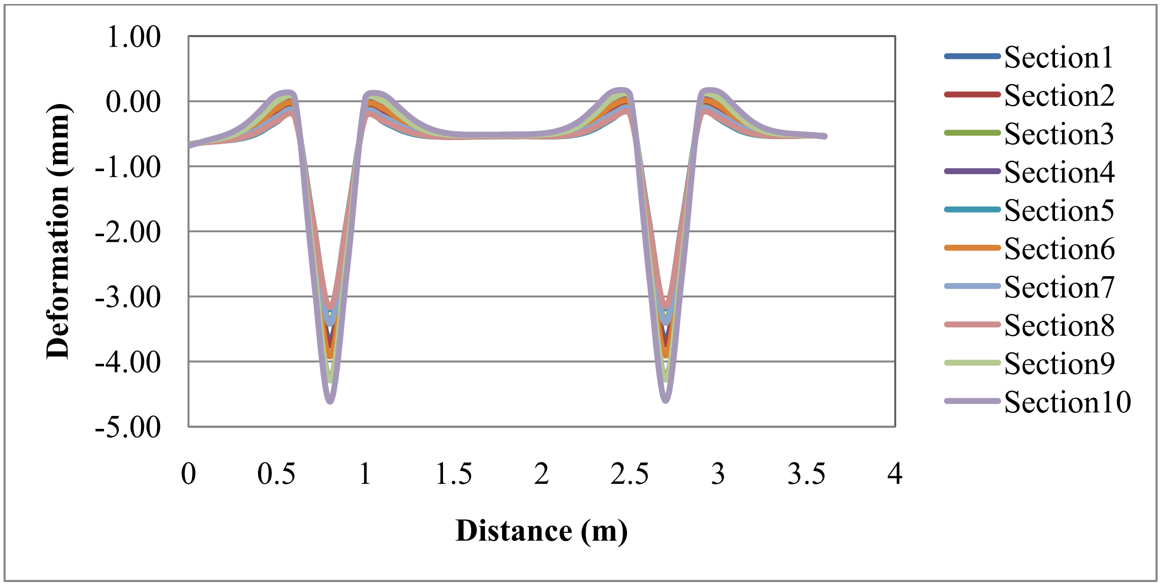


Figure 8-52 Transverse Deformation Profile for Mix Jewell (Moisture-Conditioned)

Figures 8-53 through 8-68 show the deformation along the wheel path for all the mixes. Each chart shows the deformations for both the moisture conditioned and the unconditioned samples. Each 1 meter in the chart represents one of the sections simulated so the variability in the response between each section and the other is caused by the material variability. It can be seen from the charts that the material variability can cause some instances of the moisture conditioned section to behave better than some of the unconditioned sections. Figure 8-53 includes also the results when the average material data was used as input.

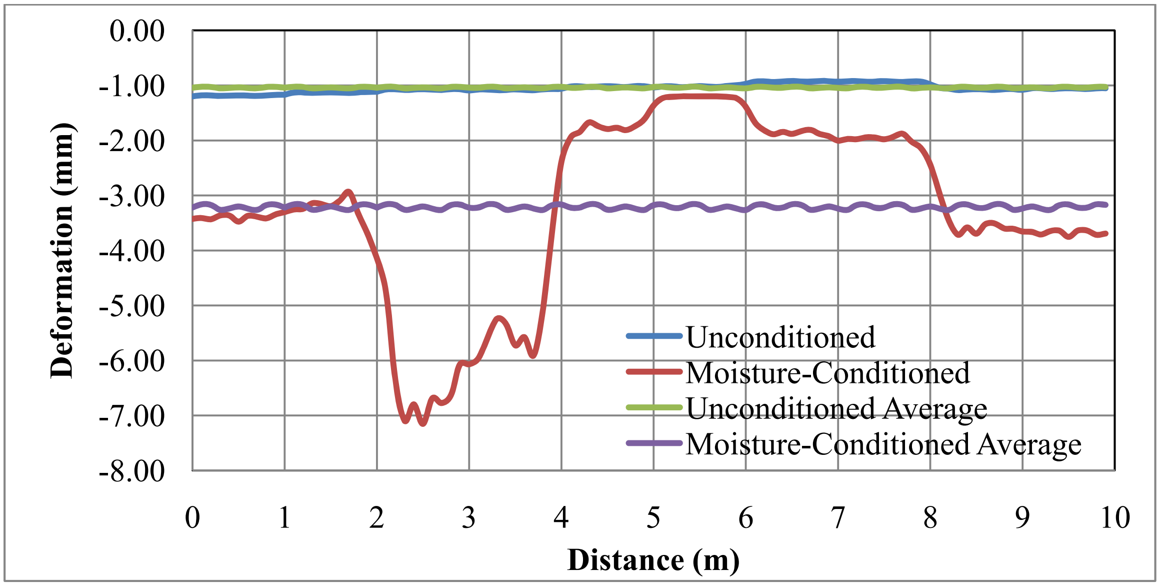


Figure 8-53 Longitudinal Deformation Profile for Mix 6N

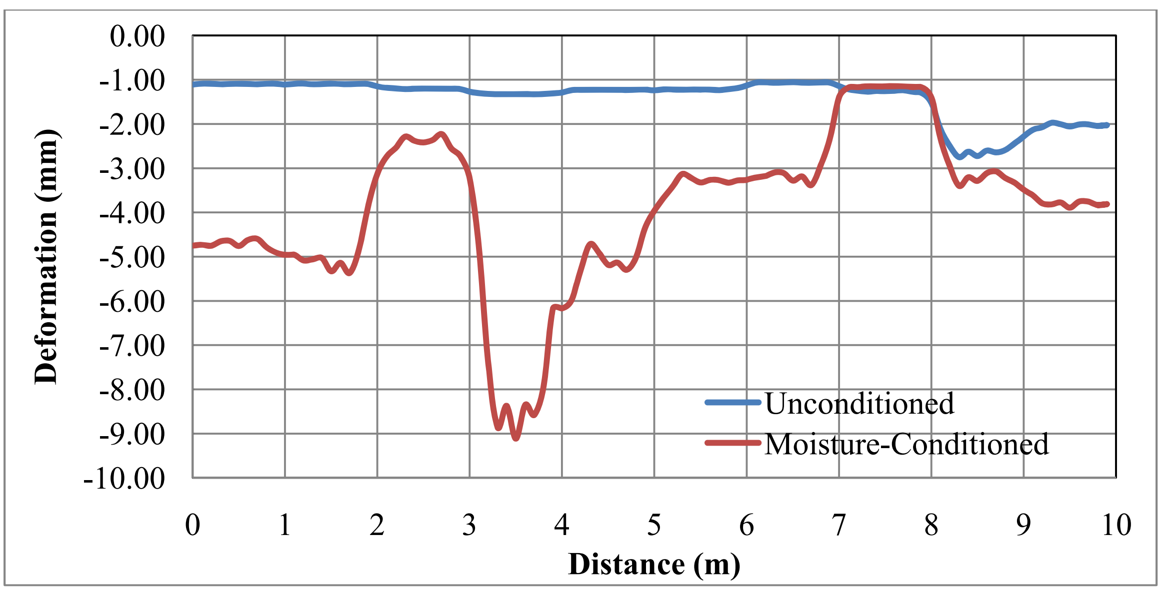


Figure 8-54 Longitudinal Deformation Profile for Mix 218

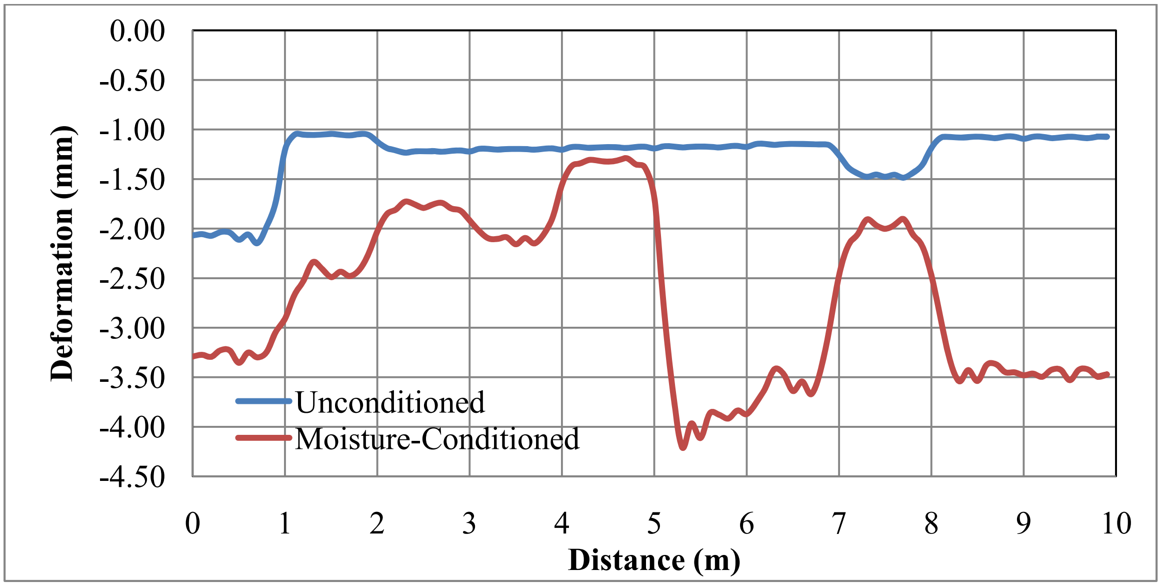


Figure 8-55 Longitudinal Deformation Profile for Mix 235I

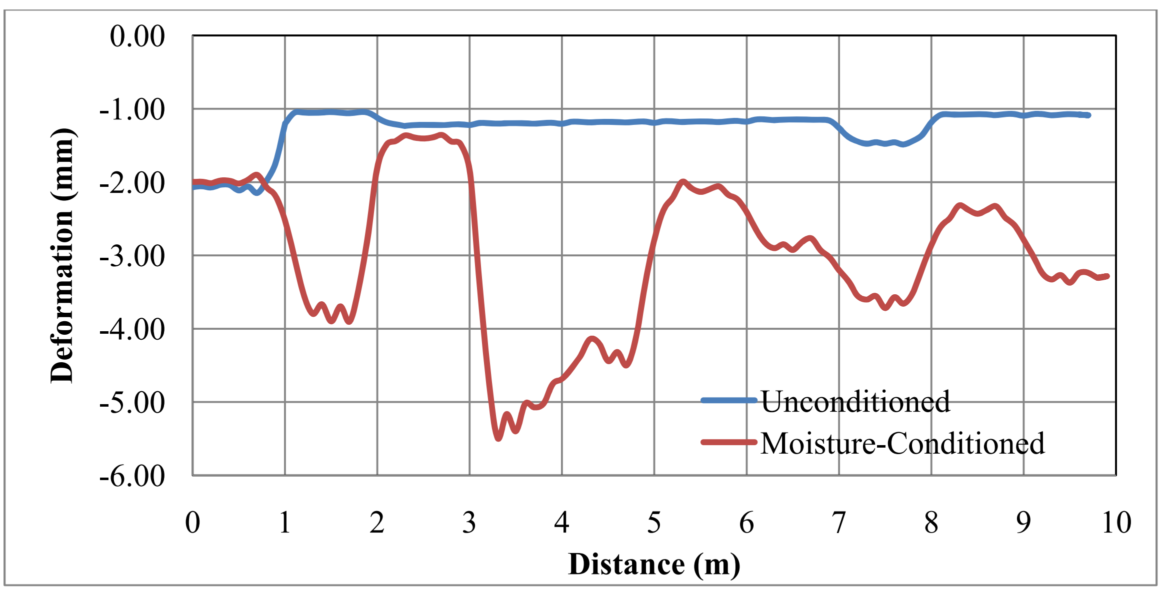


Figure 8-56 Longitudinal Deformation Profile for Mix 235S

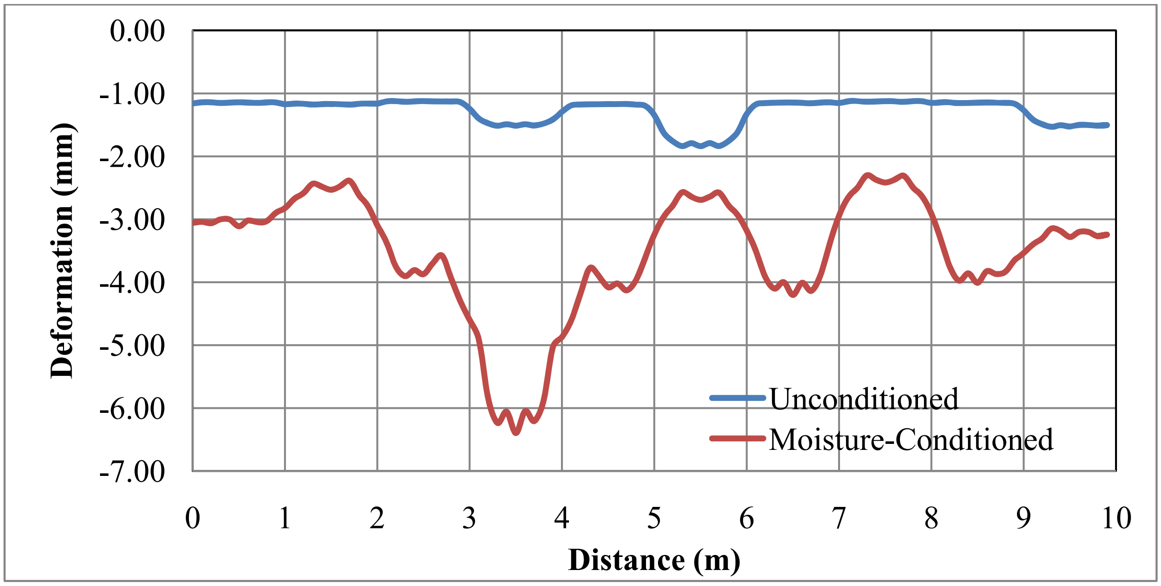


Figure 8-57 Longitudinal Deformation Profile for Mix 330B

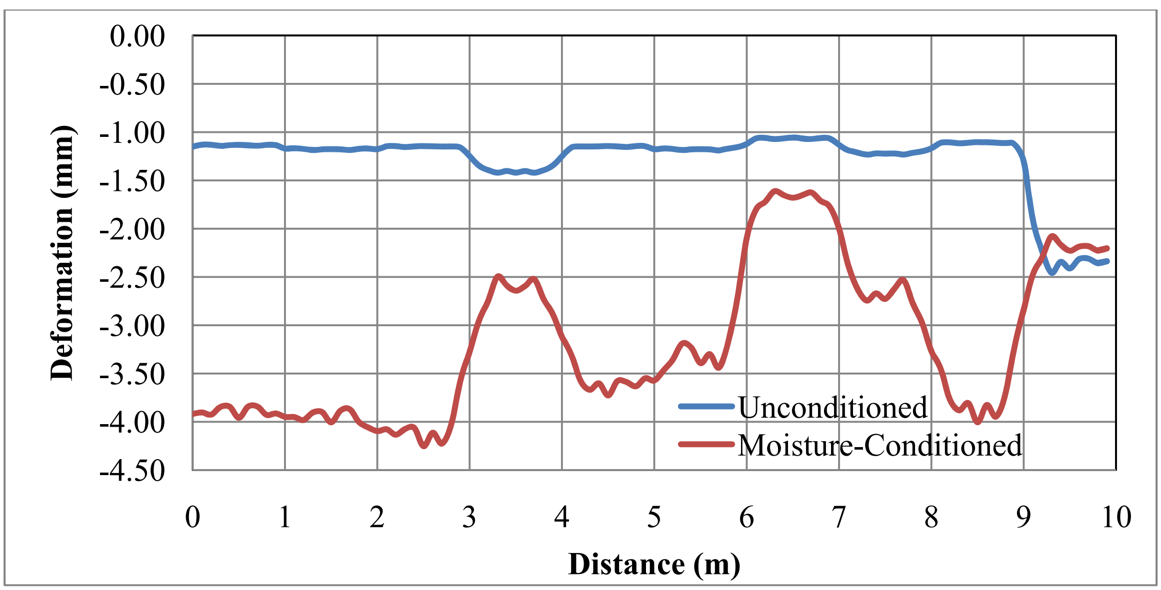


Figure 8-58 Longitudinal Deformation Profile for Mix 330I

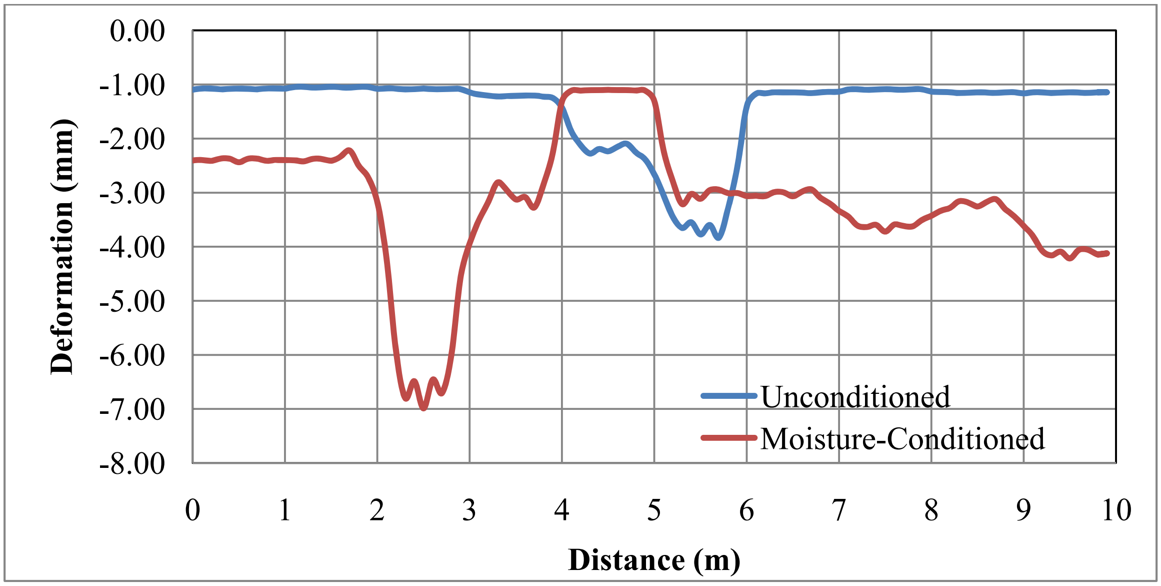


Figure 8-59 Longitudinal Deformation Profile for Mix 330S

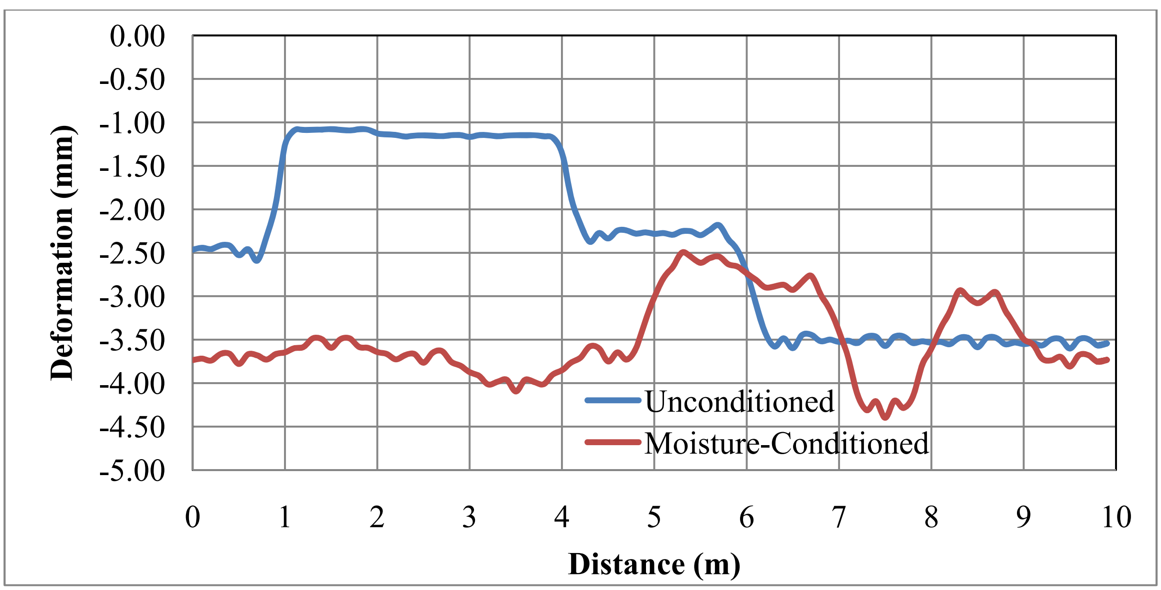


Figure 8-60 Longitudinal Deformation Profile for Mix ALT

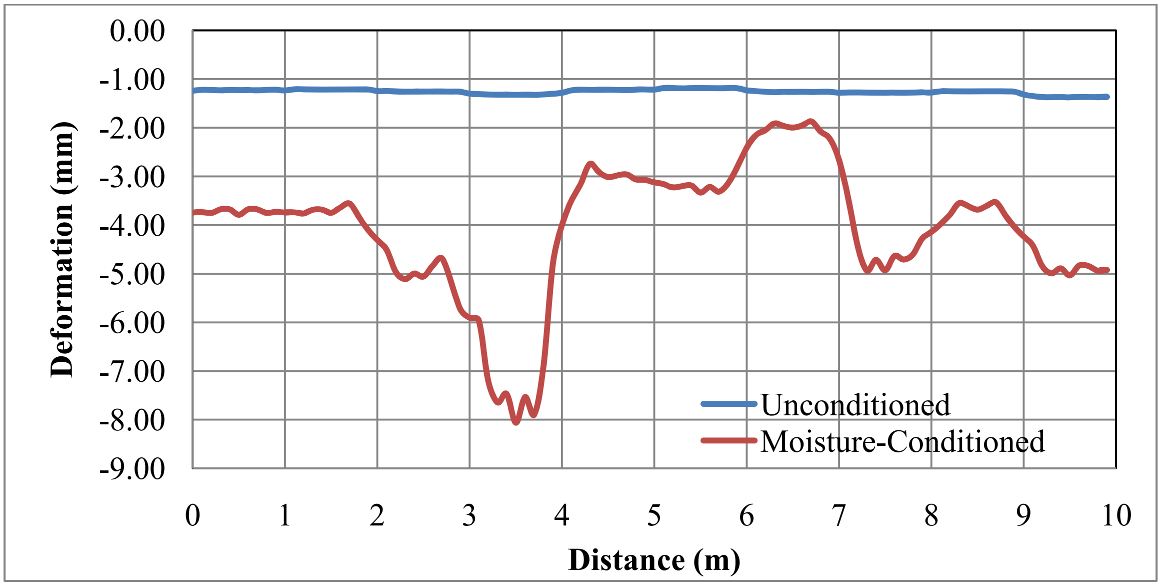


Figure 8-61 Longitudinal Deformation Profile for Mix DED

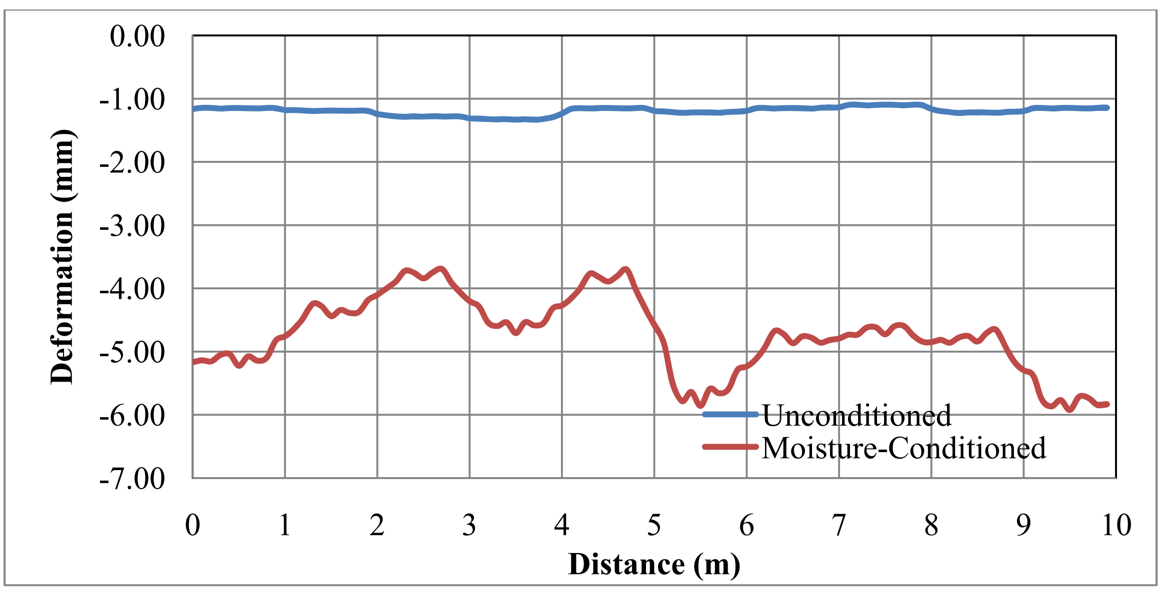


Figure 8-62 Longitudinal Deformation Profile for Mix F52

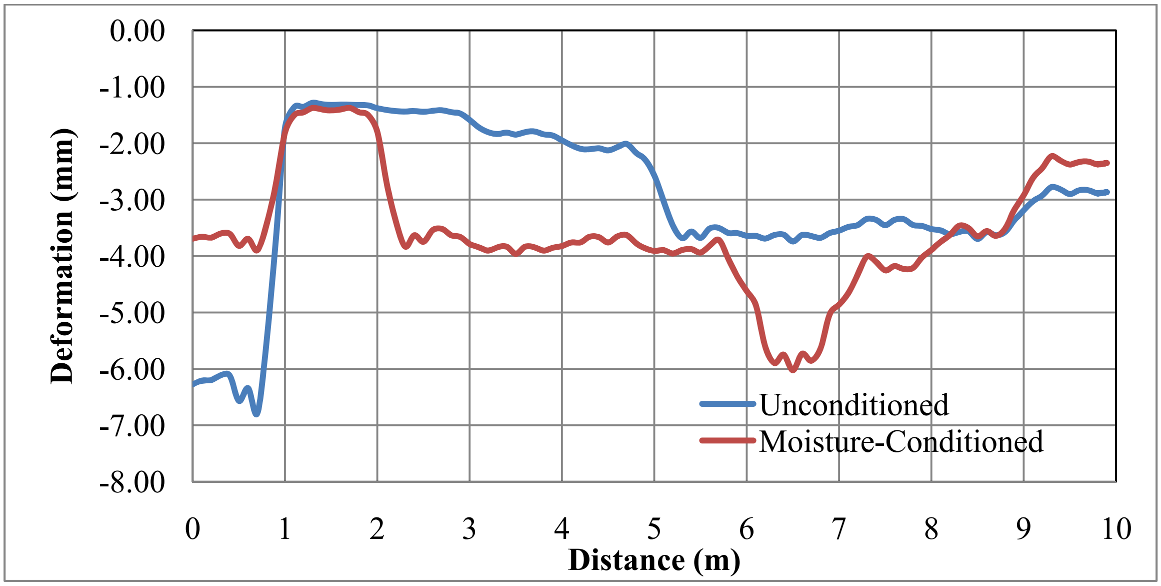


Figure 8-63 Longitudinal Deformation Profile for Mix HW4

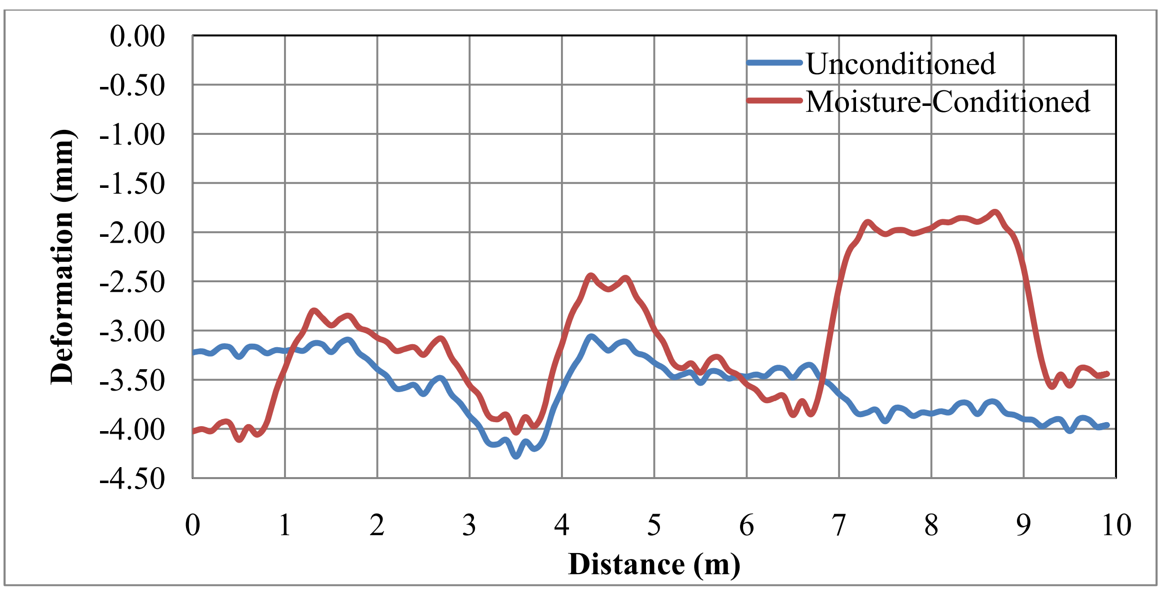


Figure 8-64 Longitudinal Deformation Profile for Mix I80B

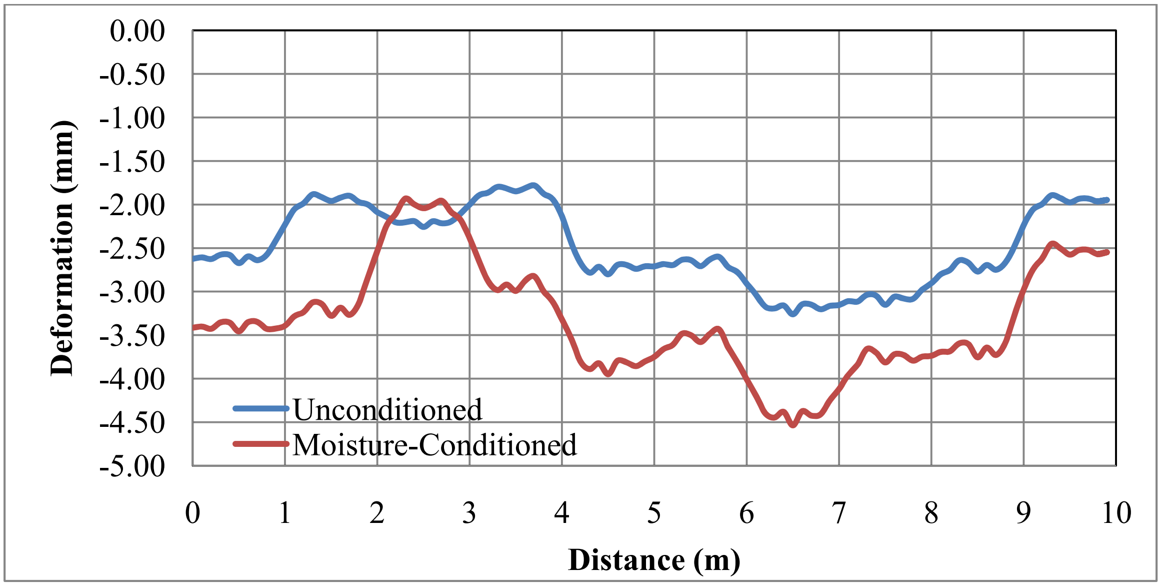


Figure 8-65 Longitudinal Deformation Profile for Mix I80S

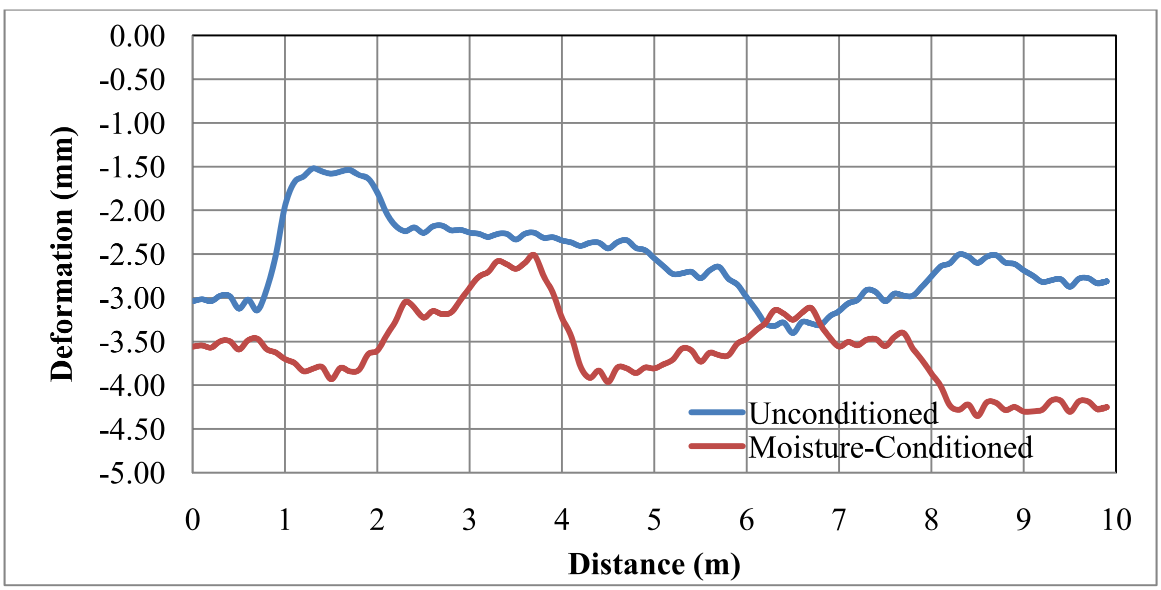


Figure 8-66 Longitudinal Deformation Profile for Mix NW

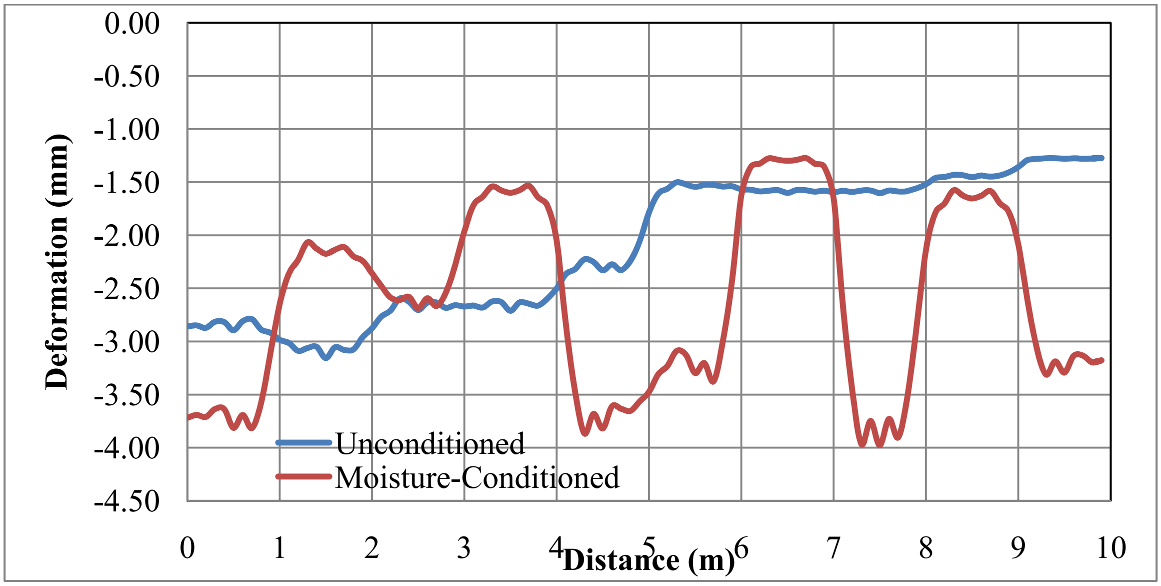


Figure 8-67 Longitudinal Deformation Profile for Mix Rose

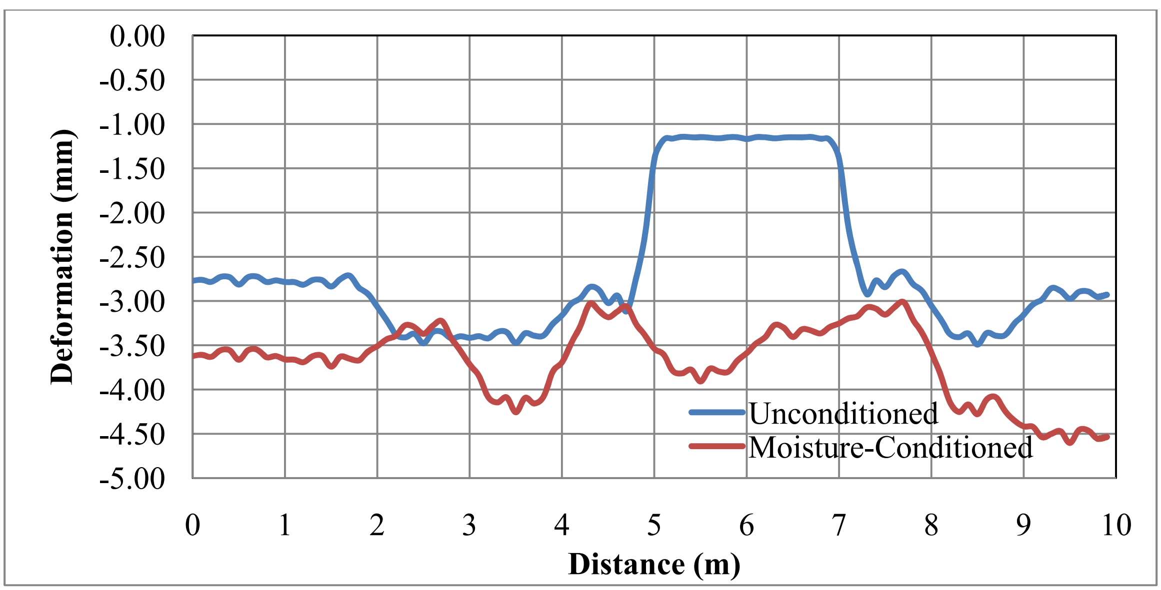


Figure 8-68 Longitudinal Deformation Profile for Mix Jewell

8.6 Analysis of finite element results

The deformation under the wheel path at the middle of each section was recorded and summarized in Tables 8-1 and 8-2 for the unconditioned and conditioned samples, respectively. Table 8-3 presents statistical summary of the results. It can be concluded from the results that the variability increased with sample conditioning for 10 out of the 16 mixes simulated. It can only be concluded that moisture conditioning of the samples increased the predicted deformation of the mixtures and this means that the mixes are more susceptible to rutting.

Table 8-1 Deformation Summary for Unconditioned Mixes

Mix	Section Deformation (mm)									
	1	2	3	4	5	6	7	8	9	10
6n	-1.20	-1.14	-1.08	-1.09	-1.03	-1.03	-1.03	-1.03	-1.03	-1.03
218	-1.11	-1.11	-1.22	-1.35	-1.25	-1.24	-1.07	-1.28	-2.74	-2.07
235I	-2.13	-1.06	-1.24	-1.22	-1.20	-1.19	-1.16	-1.49	-1.09	-1.09
235S	-2.13	-1.06	-1.24	-1.22	-1.20	-1.19	-1.16	-1.49	-1.09	-1.09
330B	-1.16	-1.19	-1.14	-1.53	-1.19	-1.86	-1.16	-1.14	-1.16	-1.54
330I	-1.15	-1.20	-1.16	-1.44	-1.16	-1.20	-1.07	-1.24	-1.12	-2.43
330S	-1.09	-1.06	-1.09	-1.23	-2.25	-3.79	-1.16	-1.10	-1.16	-1.16
ALT	-2.54	-1.10	-1.17	-1.17	-2.35	-2.31	-3.61	-3.59	-3.60	-3.62
DED	-1.25	-1.23	-1.28	-1.34	-1.24	-1.20	-1.28	-1.30	-1.27	-1.40
F52	-1.16	-1.21	-1.30	-1.35	-1.16	-1.24	-1.16	-1.11	-1.24	-1.16
HW4	-6.58	-1.34	-1.46	-1.87	-2.14	-3.69	-3.76	-3.47	-3.71	-2.92
I80B	-3.28	-3.24	-3.66	-4.30	-3.22	-3.55	-3.50	-3.94	-3.86	-4.04
I80S	-2.69	-1.98	-2.27	-1.87	-2.82	-2.72	-3.28	-3.17	-2.79	-1.99
NW	-3.14	-1.60	-2.28	-2.35	-2.45	-2.79	-3.42	-3.06	-2.62	-2.89
Rose	-2.91	-3.17	-2.72	-2.73	-2.35	-1.56	-1.62	-1.62	-1.47	-1.30
Jewell	-2.83	-2.85	-3.49	-3.49	-3.04	-1.17	-1.17	-2.86	-3.51	-2.99

Table 8-2 Deformation Summary for Conditioned Mixes

Mix	Section Deformation (mm)									
	1	2	3	4	5	6	7	8	9	10
6n	-3.49	-3.21	-7.16	-5.73	-1.81	-1.22	-1.90	-2.00	-3.71	-3.77
218	-4.77	-5.34	-2.43	-9.13	-5.20	-3.34	-3.30	-1.17	-3.30	-3.91
235I	-3.37	-2.51	-1.81	-2.17	-1.34	-4.13	-3.65	-2.02	-3.55	-3.54
235S	-2.04	-3.91	-1.42	-5.41	-4.45	-2.15	-2.94	-3.73	-2.45	-3.39
330B	-3.13	-2.55	-3.89	-6.41	-4.10	-2.71	-4.22	-2.43	-4.02	-3.30
330I	-3.97	-4.02	-4.27	-2.66	-3.74	-3.41	-3.41	-2.74	-4.02	-2.25
330S	-2.45	-2.43	-7.00	-3.14	-1.12	-3.13	-3.08	-3.74	-3.27	-4.23
ALT	-3.79	-3.61	-3.78	-4.11	-3.77	-2.63	-2.94	-4.41	-3.10	-3.82
DED	-3.80	-3.76	-5.07	-8.07	-3.03	-3.35	-2.02	-4.94	-3.70	-5.05
F52	-5.24	-4.45	-3.86	-4.72	-3.91	-5.87	-4.88	-4.74	-4.85	-5.94
HW4	-3.83	-1.43	-3.76	-3.97	-3.77	-3.95	-6.03	-4.27	-3.67	-3.67
I80B	-4.13	-2.96	-3.26	-4.05	-2.60	-3.44	-3.87	-2.04	-1.91	-3.58
I80S	-3.47	-3.29	-2.06	-3.01	-3.96	-3.59	-4.55	-3.83	-3.77	-2.59
NW	-3.60	-3.95	-3.95	-2.68	-3.98	-3.74	-3.27	-3.57	-4.37	-4.32
Rose	-3.83	-2.19	-2.70	-1.62	-3.83	-3.31	-1.32	-3.99	-1.67	-3.31
Jewell	-3.68	-3.76	-3.39	-4.27	-3.20	-3.92	-3.42	-3.17	-4.29	-4.62

Table 8-3 Summary of the Finite Element Results

Mix	Condition	Mean Deformation (mm)	Standard Deviation (mm)	CoV (%)	Ratio, Conditioned/ Unconditioned	Rank
6n	Unconditioned	-1.07	0.06	5.61	3.18	14
	Conditioned	-3.40	1.87	54.90		
218	Unconditioned	-1.44	0.54	37.25	2.90	13
	Conditioned	-4.19	2.15	51.35		
235I	Unconditioned	-1.29	0.32	24.85	2.18	8
	Conditioned	-2.81	0.95	33.81		
235S	Unconditioned	-1.29	0.32	24.85	2.48	10
	Conditioned	-3.19	1.23	38.44		
330B	Unconditioned	-1.31	0.25	18.93	2.81	12
	Conditioned	-3.67	1.17	31.81		
330I	Unconditioned	-1.32	0.40	30.53	2.62	11
	Conditioned	-3.45	0.69	19.92		
330S	Unconditioned	-1.51	0.88	57.96	2.22	9
	Conditioned	-3.36	1.53	45.53		
ALT	Unconditioned	-2.51	1.08	43.02	1.44	7
	Conditioned	-3.60	0.55	15.21		
DED	Unconditioned	-1.28	0.06	4.42	3.34	15
	Conditioned	-4.28	1.65	38.49		
F52	Unconditioned	-1.21	0.07	6.04	4.01	16
	Conditioned	-4.85	0.70	14.48		
HW4	Unconditioned	-3.09	1.55	50.12	1.24	2
	Conditioned	-3.84	1.10	28.68		
I80B	Unconditioned	-3.66	0.37	10.07	0.87	1
	Conditioned	-3.18	0.79	24.91		
I80S	Unconditioned	-2.56	0.50	19.63	1.33	4
	Conditioned	-3.41	0.72	20.99		
NW	Unconditioned	-2.66	0.52	19.60	1.41	6
	Conditioned	-3.74	0.50	13.36		
Rose	Unconditioned	-2.15	0.70	32.66	1.29	3
	Conditioned	-2.78	1.02	36.62		
Jewell	Unconditioned	-2.74	0.87	31.84	1.38	5
	Conditioned	-3.77	0.50	13.19		

CHAPTER 9 CONCLUSIONS AND RECOMMENDATIONS

In this research, sixteen mixes were collected from across the state of Iowa. The mixes were selected to cover a wide variety of materials and traffic levels. For each mix, samples were compacted using a Superpave gyratory compactor and were divided into four groups with equal average air voids and different conditioning/testing schemes. Five of the mixes were subjected to a fifth conditioning/testing scheme. Dynamic modulus, flow number, and tensile strength ratio (AASHTO T283) tests were performed on the samples. The results were compared together statistically. A finite element model was then developed using the results from the dynamic modulus test and was calibrated by the flow number test results. A stochastic finite element model was then developed using the variability of the tested materials.

This research studied the use of dynamic modulus and flow number tests in moisture susceptibility evaluation. The tests were analyzed using different approaches. Finite element analysis was used as an evaluation tool to evaluate the moisture susceptibility and variability of the mixes.

9.1 Conclusions

Based on the range of materials and the parameters tested in this research the following can be concluded:

- The dynamic modulus test is sensitive to the effect of moisture on the mixture. The extent by which the dynamic modulus value is affected due to the moisture conditioning is affected by the temperature and the loading frequency. This means that the effect of moisture varies by the loading conditions.

- For the dynamic modulus test results, the effect of moisture appears more on higher temperatures and/or lower frequencies.
- For best results, the dynamic modulus test results need to be combined either with information about the conditions at which the mix is going to be used or with a tool that helps visualize the effect of temperature over a range of temperatures and frequencies.
- Plotting a master curve provides a good tool to visualize the effect of moisture on the mix.
- All the parameters evaluated from the flow number test results gave mixed results except for the parameter "m", which provides consistent results.
- There is no evidence of a statistical difference between the ratios calculated using the average E* values and the indirect tensile test when compared to parameter "m".
- The different conditioning schemes used in conjunction with the flow number test showed no evidence of statistical difference. The effect of the different conditioning schemes of the mixes on the flow number results varied from one mix to the other and this makes them inconclusive. This can be attributed to the variability of the flow number test results.
- Linear viscoelastic modeling of asphalt material is capable of predicting the material performance. This kind of modeling is only limited to the linear viscoelastic range and is not recommended after this range.
- Finite element modeling is a good tool to identify the performance difference between the conditioned and unconditioned samples. This makes modeling a good tool to identify the moisture susceptibility of a mix and also to quantify the amount of damage.
- Moisture damage increased the mix susceptibility to rutting.

9.2 Limitations of the study

This study has some limitations that are imposed by the testing conditions. The results of the finite element analysis are limited to the linear viscoelastic range. This limitation can be eliminated by further testing of the material to be able to model the plastic deformation range. Another limitation is the complexity of the finite element model usage and this can be eliminated by developing a software that acts as a pre- and post-processor to perform data preparation and make the application more user friendly. Calibration to large number of field data is essential to make sure that the model is actually simulating what will happen in the field which would include varying pavement structures and loading conditions.

9.3 Recommendations

It is recommended based on the results of this research to do the following:

- Try the various testing/conditioning using the dynamic modulus test using LVDTs that can be used under water or by relying on the actuator LVDT, which might reduce the accuracy of the results.

- Run the dynamic modulus test only and skip the flow number test. This gives a chance to moisture condition the sample after running the control test then the sample can be tested again. This approach will reduce the variability introduced by testing two sets of samples.
- The dynamic modulus results should be related to the operating conditions.
- The use of parameter “m” calculated from the flow number test eliminates the need to test the sample to failure because to calculate this parameter, the sample does not need to reach the tertiary flow.

- Monitoring the field performance of the mixes and comparing it to the laboratory results is very important to judge the quality of the test results and to judge which test provides the most accurate results. It would also be useful to develop a finite element model based on field data and comparing its results to field conditions.
- Further testing is needed to be able to model the plastic material deformation.
- If finite element analysis is to be used as an evaluation tool for moisture damage, pre and post processing software can be developed to facilitate data entry and perform the data transformation and then help in visualizing the results.
- Variability can be also included in parameters that were considered constant in this study. It can be added to the base layer and subgrade. Variability can also be added to the thickness of the different layers.

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APPENDIX A JOB MIX FORMULAS

Form 955 ver. 6.5r

Iowa Department of Transportation

Highway Division-Office of Materials

Proportion & Production Limits For Aggregates

County: Polk   Project No.: IM-NHS-235-2(506)5--03-77   Date: 03/15/06

Project Location: I-235 Surface   Mix Design No.: 1BD6-001

Contract Mix Tonnage: 20,590   Course: Surface   Mix Size (in.): 1/2

Contractor: Des Moines Asphalt   Mix Type: HMA 30M   Design Life ESAL's 30,000,000

Material	Ident #	% in Mix	Producer & Location	Type (A or B)	Friction Type	Beds	Gsb	%Abs
1/2" cr. quartzite	ASD002	15.0%	Everest Dell Rapids, S.D.	A	2		2.650	0.20
1/2" crushed	A85006	25.0%	M.M. Ames	A	4	26,28-39	2.585	2.00
3/8" chip	A85006	20.0%	M.M. Ames	A	4	26,28-39	2.595	1.90
man. sand	A85006	30.0%	M.M. Ames	A	4	26,28-39	2.615	2.20
sand	A77502	10.0%	M.M. Johnston	A	4		2.650	0.50

Type and Source of Asphalt Binder: PG64-22 Bituminous Materials

Individual Aggregates Sieve Analysis - % Passing (Target)

Material	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
1/2" cr. quartzite	100	100	100	83	7.0	1.3	0.8	0.7	0.6	0.5	0.4
1/2" crushed	100	100	93	74	40	23	17	13	11	8.8	7.5
3/8" chip	100	100	100	90	22	3.0	2.5	1.5	1.2	1.1	1.0
man. sand	100	100	100	100	98	66	39	21	11	4.0	2.4
sand	100	100	100	100	96	87	70	44	13	1.1	0.3

Preliminary Job Mix Formula Target Gradation

	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
Upper Tolerance	100	100	100	96	62	40		18			4.0
Comb Grading	100	100	98	89	55	35	24	14	7.7	3.8	2.9
Lower Tolerance	100	100	91	82	48	30		10			0.0
S.A.sq. m/kg	Total	3.60		+0.41	0.22	0.29	0.39	0.41	0.47	0.47	0.95

Production Limits for Aggregates Approved by the Contractor & Producer.

Sieve Size in.	15.0% of mix 1/2" cr. quartzite Min	Max	25.0% of mix 1/2' crushed Min	Max	20.0% of mix 3/8" chip Min	Max	30.0% of mix man. sand Min	Max	10.0% of mix sand Min	Max
1"	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/4"	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1/2"	98.0	100.0	90.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/8"	76.0	90.0	67.0	81.0	83.0	97.0	100.0	100.0	100.0	100.0
#4	3.0	19.0	33.0	47.0	12.0	26.0	93.0	100.0	90.0	100.0
#8	0.0	6.1	18.0	28.0	0.0	8.0	58.0	72.0	80.0	90.0
#30	0.0	4.6	9.0	17.0	0.0	5.0	15.0	25.0	40.0	48.0
#200	0.0	2.2	5.0	8.5	0.0	1.5	0.0	3.0	0.0	1.0

Comments: Signed 955's on file in District 1 Materials Office.

Copies to: Des Moines Asphalt   Jefferson RCE   Marc Lamoreux   Craig Berry

Central Materials   Mark Trueblood   Cheryl Barton

The above target gradations and production limits have been discussed with and agreed to by an authorized representative of the aggregate producer.

Signed: ______________________ Producer

Signed: ______________________ Contractor

Form 956 ver. 6.5r

Iowa Department of Transportation

Highway Division - Office of Materials

HMA Gyratory Mix Design

County :	Polk		Project : IM-NHS-235-2(506)5--03-77	Mix No. :	1BD6-001
Mix Size (in.) :	1/2	Type A	Contractor : Des Moines Asphalt	Contract No. :	77 2352 500
Mix Type:	HMA 30M	L - 2	Design Life ESAL's : 30,000,000	Date Reported :	03/15/06
Intended Use :	Surface		Project Location : I-235 Surface		

Aggregate	% in Mix	Source ID	Source Location	Beds	Gsb	%Abs	FAA
1/2" cr. quartzite	15.0%	ASD002	Everest Dell Rapids, S.D.		2.650	0.20	48.0
1/2" crushed	25.0%	A85006	M.M. Ames	26,28-39	2.585	2.30	48.0
3/8' chip	20.0%	A85006	M.M. Ames	26,28-39	2.595	1.90	48.0
man. sand	30.0%	A85006	M.M. Ames	26,28-39	2.615	2.20	48.0
sand	10.0%	A77502	M.M. Johnston		2.650	0.50	41.0

Job Mix Formula - Combined Gradation (Sieve Size in.)

1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
					Upper Tolerance					
100	100	100	96	62	40		18			4.9
100	100	98	89	55	35	24	14	7.7	3.8	2.9
100	100	91	82	48	30		10			0.9
					Lower Tolerance					

Asphalt Binder Source and Grade: Bituminous Materials PG64-22

Gyratory Data

% Asphalt Binder	5.10	5.60	**5.62**	6.10		Number of Gyrations
Corrected Gmb @ N-Des	2.350	2.381	**2.381**	2.388		N-Initial
Max. Sp.Gr. (Gmm)	2.494	2.481	**2.480**	2.467		8
% Gmm @ N- Initial	85.1	86.5	**86.5**	87.3		N-Design
%Gmm @ N-Max	95.6	97.4	**97.4**	98.1		109
% Air Voids	5.8	4.0	**4.0**	3.2		N-Max
% VMA	14.6	14.0	**14.0**	14.2		174
% VFA	60.5	71.1	**71.3**	77.4		Gsb for Angularity
Film Thickness	10.69	11.81	**11.85**	13.00		Method A
Filler Bit. Ratio	0.75	0.68	**0.68**	0.62		2.623
Gsb	2.612	2.612	**2.612**	2.612		Pba / %Abs Ratio
Gse	2.703	2.711	**2.710**	2.717		0.88
Pbe	3.85	4.25	**4.27**	4.68		Slope of Compaction
Pba	1.32	1.43	**1.42**	1.51		Curve
% New Asphalt Binder	100.0	100.0	**100.0**	100.0		12.3
Asphalt Binder Sp.Gr. @ 25c	1.022	1.022	**1.022**	1.022		Mix Gmm Linearity
% Water Abs	1.62	1.62	**1.62**	1.62		Good
S.A. m^2 / Kg.	3.60	3.60	**3.60**	3.60		Pb Range Check
% + 4 Type 4 Agg. Or Better	100.0	100.0	**100.0**	100.0		1.00
% + 4 Type 2 or 3 Agg.	31.0	31.0	**31.0**	31.0		Specification Check
Angularity-method A	46	46	**46**	46		Comply
% Flat & Elongated	0.1	0.1	**0.1**	0.1		TSR Check
Sand Equivalent	73	73	**73**	73		

Disposition : An asphalt content of 5.5% is recommended to start this project.

Data shown in 5.62% column is interpolated from test data.

Comments : QMA Verification Complies. Final Approval Based On Plant Produced Mix.

Copies to : Des Moines Asphalt, Jefferson RCE, Marc Lamoreux, Craig Berry, Central Materials, Mark Trueblood, Cheryl Barton

Mix Designer & Cert.# : D. Morton CI-235 Signed : ____________

Form 956 ver. 6.5r

Iowa Department of Transportation

Highway Division - Office of Materials
HMA Gyratory Mix Design

County :	Polk	Project : IM-NHS-235-2(502)12--03-77	Mix No. : 1BD6-014
Mix Size (in.) :	1/2 Type A	Contractor : Des Moines Asphalt	Contract No. :
Mix Type:	HMA 30M L - 4	Design Life ESAL's : 30M	Date Reported : 06/13/06
Intended Use :	Intermediate	Project Location : I-235 Intermediate	

Aggregate	% in Mix	Source ID	Source Location	Beds	Gsb	%Abs	FAA
1/2" crushed	20.0%	A85006	M.M. Ames	26,28-39	2.585	2.00	48.0
3/8" chip	29.0%	A85006	M.M. Ames	26,28-39	2.595	1.90	48.0
man. Sand	30.0%	A85006	M.M. Ames	26,28-39	2.615	2.20	48.0
sand	6.0%	A77502	M.M. Johnston		2.650	0.50	4[illegible].0
Classified RAP	15.0%	1-RAP6-1	Des Moines Asphalt		2.588	2.22	42.0

Job Mix Formula - Combined Gradation (Sieve Size in.)

	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
Upper Tolerance	100	100	100	97	67	63		20			6
	100	100	98	90	60	58	26	16	9.3	5.4	4.0
Lower Tolerance	100	100	91	83	53	53		12			2.0

Asphalt Binder Source and Grade: Bituminous Materials PG64-22

Gyratory Data

% Asphalt Binder	4.70	5.20	**5.61**	5.70		
Corrected Gmb @ N-Des.	2.319	2.327	**2.369**	2.378		Number of Gyrations
Max. Sp.Gr. (Gmm)	2.501	2.484	**2.468**	2.464		N-Initial
% Gmm @ N- Initial	84.4	84.6	**86.9**	87.4		8
%Gmm @ N-Max	95.9	95.1	**97.3**	97.8		N-Design
% Air Voids	7.3	6.3	**4.0**	3.5		109
% VMA	15.0	15.2	**14.0**	13.8		N-Max
% VFA	51.6	58.4	**71.7**	74.7		174
Film Thickness	7.75	8.84	**9.81**	10.02		Gsb for Angularity
Filler Bit. Ratio	1.17	1.02	**0.93**	0.90		Method A
Gsb	2.501	2.601	**2.601**	2.601		2.614
Gse	2.594	2.696	**2.695**	2.695		Pba / %Abs Ratio
Pbe	3.41	3.89	**4.32**	4.41		0.69
Pba	1.35	1.38	**1.37**	1.37		Slope of Compaction Curve
% New Asphalt Binder	85.3	86.8	**87.8**	88.0		12.8
Asphalt Binder Sp.Gr. @ 25c	1.020	1.020	**1.020**	1.020		Mix Gmm Linearity
% Water Abs	1.97	1.97	**1.97**	1.97		Excellent
S.A. m^2 / Kg.	4.40	4.40	**4.40**	4.40		Pb Range Check
% + 4 Type 4 Agg. Or Better	88.7	88.7	**88.7**	88.7		1.00
% + 4 Type 2 or 3 Agg.	0.0	0.0	**0.0**	0.0		Specification Check
Angularity-method A						Comply
% Flat & Elongated	0.9	0.9	**0.9**	0.9		TSR Check
Sand Equivalent	89	89	**89**	89		

Disposition : An asphalt content of 5.5% is recommended to start this project.

Data shown in 5.61% column is interpolated from test data.

The % ADD AC to start project is 4.9%

Comments : QMA Verification Complies. Final Approval Based On Plant Produced Mix

Copies to : Des Moines Asphalt, Marshalltown RCE, Marc Lamoreux, Craig Berry, Central Materials, Vicky Rink, Cheryl Barton

Mix Designer & Cert.# : D.Morton CI-235 Signed : ____________________

Form 955 ver. 6.5r

Iowa Department of Transportation

Highway Division-Office of Materials

Proportion & Production Limits For Aggregates

County : Polk Project No.: IM-NHS-235-2(502)12--03-77 Date: 06/13/06
Project Location: I-235 Intermediate Mix Design No.: IBD6-014
Contract Mix Tonnage: 27,033 Course: Intermediate Mix Size (in.): 1/2
Contractor: Des Moines Asphalt Mix Type: HMA 30M Design Life ESAL's 30M

Material	Ident #	% in Mix	Producer & Location	Type (A or B)	Friction Type	Beds	Gsb	%Abs
1/2" crushed	A35006	20.0%	M.M. Ames	A	4	26,28-39	2.585	2.00
3/8" chip	A35006	29.0%	M.M. Ames	A	4	26,28-39	2.595	1.90
man. Sand	A35006	30.0%	M.M. Ames	A	4	26,28-39	2.615	2.20
sand	A77502	6.0%	M.M. Johnston	A	4		2.650	0.50
Classified RAP	1-RAP6-1	15.0%	Des Moines Asphalt				2.588	2.22
Type and Source of Asphalt Binder:			PG64-22 Bituminous Materials					

Individual Aggregates Sieve Analysis - % Passing (Target)

Material	1"	3/4"	1/2'	3/8"	#4	#8	#16	#30	#50	#100	#200
1/2" crushed	100	100	93	74	40	23	17	13	11	8.8	7.5
3/8" chip	100	100	100	90	22	3.0	2.5	1.5	1.2	1.1	1.0
man. Sand	100	100	100	100	98	66	39	21	11	4.0	2.4
sand	100	100	100	100	96	87	70	44	13	1.1	0.3
Classified RAP	100	99	93	86	69	52	39	28	18	14	10

Preliminary Job Mix Formula Target Gradation

Upper Tolerance	100	100	100	97	67	43		20			6.0
Comb Grading	100	100	98	90	60	38	26	16	9.3	5.4	4.0
Lower Tolerance	100	100	91	83	53	33		12			2.0
S.A.sq. m/kg	Total	4.40		+0.41	0.25	0.31	0.42	0.46	0.57	0.66	1.31

Production Limits for Aggregates Approved by the Contractor & Producer.

Sieve Size in.	20.0% of mix 1/2" crushed		29.0% of mix 3/8" chip		30.0% of mix man. Sand		6.0% of mix sand		15.0% of mix Classified RAP		
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	
1"	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	98.0	100.0	
3/4"	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	92.0	100.0	
1/2"	90.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	86.0	100.0	
3/8"	67.0	81.0	83.0	97.0	100.0	100.0	100.0	100.0	79.0	93.0	
#4	33.0	47.0	12.0	26.0	93.0	100.0	90.0	100.0	62.0	76.0	
#8	18.0	28.0	0.0	12.0	58.0	72.0	80.0	90.0	47.0	57.0	
#30	9.0	17.0	0.0	6.0	15.0	25.0	40.0	48.0	24.0	32.0	
#200	5.5	8.5	0.0	1.5	0.4	3.0	0.0	1.0	8.0	12.0	

Comments:

Copies to: Des Moines Asphalt Marc Lamoreux Cheryl Barton Craig Berry
Vicky Rink Central Materials Marshalltown RCE

The above target gradations and production limits have been discussed with and agreed to by an authorized representative of the aggregate producer.

Signed: ______________________ Producer

Signed: ______________________ Contractor

Form 956 ver. 6.5r

Iowa Department of Transportation

Highway Division - Office of Materials
HMA Gyratory Mix Design

County :	Jasper		Project : NHSN-330-1(24)--2R-50	Mix No. :	1B06-007
Mix Size (in.) :	3/4	Type A	Contractor : Cessford Construction	Contract No. :	24003
Mix Type:	HMA 1M	None	Design Life ESAL's : 1M	Date Reported :	05/10/06
Intended Use :	Base		Project Location : Ia 330 from Jasper County Line N. to US30		

Aggregate	% in Mix	Source ID	Source Location	Beds	Gsb	%Abs	FAA
3/4 #235 Lmst.	20.0%	A64004	Cessford - LeGrand	8-27	2.551	2.35	
3/4 #113 Lmst.	30.0%	A64004	Cessford - LeGrand	8-27	2.573	2.30	
Man. Sand Prim.	10.0%	A64004	Cessford - LeGrand	8-27	2.592	2.37	49.3
3/8 Conc. Sand	40.0%	A64502	Martin Marietta - Marshalltown		2.627	0.66	41.0

Job Mix Formula - Combined Gradation (Sieve Size in.)

1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
					Upper Tolerance					
100	100	94	85	67	54		28			5.7
100	100	87	78	60	49	38	24	8.6	4.6	3.7
100	93	80	71	53	44		20			1.7
					Lower Tolerance					

Asphalt Binder Source and Grade: Bituminous Tama PG58-28

Gyratory Data

% Asphalt Binder	5.73	6.25	**6.31**	6.75		Number of Gyrations
Corrected Gmb @ N-Des	2.322	2.330	**2.333**	2.356		N-Initial
Max. Sp.Gr. (Gmm)	2.442	2.421	**2.418**	2.397		7
% Gmm @ N- Initial	89.4	90.5	**90.8**	92.6		N-Design
%Gmm @ N Max	96.0	97.1	**97.4**	99.2		68
% Air Voids	4.9	3.8	**3.5**	1.7		N-Max
% VMA	15.6	15.7	**15.7**	15.2		104
% VFA	68.4	76.1	**77.7**	88.8		Gsb for Angularity
Film Thickness	10.05	11.29	**11.46**	12.61		Method A
Filler Bit. Ratio	0.78	0.70	**0.69**	0.63		2.618
Gsb	2.592	2.592	**2.592**	2.592		Pba / %Abs Ratio
Gse	2.665	2.661	**2.660**	2.653		0.61
Pbe	4.71	5.29	**5.36**	5.90		Slope of Compaction
Pba	1.09	1.03	1.01	0.91		Curve
% New Asphalt Binder	100.0	100.0	**100.0**	100.0		17.7
Asphalt Binder Sp.Gr. @ 25c	1.028	1.028	**1.028**	1.028		Mix Gmm Linearity
% Water Abs	1.66	1.66	**1.66**	1.66		Good
S.A. m^2 / Kg.	4.68	4.68	**4.68**	4.68		Pb Range Check
% + 4 Type 4 Agg. Or Better	100.0	100.0	**100.0**	100.0		1.02
% + 4 Type 2 or 3 Agg.	0.0	0.0	**0.0**	0.0		Specification Check
Angularity-method A	42	42	**42**	42		Comply
% Flat & Elongated	0.5	0.5	**0.5**	0.5		TSR Check
Sand Equivalent	91	91	**91**	91		

Disposition : An asphalt content of 6.3% is recommended to start this project.
Data shown in 6.31% column is interpolated from test data.

Comments : QMA Verification Complies. Final approval based on plant produced mix.

Copies to : Cessford Construction Central Materials Marshalltown RCE Marc Lamoreux
Cheryl Barton Jim Bailey

Mix Designer & Cert.# : Ted Huisman CI-515 Signed : ____________________

Form 955 ver. 6.5r

Iowa Department of Transportation

Highway Division-Office of Materials

Proportion & Production Limits For Aggregates

County : Jasper Project No.: NHSN-330-1(24)--2R-50 Date: 05/10/06

Project Location: Ia 330 from Jasper County Line N. to US30 Mix Design No.: 1BD6-007

Contract Mix Tonnage: 15,000 Course: Base Mix Size (in.): 3/4

Contractor: Cessford Construction Mix Type: HMA 1M Design Life ESAL's 1M

Material	Ident #	% in Mix	Producer & Location	Type (A or B)	Friction Type	Beds	Gsb	%Abs
3/4 #235 Lmst.	A64004	20.0%	Cessford - LeGrand	A	4	8-27	2.551	2.35
3/4 #113 Lmst.	A64004	30.0%	Cessford - LeGrand	A	4	8-27	2.573	2.30
Man. Sand Prim.	A64004	10.0%	Cessford - LeGrand	A	4	8-27	2.592	2.37
3/8 Conc. Sand	A64502	40.0%	Martin Marietta - Marshalltown	A	4		2.627	0.66

Type and Source of Asphalt Binder: PG58-28 Bituminous Tama

Individual Aggregates Sieve Analysis - % Passing (Target)

Material	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
3/4 #235 Lmst.	100	100	70	45	9.2	3.3	3.0	2.9	2.8	2.7	2.6
3/4 #113 Lmst.	100	100	78	62	32	20	15	13	11	10	8.3
Man. Sand Prim.	100	100	100	100	97	67	37	17	9.6	5.3	3.6
3/8 Conc. Sand	100	100	100	100	98	88	73	44	9.2	1.2	0.8

Preliminary Job Mix Formula Target Gradation

Upper Tolerance	100	100	94	85	67	54		28			5.7
Comb Grading	100	100	87	78	60	49	38	24	8.6	4.6	3.7
Lower Tolerance	100	93	80	71	53	44		20			1.7
S.A.sq m/kg	Total	4.68		+0.41	0.25	0.40	0.62	3.68	0.53	0.56	1.21

Production Limits for Aggregates Approved by the Contractor & Producer.

Sieve Size in.	20.0% of mix 3/4 #235 Lmst. Min	Max	30.0% of mix 3/4 #113 Lmst. Min	Max	10.0% of mix Man. Sand Prim. Min	Max	40.0% of mix 3/8 Conc. Sand Min	Max		
1"	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
3/4"	98.0	100.0	98.0	100.0	100.0	100.0	100.0	100.0		
1/2"	65.0	75.0	74.0	84.0	100.0	100.0	100.0	100.0		
3/8"	38.0	50.0	56.0	68.0	100.0	100.0	100.0	100.0		
#4	2.0	12.0	27.0	39.0	95.0	100.0	90.0	100.0		
#8	0.0	6.0	16.0	28.0	63.0	75.0	85.0	95.0		
#30	0.0	5.0	7.0	17.0	14.0	24.0	38.0	48.0		
#200	0.0	4.0	5.0	9.0	0.0	4.0	0.0	1.5		

Comments:

Copies to: Cessford Construction Marshalltown RCE Marc Lamoreux Cheryl Barton

Central Materials Jim Dailey

The above target gradations and production limits have been discussed with and agreed to by an authorized representative of the aggregate producer.

Signed: ______________________ Producer

Signed: ______________________ Contractor

Form 956 ver. 6.5r

Iowa Department of Transportation

Highway Division - Office of Materials
HMA Gyratory Mix Design

County :	Jasper		Project : NHSN-330-1(24)--2R-50	Mix No. : 1BD6-012
Mix Size (in.) :	1/2	Type A	Contractor : Cessford Construction	Contract No. : 24(03
Mix Type:	HMA 10M	None	Design Life ESAL's : 10M	Date Reported : 05/30/06
Intended Use :	Intermediate		Project Location : Ia 330 from Jasper County Line N. to US30	

Aggregate	% in Mix	Source ID	Source Location	Beds	Gsb	%Abs	FAA
Man. Sand Sec.	25.0%	A64004	Cessford - LeGrand	3-27	2.616	2.01	49.0
1/2 #225 Lmst.	20.0%	A64004	Cessford - LeGrand	3-27	2.574	2.30	
1/2 #220 Lmst.	30.0%	A64004	Cessford - LeGrand	3-27	2.607	1.88	
3/8 Conc. Sand	25.0%	A64502	Martin Marietta - Marshalltown		2.627	0.66	41.0

Job Mix Formula - Combined Gradation (Sieve Size in.)

	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
Upper Tolerance	100	100	100	95	71	51		25			6.3
	100	100	99	88	64	46	33	21	8.6	5.2	4.3
Lower Tolerance	100	100	92	81	57	41		17			2.3

Asphalt Binder Source and Grade: Bituminous Tama PG64-22

Gyratory Data

% Asphalt Binder	5.50	**5.93**	6.00	6.50		Number of Gyrations
Corrected Gmb @ N-Des	2.323	**2.350**	2.355	2.362		N-Initial
Max. Sp.Gr. (Gmm)	2.461	**2.448**	2.446	2.428		8
% Gmm @ N- Initial	86.3	**87.5**	87.8	90.2		N-Design
%Gmm @ N-Max	95.7	**97.3**	97.6	98.6		96
% Air Voids	5.6	**4.0**	3.7	2.7		N-Max
% VMA	15.8	**15.2**	15.1	15.3		152
% VFA	64.6	**73.8**	75.4	82.2		Gsb for Angularity
Film Thickness	9.55	**10.36**	10.50	11.57		Method A
Filler Bit. Ratio	0.95	**0.87**	0.86	0.78		2.621
Gsb	2.608	**2.608**	2.608	2.608		Pba / %Abs Ratio
Gse	2.678	**2.681**	2.682	2.682		0.63
Pbe	4.53	**4.91**	4.98	5.48		Slope of Compaction Curve
Pba	1.03	**1.07**	1.09	1.09		13.1
% New Asphalt Binder	100.0	**100.0**	100.0	100.0		Mix Gmm Linearity
Asphalt Binder Sp.Gr. @ 25c	1.028	**1.028**	1.028	1.028		Excellent
% Water Abs	1.69	**1.69**	1.69	1.69		Pb Range Check
S.A. m^2 / Kg	4.74	**4.74**	4.74	4.74		1.00
% + 4 Type 4 Agg. Or Better	100.0	**100.0**	100.0	100.0		Specification Check
% + 4 Type 2 or 3 Agg.	0.0	**0.0**	0.0	0.0		Comply
Angularity-method A	43	**43**	43	43		TSR Check
% Flat & Elongated	0.8	**0.8**	0.8	0.8		
Sand Equivalent	92	**92**	92	92		

Disposition : An asphalt content of 5.9% is recommended to start this project.
Data shown in 5.93% column is interpolated from test data.

Comments : QMA Verification Complies. Final approval based on plant produced mix.

Copies to : Cessford Construction Marc Lamoreux Cheryl Barton Central Materials
Mark Trueblood Marshalltown RCE Jim Bailey

Mix Designer & Cert.# : T Huisman CI-515 Signed : ____________

Form 955 ver. 6.5

Iowa Department of Transportation

Highway Division-Office of Materials

Proportion & Production Limits For Aggregates

County: Jasper　Project No.: NHSN-330-1(24)--2R-50　Date: 05/30/06

Project Location: Ia 330 from Jasper County Line N. to US30　Mix Design No.: 1BD6-012

Contract Mix Tonnage:　Course: Intermediate　Mix Size (in.): 1/2

Contractor: Cessford Construction　Mix Type: HMA 10M　Design Life ESAL's 10M

Material	Ident #	% in Mix	Producer & Location	Type (A or B)	Friction Type	Beds	Gsb	%Abs
Man. Sand Sec.	A64004	25.0%	Cessford - LeGrand	A	4	8-27	2.616	2.01
1/2 #225 Lmst.	A64004	20.0%	Cessford - LeGrand	A	4	8-27	2.574	2.30
1/2 #220 Lmst.	A64004	30.0%	Cessford - LeGrand	A	4	8-27	2.607	1.88
3/8 Conc. Sand	A64502	25.0%	Martin Marietta - Marshalltown	A	4		2.627	0.66

Type and Source of Asphalt Binder: PG64-22　Bituminous Tama

Individual Aggregates Sieve Analysis - % Passing (Target)

Material	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
Man. Sand Sec.	100	100	100	100	100	65	35	17	8.0	4.7	3.7
1/2 #225 Lmst.	100	100	98	73	17	4.8	3.9	3.7	3.5	3.4	3.2
1/2 #220 Lmst.	100	100	95	78	38	23	18	15	12	10	8.4
3/8 Conc. Sand	100	100	100	100	98	88	73	44	9.2	1.2	0.8

Preliminary Job Mix Formula Target Gradation

Upper Tolerance	100	100	100	95	71	51		25			6.3
Comb Grading	100	100	95	88	64	46	33	21	8.6	5.2	4.3
Lower Tolerance	100	100	92	81	57	41		17			2.3
S.A.sq. m/kg	Total	4.74		+0.41	0.26	0.38	0.54	0.59	0.53	0.64	1.40

Production Limits for Aggregates Approved by the Contractor & Producer.

Sieve Size	25.0% of mix Man. Sand Sec.		20.0% of mix 1/2 #225 Lmst.		30.0% of mix 1/2 #220 Lmst.		25.0% of mix 3/8 Conc. Sand			
in.	Min	Max	Min	Max	Min	Max	Min	Max		
1"	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
3/4"	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
1/2"	100.0	100.0	98.0	100.0	98.0	100.0	100.0	100.0		
3/8"	100.0	100.0	70.0	80.0	74.0	86.0	100.0	100.0		
#4	95.0	100.0	13.0	25.0	33.0	45.0	90.0	100.0		
#8	60.0	73.0	0.0	8.0	17.0	27.0	85.0	95.0		
#30	12.0	22.0	0.0	6.0	9.0	18.0	38.0	48.0		
#200	0.0	4.0	0.0	5.0	6.5	9.0	0.0	1.5		

Comments: Signatures on file in District 1 Materials Office.

Copies to: Cessford Construction　Marc Lamoreux　Cheryl Barton　Central Materials

Mark Trueblood　Marshalltown RCE　Jim Dailey

The above target gradations and production limits have been discussed with and agreed to by an authorized representative of the aggregate producer.

Signed: ____________________ Producer

Signed: ____________________ Contractor

Form 956 ver. 6.5r

Iowa Department of Transportation

Highway Division - Office of Materials

HMA Gyratory Mix Design

County :	Jasper		Project : NHSN-330-1(24)--2R-50	Mix No. :	1BD6-015
Mix Size (in.) :	1/2	Type A	Contractor : Cessford Construction	Contract No. :	24003
Mix Type:	HMA 10M	L - 2	Design Life ESAL's : 10M	Date Reported :	06/19/06
Intended Use :	Surface		Project Location : Ia 330 from Jasper County Line N. to US30		

Aggregate	% in Mix	Source ID	Source Location	Beds	Gsb	%Abs	FAA
Manf. Sand Combined	25.0%	A64004	Cessford - LeGrand	3-27	2.601	2.24	49.0
1/2 #220 Lmst.	38.0%	A64004	Cessford - LeGrand	3-27	2.607	1.88	
5/8 5/8 X #4 Slag	12.0%	A70008	Linwood - Montpelier		3.721	1.32	
3/8 Conc. Sand	25.0%	A64502	Martin Marietta - Marshalltown		2.627	0.66	41.0

Job Mix Formula - Combined Gradation (Sieve Size in.)

	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
Upper Tolerance	100	100	100	94	73	54		25			6.5
	100	100	99	87	66	49	35	21	9.4	5.5	4.5
Lower Tolerance	100	100	92	80	59	44		17			2.5

Asphalt Binder Source and Grade: Bituminous Tama PG64-22

Gyratory Data

% Asphalt Binder	5.50	6.00	**6.04**	6.50		<u>Number of Gyrations</u>
Corrected Gmb @ N-Des.	2.410	2.424	**2.425**	2.436		N-Initial
Max. Sp.Gr. (Gmm)	2.552	2.527	**2.526**	2.514		8
% Gmm @ N- Initial	86.7	88.0	**88.0**	88.8		N-Design
%Gmm @ N-Max	95.7	97.2	**97.3**	98.1		96
% Air Voids	5.6	4.1	**4.0**	3.1		N-Max
% VMA	15.9	15.9	**15.9**	15.9		152
% VFA	65.0	74.3	**74.8**	80.5		<u>Gsb for Angularity</u>
Film Thickness	8.89	10.08	**10.15**	10.90		<u>Method A</u>
Filler Bit. Ratio	1.03	0.90	**0.90**	0.84		2.617
Gsb	2.708	2.708	**2.708**	2.708		<u>Pba / %Abs Ratio</u>
Gse	2.791	2.784	**2.789**	2.792		0.69
Pbe	4.43	5.02	**5.05**	5.43		<u>Slope of Compaction</u>
Pba	1.13	1.04	**1.11**	1.15		<u>Curve</u>
% New Asphalt Binder	100.0	100.0	**100.0**	100.0		13.9
Asphalt Binder Sp.Gr. @ 25c	1.033	1.033	**1.033**	1.033		<u>Mix Gmm Linearity</u>
% Water Abs	1.60	1.60	**1.60**	1.60		Good
S.A. m^2 / Kg.	4.98	4.98	**4.98**	4.98		<u>Pb Range Check</u>
% + 4 Type 4 Agg. Or Better	100.0	100.0	**100.0**	100.0		1.00
% + 4 Type 2 or 3 Agg.	34.2	34.2	**34.2**	34.2		<u>Specification Check</u>
Angularity-method A	44	44	**44**	44		Comply
% Flat & Elongated	1.0	1.0	**1.0**	1.0		<u>TSR Check</u>
Sand Equivalent	91	91	**91**	91		

Disposition : An asphalt content of <u>6.0%</u> is recommended to start this project.

Data shown in <u>6.04%</u> column is interpolated from test data.

Comments : QMA Verification Complies. Final approval based on plant produced mix.

Copies to : Cessford Construction Marc Lamoreux Cheryl Barton Central Materials
Jim Bailey Marshalltown RCE

Mix Designer & Cert.# : Ted Huisman CI-515 Signed : ____________________

Form 955 ver. 6.5r

Iowa Department of Transportation

Highway Division-Office of Materials

Proportion & Production Limits For Aggregates

County : Jasper Project No.: NHSN-330-1(24)--2R-50 Date: 06/19/06

Project Location: Ia 330 from Jasper County Line N. to US30 Mix Design No.: 1BD6-015

Contract Mix Tonnage: 28,500 Course: Surface Mix Size (in.): 1/2

Contractor: Cessford Construction Mix Type: HMA 10M Design Life ESAL's 10M

Material	Ident #	% in Mix	Producer & Location	Type (A or B)	Friction Type	Beds	Gsb	%Abs
Manf. Sand Combined	A64004	25.0%	Cessford - LeGrand	A	4	8-27	2.601	2.24
1/2 #220 Lmst.	A64004	38.0%	Cessford - LeGrand	A	4	8-27	2.607	1.88
5/8 5/8 X #4 Slag	A70008	12.0%	Linwood - Montpelier	A	2		3.721	1.32
3/8 Conc. Sand	A64502	25.0%	Martin Marietta - Marshalltown	A	4		2.627	0.66

Type and Source of Asphalt Binder: PG64 22 Bituminous Tama

Individual Aggregates Sieve Analysis - % Passing (Target)

Material	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
Manf. Sand Combined	100	100	100	100	100	74	41	21	11	5.3	3.5
1/2 #220 Lmst.	100	100	99	80	41	22	16	13	11	9.8	8.8
5/8 5/8 X #4 Slag	100	100	96	55	3.2	1.8	1.6	1.4	1.3	1.1	1.0
3/8 Conc. Sand	100	100	100	100	98	88	73	44	9.2	1.2	0.8

Preliminary Job Mix Formula Target Gradation

	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
Upper Tolerance	100	100	100	94	73	54		25			6.5
Comb Grading	100	100	99	87	66	49	35	21	9.4	5.5	4.5
Lower Tolerance	100	100	92	80	59	44		17			2.5
S.A.sq. m/kg	Total	4.98		+0.41	0.27	0.40	0.57	0.61	0.58	0.67	1.49

Production Limits for Aggregates Approved by the Contractor & Producer.

Sieve Size in.	25.0% of mix Manf. Sand Combined		38.0% of mix 1/2 #220 Lmst.		12.0% of mix 5/8 5/8 X #4 Slag		25.0% of mix 3/8 Conc. Sand			
	Min	Max	Min	Max	Min	Max	Min	Max		
1"	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
3/4"	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
1/2"	100.0	100.0	98.0	100.0	90.0	100.0	100.0	100.0		
3/8"	98.0	100.0	74.0	86.0	45.0	59.0	100.0	100.0		
#4	95.0	100.0	33.0	45.0	0.0	10.2	90.0	100.0		
#8	67.0	78.0	17.0	27.0	0.0	9.0	85.0	95.0		
#30	16.0	26.0	9.0	18.0	0.0	5.0	38.0	48.0		
#200	0.0	4.0	6.5	9.0	0.0	2.5	0.0	1.5		

Comments:

Copies to: Cessford Construction Marc Lamoreux Cheryl Barton Central Materials
Jim Bailey Marshalltown RCE

The above target gradations and production limits have been discussed with and agreed to by an authorized representative of the aggregate producer.

Signed: ______________________ Producer

Signed: ______________________ Contractor

Form 956 ver. 6.5r

Iowa Department of Transportation

Highway Division - Office of Materials
HMA Gyratory Mix Design

County :	Greene		Project : STPN-4-2(36)--2J-37	Mix No. : 1BD6-029
Mix Size (in.) :	1/2	Type B	Contractor : Henningsen Const	Contract No. :
Mix Type:	HMA 1M	None	Design Life ESAL's :	Date Reported : 10/02/06
Intended Use :	Intermediate		Project Location : On IA 4 From US 30 To IA 175 In Calhoun County	

Aggregate	% in Mix	Source ID	Source Location	Beds	Gsb	%Abs	FAA
3/4 Stone	25.0%	A94002	Martin Marietta Fort Dodge Mine	36-42	2.644	0.81	45.0
3/8 Stone Chips	20.0%	A94002	Martin Marietta Fort Doge Mine	36-42	2.614	0.83	45.0
3/4 Screen Gravel	37.0%	New Pit	Becker Gravel Haupert Pit		2.526	2.53	40.0
1/4 Conc Sand	18.0%		Hallett Jefferson		2.614	0.87	40.0

Job Mix Formula - Combined Gradation (Sieve Size in.)

	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
Upper Tolerance	100	100	98	93	66	52		25			6.3
	100	100	91	86	59	47	35	21	10	5.7	4.3
Lower Tolerance	100	100	84	79	52	42		17			2.3

Asphalt Binder Source and Grade: Flint Hills Algona PG 58-28

Gyratory Data

% Asphalt Binder	4.50	5.00	**5.47**	5.50	6.00	
Corrected Gmb @ N-Des.	2.321	2.329	**2.338**	2.339	2.352	Number of Gyrations
Max. Sp.Gr. (Gmm)	2.471	2.450	**2.436**	2.435	2.409	N-Initial
% Gmm @ N- Initial	87.9	88.5	**89.7**	89.8	91.1	7
%Gmm @ N-Max	94.7	96.0	**96.8**	96.8	98.5	N-Design
% Air Voids	6.1	4.9	**4.0**	3.9	2.4	76
% VMA	14.4	14.5	**14.6**	14.6	14.6	N-Max
% VFA	57.7	66.0	**72.6**	73.0	83.7	117
Film Thickness	7.47	8.57	**9.46**	9.51	10.85	Gsb for Angularity
Filler Bit. Ratio	1.16	1.01	**0.92**	0.91	0.80	Method A
Gsb	2.588	2.588	**2.588**	2.588	2.588	2.574
Gse	2.645	2.642	**2.642**	2.645	2.634	Pba / %Abs Ratio
Pbe	3.68	4.23	**4.66**	4.69	5.35	0.55
Pba	0.86	0.81	**0.81**	0.86	0.70	Slope of Compaction Curve
% New Asphalt Binder	100.0	100.0	**100.0**	100.0	100.0	17.3
Asphalt Binder Sp.Gr. @ 25c	1.030	1.030	**1.030**	1.030	1.030	Mix Gmm Linearity
% Water Abs	1.46	1.46	**1.46**	1.46	1.46	Good
S.A. m^2 / Kg.	4.93	4.93	**4.93**	4.93	4.93	Pb Range Check
% + 4 Type 4 Agg. Or Better	100.0	100.0	**100.0**	100.0	100.0	1.50
% + 4 Type 2 or 3 Agg.	0.0	0.0	**0.0**	0.0	0.0	Specification Check
Angularity-method A	40	40	**40**	40	40	Comply
% Flat & Elongated	1.9	1.9	**1.9**	1.9	1.9	TSR Check
Sand Equivalent	78	78	**78**	78	78	

Disposition : An asphalt content of 5.5% is recommended to start this project.
Data shown in 5.47% column is interpolated from test data.

Comments : QMA Verification OK. Final approval based upon plant produced mix.
Made with the addition of Washed Sand.

Copies to : Henningsen Const, Marc Lamoreux, Cheryl Barton, Central Materials, Jefferson RCE, Mark Trueblood-M.Marietta, Craig Berry

Mix Designer & Cert.# : Scott Schoenrock SW130 Signed : ____________

Form 955 ver. 6.5r

Iowa Department of Transportation

Highway Division-Office of Materials

Proportion & Production Limits For Aggregates

County : Greene   Project No.: STPN-4-2(36)--2J-37   Date: 10/02/06

Project Location: On IA 4 From US 30 To IA 175 In Calhoun County   Mix Design No.: 1BD6-029

Contract Mix Tonnage: Course: Intermediate   Mix Size (in.): 1/2

Contractor: Henningsen Const   Mix Type: HMA 1M   Design Life ESAL's

Material	Ident #	% in Mix	Producer & Location	Type (A or B)	Friction Type	Beds	Gsb	%Abs
3/4 Stone	A94002	25.0%	Martin Marietta Fort Dodge Mine	A	4	36-42	2.644	0.81
3/8 Stone Chips	A94002	20.0%	Martin Marietta Fort Doge Mine	A	4	36-42	2.614	0.83
3/4 Screen Gravel	New Pit	37.0%	Becker Gravel Haupert Pit	A	4		2.526	2.53
1/4 Conc Sand		18.0%	Hallett Jefferson	A	4		2.614	0.87

Type and Source of Asphalt Binder: PG 58-28 Flint Hills Algona

Individual Aggregates Sieve Analysis - % Passing (Target)

Material	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
3/4 Stone	100	100	77	63	36	25	20	17	14	10	7.5
3/8 Stone Chips	100	100	100	100	24	8.0	5.0	3.5	2.5	2.0	1.7
3/4 Screen Gravel	100	100	91	88	73	59	45	29	14	6.5	5.2
1/4 Conc Sand	100	100	100	100	100	92	69	32	5.8	1.1	0.8

Preliminary Job Mix Formula Target Gradation

Upper Tolerance	100	100	98	93	66	52		25			6.3
Comb Grading	100	100	91	86	59	47	35	21	10	5.7	4.3
Lower Tolerance	100	100	84	79	52	42		17			2.3
S.A.sq. m/kg	Total	4.93		+0.41	0.24	0.38	0.58	0.62	0.63	0.69	1.40

Production Limits for Aggregates Approved by the Contractor & Producer.

Sieve Size	25.0% of mix 3/4 Stone		20.0% of mix 3/8 Stone Chips		37.0% of mix 3/4 Screen Gravel		18.0% of mix 1/4 Conc Sand			
in.	Min	Max	Min	Max	Min	Max	Min	Max		
1"	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
3/4"	98.0	100.0	100.0	100.0	98.0	100.0	100.0	100.0		
1/2"	70.0	84.0	100.0	100.0	84.0	98.0	100.0	100.0		
3/8"	56.0	70.0	98.0	100.0	80.0	94.0	100.0	100.0		
#4	26.0	40.0	23.0	37.0	70.0	84.0	95.0	100.0		
#8	17.0	27.0	4.0	14.0	59.0	69.0	87.0	97.0		
#30	11.0	19.0	3.0	11.0	31.0	39.0	28.0	36.0		
#200	4.0	8.0	0.0	5.0	1.7	5.7	0.0	1.5		

Comments:

Copies to: Henningsen Const   Dist 1 Lab

The above target gradations and production limits have been discussed with and agreed to by an authorized representative of the aggregate producer.

Signed: ______________________ Producer

Signed: ______________________ Contractor

Form 956 ver. 6.5r

Iowa Department of Transportation

Highway Division - Office of Materials

HMA Gyratory Mix Design

County :	Pottawattamie	Project : IMN-080-1(299)10--0E-78	Mix No. :	4BD6-25
Mix Size (in.) :	3/4 Type A	Contractor : Western Engineering	Contract No. :	24620
Mix Type:	HMA 30M L - 2	Design Life ESAL's : 30,000,000	Date Reported :	06/25/06
Intended Use :	Surface	Project Location : I-80 from 1.5 M N of US6 N, 10 Miles (EBL,WBL)		

Aggregate	% in Mix	Source ID	Source Location	Beds	Gsb	%Abs	FAA
3/4" Qtz	15.0%	ASD010	LG Everest		2.559	0.60	45.0
MS QT2	10.0%	ASD010	LG Everest		2.639	0.80	47.0
3/8" Limestone	44.0%	A78002	Schildberg	25B-25E	2.587	1.80	45.0
AC Sand	10.0%	ANE514	Lyman Richie		2.610	0.60	39.8
RAP	20.0%		ABC6-78		2.829	0.47	47.1

Job Mix Formula - Combined Gradation (Sieve Size in.)

	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
Upper Tolerance	100	100	97	86	61	40		24			5.8
	100	100	90	79	54	35	26	20	11	5.4	3.8
Lower Tolerance	100	93	83	72	47	30		16			1.8

Asphalt Binder Source and Grade: Flint Hills Omaha PG64-22

Gyratory Data

% Asphalt Binder	4.75	5.00	**5.06**	5.25	5.75	Number of Gyrations
Corrected Gmb @ N-Des.	2.345	2.350	**2.353**	2.363	2.367	N-Initial
Max. Sp.Gr. (Gmm)	2.458	2.453	**2.451**	2.447	2.430	8
% Gmm @ N- Initial	86.8	87.0	**87.1**	87.6	88.2	N-Design
%Gmm @ N-Max	96.6	97.1	**97.3**	97.9	98.7	109
% Air Voids	4.6	4.2	**4.0**	3.4	2.6	N-Max
% VMA	15.7	15.8	**15.7**	15.5	15.9	174
% VFA	70.8	73.4	**74.6**	77.9	83.8	Gsb for Angularity
Film Thickness	10.93	11.33	**11.45**	11.79	12.90	Method A
Filler Bit. Ratio	0.78	0.75	**0.75**	0.72	0.66	2.615
Gsb	2.651	2.651	**2.651**	2.651	2.651	Pba / %Abs Ratio
Gse	2.639	2.644	**2.644**	2.647	2.647	-0.09
Pbe	4.92	5.10	**5.15**	5.31	5.81	Slope of Compaction
Pba	-0.18	-0.10	**-0.10**	-0.06	-0.06	Curve
% New Asphalt Binder	82.8	83.8	**84.0**	84.6	86.0	13.2
Asphalt Binder Sp.Gr. @25c	1.034	1.034	**1.034**	1.034	1.034	Mix Gmm Linearity
% Water Abs	1.12	1.12	**1.12**	1.12	1.12	Good
S.A. m^2 / Kg.	4.50	4.50	**4.50**	4.50	4.50	Pb Range Check
% +4 Type 4 Agg. Or Better	100.0	100.0	**100.0**	100.0	100.0	1.00
% +4 Type 2 or 3 Agg.	54.8	54.8	**54.8**	54.8	54.8	Specification Check
Angularity-method A	45	45	**45**	45	45	Comply
% Flat & Elongated	0.8	0.8	**0.8**	0.8	0.8	TSR Check
Sand Equivalent	81	81	**81**	81	81	80.4

Disposition : An asphalt content of 5.1% is recommended to start this project.

Data shown in 5.06% column is interpolated from test data.

The % ADD AC to start project is 4.2%

Comments : ____________________

Copies to : Western Engineering Ames Cook-2 CBRCE

Tupper-2 Lab-5 File

Mix Designer & Cert.# : Marvin Seavey SW 160 Signed : (signature)

Form 955 ver. 6.5r

Iowa Department of Transportation

Highway Division-Office of Materials

Proportion & Production Limits For Aggregates

County : Pottawattamie Project No.: IMN-080-1(299)10--0E-78 Date: 06/29/06

Project Location: I-80 from 1.5 M N of US6 N, 10 Miles (EBL,WBL) Mix Design No.: 4BD6-25

Contract Mix Tonnage: 48,438 Course: Surface Mix Size (in.): 3/4

Contractor: Western Engineering Mix Type: HMA 30M Design Life ESAL's: 30,000,000

Material	Ident #	% in Mix	Producer & Location	Type (A or B)	Friction Type	Beds	Gsb	%Abs
3/4" Qtz	ASD010	16.0%	LG Everest	A	2		2.659	0.60
MS QTZ	ASD010	10.0%	LG Everest	A	2		2.639	0.80
3/8" Limestone	A78002	44.0%	Schildberg	A	4	25B-25E	2.587	1.80
AC Sand	ANE514	10.0%	Lyman Richie	A	4		2.610	0.60
RAP		20.0%	ABC6-78	A	3		2.829	0.47

Type and Source of Asphalt Binder: PG64-22 Flint Hills Omaha

Individual Aggregates Sieve Analysis - % Passing (Target)

Material	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
3/4" Qtz	100	100	53	20	3.0	2.0	1.6	1.0	0.9	0.8	0.5
MS QTZ	100	100	100	100	99	82	57	30	21	5.4	1.9
3/8" Limestone	100	100	99	91	52	19	10	7.7	6.9	6.4	5.6
AC Sand	100	100	100	100	100	98	92	80	32	4.4	1.0
RAP	100	100	91	80	52	41	32	25	15	7.5	5.1

Preliminary Job Mix Formula Target Gradation

Upper Tolerance	100	100	97	86	61	40		24			5.8
Comb Grading	100	100	90	79	54	35	26	20	11	5.4	3.8
Lower Tolerance	100	93	83	72	47	30		16			1.8
S.A.sq. m/kg	Total	4.50		+0.41	0.22	0.29	0.42	0.56	0.70	0.66	1.26

Production Limits for Aggregates Approved by the Contractor & Producer.

Sieve Size in.	16.0% of mix 3/4" Qtz		10.0% of mix MS QTZ		44.0% of mix 3/8" Limestone		10.0% of mix AC Sand		20.0% of mix RAP		
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	
1"	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0			
3/4"	98.0	100.0	100.0	100.0	98.0	100.0	100.0	100.0			
1/2"	53.0	67.0	100.0	100.0	92.0	100.0	100.0	100.0			
3/8"	16.0	30.0	98.0	100.0	84.0	98.0	100.0	100.0			
#4	0.0	5.0	93.0	100.0	45.0	59.0	98.0	100.0			
#8	0.0	4.0	74.0	86.0	14.0	24.0	93.0	100.0			
#30	0.0	3.0	25.0	35.0	3.7	11.7	76.0	84.0			
#200	0.0	2.0	0.0	4.0	0.0	6.0	0.0	3.0			

Comments: Signed 955's on file in Dist Matls office.

Copies to: Western Engineering Ames Cook-2 CB RCE Tupper-2

Lab-5 File CB Lab

The above target gradations and production limits have been discussed with and agreed to by an authorized representative of the aggregate producer.

Signed: ______________________ Producer

Signed: ______________________ Contractor

Form 956 ver. 6.5r

Iowa Department of Transportation

Highway Division - Office of Materials
HMA Gyratory Mix Design

County :	Dallas		Project : STP-U-5970(607)--70-25	Mix No. :	1BD6-016
Mix Size (in.) :	1/2	Type A	Contractor : Des Moines Asphalt	Contract No. :	260623
Mix Type:	HMA 1M		Design Life ESAL's : 1M	Date Reported :	06/20/06
Intended Use :	Intermediate		Project Location : Dallas County, Rose st.		

Aggregate	% in Mix	Source ID	Source Location	Beds	Gsb	%Abs	FAA
1/2" crushed	35.0%	A85006	M.M. Ames	26,28-39	2.585	2.00	48.0
man. Sand	16.0%	A85006	M.M. Ames	26,28-39	2.615	2.20	48.0
sand	29.0%	A77502	M.M. Johnston		2.650	0.50	41.0
Classified RAP	20.0%	1-RAP6-1	Des Moines Asphalt		2.588	2.22	42.0

Job Mix Formula - Combined Gradation (Sieve Size in.)

	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
Upper Tolerance	100	100	100	95	78	59		30			7
	100	100	96	88	71	54	40	26	13	6.8	5.0
Lower Tolerance	100	100	89	81	64	49		22			3.0

Asphalt Binder Source and Grade: Bituminous Materials-DM PG64-22

Gyratory Data

% Asphalt Binder	5.60	**5.98**	6.10	6.60		Number of Gyrations
Corrected Gmb @ N-Des.	2.350	**2.361**	2.364	2.376		N-Initial
Max. Sp.Gr. (Gmm)	2.476	**2.459**	2.454	2.439		7
%Gmm @ N- Initial	88.6	**89.6**	90.0	90.8		N-Design
%Gmm @ N-Max	95.9	**96.9**	97.3	98.2		76
% Air Voids	5.1	**4.0**	3.7	2.6		N-Max
% VMA	15.0	**14.9**	14.9	14.9		117
% VFA	66.0	**73.2**	75.4	82.7		Gsb for Angularity
Film Thickness	7.37	**8.11**	8.33	9.11		Method A
Filler Bit. Ratio	1.18	**1.07**	1.04	0.95		2.627
Gsb	2.609	**2.609**	2.609	2.609		Pba / %Abs Ratio
Gse	2.705	**2.704**	2.701	2.705		0.83
Pbe	4.29	**4.72**	4.85	5.30		Slope of Compaction
Pba	1.39	**1.37**	1.33	1.39		Curve
% New Asphalt Binder	83.7	**84.8**	85.1	86.3		16.8
Asphalt Binder Sp.Gr. @ 25c	1.020	**1.020**	1.020	1.020		Mix Gmm Linearity
% Water Abs	1.64	**1.64**	1.64	1.64		Excellent
S.A. m^2 / Kg.	5.82	**5.82**	5.82	5.82		Pb Range Check
% + 4 Type 4 Agg. Or Better	77.5	**77.5**	77.5	77.5		1.00
% + 4 Type 2 or 3 Agg.	0.0	**0.0**	0.0	0.0		Specification Check
Angularity-method A						Comply
% Flat & Elongated	0.9	**0.9**	0.9	0.9		TSR Check
Sand Equivalent	86	**86**	86	86		

Disposition : An asphalt content of 6.0% is recommended to start this project.

Data shown in 5.98% column is interpolated from test data.

The % ADD AC to start project is 5.1%

Comments : QMA Verification Complies. Final approval based on plant produced mix.

Copies to: Des Moines Asphalt, Marc Lamoreux, Cheryl Barton, Central Materials, Craig Berry, Vicky Rink, Mark Trueblood

Mix Designer & Cert.# : D.Morton CI-235 Signed : ______________

Form 955 ver. 6.5r

Iowa Department of Transportation

Highway Division-Office of Materials

Proportion & Production Limits For Aggregates

County :	Dallas	Project No.:	STP-U-5970(607)--70-25	Date:	06/20/06
Project Location:	Dallas County			Mix Design No.:	1BD6-016
Contract Mix Tonnage:		Course:	Intermediate	Mix Size (in.):	1/2
Contractor:	Des Moines Asphalt	Mix Type:	HMA 1M	Design Life ESAL's 1M	

Material	Ident #	% in Mix	Producer & Location	Type (A or B)	Friction Type	Beds	Gsb	%Abs
1/2" crushed	A85006	35.0%	M.M. Ames	A	4	26,28-39	2.585	2.00
man. Sand	A85006	16.0%	M.M. Ames	A	4	26,28-39	2.615	2.20
sand	A77502	29.0%	M.M Johnston	A	4		2.650	0.50
Classified RAP	1-RAP6-1	20.0%	Des Moines Asphalt				2.588	2.22

Type and Source of Asphalt Binder: PG64 22 Bituminous Materials-DM

Individual Aggregates Sieve Analysis - % Passing (Target)

Material	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
1/2" crushed	100	100	93	74	40	23	17	13	11	8.8	7.5
man. Sand	100	100	100	100	98	66	39	21	11	4.0	2.4
sand	100	100	100	100	96	87	70	44	13	1.1	0.3
Classified RAP	100	99	93	86	69	52	39	28	18	14	10

Preliminary Job Mix Formula Target Gradation

	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
Upper Tolerance	100	100	100	95	78	59		30			7.0
Comb Grading	100	100	96	88	71	54	40	26	13	6.8	5.0
Lower Tolerance	100	100	89	81	64	49		22			3.0
S.A.sq m/kg	Total	5.82		+0.41	0.29	0.44	0.66	0.75	0.79	0.83	1.65

Production Limits for Aggregates Approved by the Contractor & Producer.

Sieve Size	35.0% of mix 1/2" crushed		16.0% of mix man. Sand		29.0% of mix sand		20.0% of mix Classified RAP			
in.	Min	Max	Min	Max	Min	Max	Min	Max		
1"	100.0	100.0	100.0	100.0	100.0	100.0	98.0	100.0		
3/4"	98.0	100.0	100.0	100.0	100.0	100.0	92.0	100.0		
1/2"	90.0	100.0	100.0	100.0	100.0	100.0	86.0	100.0		
3/8"	67.0	81.0	100.0	100.0	98.0	100.0	79.0	93.0		
#4	33.0	47.0	93.0	100.0	90.0	100.0	62.0	76.0		
#8	18.0	28.0	58.0	72.0	80.0	90.0	47.0	57.0		
#30	9.0	17.0	15.0	25.0	40.0	48.0	24.0	32.0		
#200	5.5	8.5	0.0	3.0	0.0	1.0	8.0	12.0		

Comments:

Copies to: Des Moines Asphalt Marc Lamoreux Cheryl Barton Central Materials
Craig Berry Vicky Rink Mark Trueblood

The above target gradations and production limits have been discussed with and agreed to by an authorized representative of the aggregate producer.

Signed: ______________________ Signed: ______________________

Producer Contractor

Form 956 ver. 6.5r

Iowa Department of Transportation

Highway Division Office of Materials

HMA Gyratory Mix Design

County :	Iowa		Project : STP-S-CO48(44)--5E-48	Mix No. :	ABD6-6033
Mix Size (in.) :	1/2	Type A	Contractor : Manatt's Inc.	Contract No. :	48 CO48 044
Mix Type:	HMA 300K		Design Life ESAL's : 300,000	Date Reported :	09/07/06
Intended Use :	Surface		Project Location : F-52, Poweshiek County Line to V-52.		

Aggregate	% in Mix	Source ID	Source Location	Beds	Gsb	%Abs	FAA
1/2" Asphalt Stone	55.0%	A54002	Douds (Keswick Quarry)	13 17	2.555	3.17	49.1
Manf. Sand	5.0%	A54004	Doud's (Ollie Quarry)	13-18	2.644	0.73	44.3
Nat. Sand	40.0%	A48508	Marengo Ready Mix (Disterhoff)		2.606	0.72	40.0

Job Mix Formula - Combined Gradation (Sieve Size in.)

	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
Upper Tolerance	100	100	100	93	69	53		29			6.4
	100	100	97	86	62	48	38	25	10	5.6	4.4
Lower Tolerance	100	100	90	79	55	43		21			2.4

Asphalt Binder Source and Grade: Bituminous @ Tama PG 58-28

Gyratory Data

% Asphalt Binder	5.35	**5.65**	5.85	6.35		Number of Gyrations
Corrected Gmb @ N-Des.	2.333	**2.347**	2.357	2.379		N-Initial
Max. Sp.Gr. (Gmm)	2.445	**2.433**	2.424	2.408		7
% Gmm @ N- Initial	89.7	**90.5**	91.1	93.2		N-Design
%Gmm @ N-Max	95.2	**97.3**	98.0	99.1		68
% Air Voids	4.6	**3.5**	2.8	1.2		N-Max
% VMA	14.4	**14.2**	14.0	13.7		104
% VFA	68.2	**75.4**	80.3	91.2		Gsb for Angularity
Film Thickness	8.43	**9.08**	9.53	10.46		Method A
Filler Bit. Ratio	1.01	**0.94**	0.89	0.81		2.604
Gsb	2.580	**2.580**	2.580	2.580		Pba / %Abs Ratio
Gse	2.652	**2.650**	2.648	2.650		0.51
Pbe	4.33	**4.66**	4.89	5.37		Slope of Compaction
Pba	1.08	**1.05**	1.02	1.05		Curve
% New Asphalt Binder	100.0	**100.0**	100.0	100.0		17.4
Asphalt Binder Sp.Gr. @ 25c	1.027	**1.027**	1.027	1.027		Mix Gmm Linearity
% Water Abs	2.07	**2.07**	2.07	2.07		Excellent
S.A. m^2 / Kg.	5.13	**5.13**	5.13	5.13		Pb Range Check
% + 4 Type 4 Agg. Or Better	100.0	**100.0**	100.0	100.0		1.00
% + 4 Type 2 or 3 Agg.	0.0	**0.0**	0.0	0.0		Specification Check
Angularity-method A	42	**42**	42	42		Comply
% Flat & Elongated	3.0	**3.0**	3.0	3.0		TSR Check
Sand Equivalent	84	**84**	84	84		

Disposition : An asphalt content of 5.7% is recommended to start this project.

Data shown in 5.65% column is interpolated from test data.

Comments : ______________________________

Copies to :	Manatt's Inc.	Iowa Co. Eng.	Roger Boulet	Dennis Lohrer
	Dist. 6 Lab.		Area Inspector (Dist.5 Matl's)	Producer's

Mix Designer & Cert.# : Brad Karsten CI 391 Signed : ______________

Form 955 ver. 6.5r

Iowa Department of Transportation

Highway Division-Office of Materials

Proportion & Production Limits For Aggregates

County : Iowa | Project No.: STP-S-CO48(44)--5E-48 | Date: 09/07/06

Project Location: F-52, Poweshiek County Line to V-52. | Mix Design No.: ABD6-5033

Contract Mix Tonnage: 28,050 | Course: Surface | Mix Size (in.): 1/2

Contractor: Manatt's Inc. | Mix Type: HMA 300K | Design Life ESAL's 300,000

Material	Ident #	% in Mix	Producer & Location	Type (A or B)	Friction Type	Beds	Gsb	%Abs
1/2" Asphalt Stone	A54002	55.0%	Doud's (Keswick Quarry)	A	4	13-17	2.555	3.17
Manf. Sand	A54004	5.0%	Doud's (Ollie Quarry)	A	4	13-18	2.644	0.73
Nat. Sand	A48508	40.0%	Marengo Ready Mix (Disterhoff)	A	4		2.606	0.72

Type and Source of Asphalt Binder: PG 58-28 Bituminous @ Tama

Individual Aggregates Sieve Analysis - % Passing (Target)

Material	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
1/2" Asphalt Stone	100	100	95	74	34	16	11	9.6	9.0	8.4	7.3
Manf. Sand	100	100	100	99	97	72	52	37	25	11	3.1
Nat. Sand	100	100	100	100	96	88	72	45	10	1.1	0.5

Preliminary Job Mix Formula Target Gradation

	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
Upper Tolerance	100	100	100	93	69	53		29			6.4
Comb Grading	100	100	97	86	62	48	38	25	10	5.6	4.4
Lower Tolerance	100	100	90	79	55	43		21			2.4
S.A.sq. m/kg	Total	5.13		-0.41	0.25	0.39	0.61	0.72	0.63	0.69	1.43

Production Limits for Aggregates Approved by the Contractor & Producer.

Sieve Size in.	55.0% of mix 1/2" Asphalt Stone		5.0% of mix Manf. Sand		40.0% of mix Nat. Sand				
	Min	Max	Min	Max	Min	Max			
1"	100.0	100.0	100.0	100.0	100.0	100.0			
3/4"	100.0	100.0	100.0	100.0	100.0	100.0			
1/2"	88.0	100.0	98.0	100.0	100.0	100.0			
3/8"	67.0	81.0	92.0	100.0	98.0	100.0			
#4	27.0	41.0	90.0	100.0	89.0	100.0			
#8	11.0	21.0	67.0	77.0	83.0	93.0			
#30	5.6	13.6	33.0	41.0	41.0	49.0			
#200	5.3	9.3	1.1	5.1	0.0	2.5			

Comments: Signatures on File in District 6 Materials Office

Copies to: Manatt's Inc. | Iowa Co. Eng. | Roger Boulet | Dennis Lohrer

Dist. 6 Lab. | Area Inspector (Dist.5 Matl's) | Producer's

The above target gradations and production limits have been discussed with and agreed to by an authorized representative of the aggregate producer.

Signed: ______________________ Producer

Signed: ______________________ Contractor

Form 955 ver. 6.5r

Iowa Department of Transportation

Highway Division-Office of Materials

Proportion & Production Limits For Aggregates

County :	Iowa	Project No.:	STP-S-CO48(44)--5E-48	Date:	09/07/06
Project Location:	F-52, Powshiek County Line to V-52.			Mix Design No.:	ABD6-5033
Contract Mix Tonnage:	28,050	Course:	Surface	Mix Size (in.):	1/2
Contractor:	Manatt's Inc.	Mix Type:	HMA 300K	Design Life ESAL's	300,000

Material	Ident #	% in Mix	Producer & Location	Type (A or B)	Friction Type	Beds	Gsb	%Abs
1/2" Asphalt Stone	A54002	55.0%	Doud's (Keswick Quarry)	A	4	13-17	2.555	3.17
Manf. Sand	A54004	5.0%	Doud's (Ollie Quarry)	A	4	13-18	2.644	0.73
Nat. Sand	A48508	40.0%	Marengo Ready Mix (Disterhoff)	A	4		2.606	0.72

Type and Source of Asphalt Binder: PG 58-28 Bituminous @ Tama

Individual Aggregates Sieve Analysis - % Passing (Target)

Material	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
1/2" Asphalt Stone	100	100	95	74	34	16	11	9.6	9.0	8.4	7.3
Manf. Sand	100	100	100	99	97	72	52	37	25	11	3.1
Nat. Sand	100	100	100	100	96	88	72	45	10	1.1	0.5

Preliminary Job Mix Formula Target Gradation

Upper Tolerance	100	100	100	93	69	53		29			6.4
Comb Grading	100	100	97	86	62	48	38	25	10	5.6	4.4
Lower Tolerance	100	100	90	79	55	43		21			2.4
S.A.sq. m/kg	Total	5.13		-0.41	0.25	0.39	0.61	0.72	0.63	0.69	1.43

Production Limits for Aggregates Approved by the Contractor & Producer.

Sieve Size in.	55.0% of mix 1/2" Asphalt Stone		5.0% of mix Manf. Sand		40.0% of mix Nat. Sand				
	Min	Max	Min	Max	Min	Max			
1"	100.0	100.0	100.0	100.0	100.0	100.0			
3/4"	100.0	100.0	100.0	100.0	100.0	100.0			
1/2"	88.0	100.0	98.0	100.0	100.0	100.0			
3/8"	67.0	81.0	92.0	100.0	98.0	100.0			
#4	27.0	41.0	90.0	100.0	89.0	100.0			
#8	11.0	21.0	67.0	77.0	83.0	93.0			
#30	5.6	13.6	33.0	41.0	41.0	49.0			
#200	5.3	9.3	1.1	5.1	0.0	2.5			

Comments: Signatures on File in District 6 Materials Office

Copies to: Manatt's Inc. Iowa Co. Eng. Roger Boulet Dennis Lohrer
Dist. 6 Lab Area Inspector (Dist.5 Matl's) Producer's

The above target gradations and production limits have been discussed with and agreed to by an authorized representative of the aggregate producer.

Signed: ______________________ Signed: ______________________
Producer Contractor

Iowa Department of Transportation
Highway Division - Office of Materials
HMA Gyratory Mix Design

County: STORY	Project: SPN-09-5(01)--2J-05		Mix No.: 1DD0-01#
Mix Size (in.): 1/2	Contractor: MANATTS INC		Contract No.: 85-0695-01
Mix Type: HMA 3M	Design Life ESAL's: 3,000,000		Date Reported: 5/27/2003
Intended Use: Surface	Project Location: 6TH & GRAND AVE		

Aggregate,	1/2 CR ASPH EC	A85006	MARTIN MARIETTA AMES	26,28-39	@	45.0%
Source IDs,	1/4 CL CHIP GC	A85006	MARTIN MARIETTA AMES	19-25	@	10.0%
Source Loc.,	MANF SAND EC	A85006	MARTIN MARIETTA AMES	26,28-39	@	20.0%
ds & % in Mix:	SAND	A85510	HALLETT MTLS AMES S PIT		@	25.0%

Job Mix Formula - Combined Grdation (Sieve Size in.)

1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
					Upper Tolerance					
100	100	100	95	69	52		24			6.2
100	100	98	88	62	47	33	20	9.2	4.8	4.2
100	100	91	81	55	42		16			2.2
					Lower Tolerance					

Asphalt Binder Source and Grade: BITUMINOUS MTLS PG 64-22

	Gyratory Data				Interpolated	
% Asphalt Binder	5.15	5.65	6.15		5.41	Number of Gyrations
Corrected Gmb @ N-Des.	2.351	2.371	2.376		2.361	N-Initial
Max. Sp.Gr. (G_{mm})	2.466	2.454	2.426		2.46	7
% G_{mm} @ N-Initial	87.6	88.7	89.7		88.1	N-Design
% G_{mm} @ N-Max	96.5	97.8	99.1		97.1	86
% Air Voids	4.7	3.4	2.1		4	N-Max
% VMA	14.6	14.3	14.6		14.4	134
% VFA	68	76.3	85.9		72.3	Gsb for Angularity
Film Thickness	9.2	10.1	11.6		9.7	Method A
Filler Bit. Ratio	0.97	0.89	0.77		0.93	2.6
G_{sb}	2.61	2.61	2.61		2.61	Pba/%Abs Ratio
G_{se}	2.668	2.675	2.662		2.668	0.47
P_{be}	4.34	4.74	5.43		4.55	Slope of Compaction
P_{ba}	0.86	0.96	0.77		0.86	Curve
% New Asphalt Binder	100	100	100		100	14.3
Asphalt Binder Sp.Gr. @25c	1.031	1.031	1.031		1.031	Mix Gmm Linearity
% Water Abs	1.83	1.83	1.83		1.83	-
S.A m^2/Kg.	4.69	4.69	4.69		4.69	Pb Range Check
%+4 Type Agg. Or Better	99	99	99		99	-
%+4 Type 2 or 3 Agg.	1	1	1		1	Specification Check
Angularity-method A	43	43	43		43	-
% Flat & Elongated	0.3	0.3	0.3		0.3	TSR Check
Sand Equivalent	86	86	86		86	

Disposition: An asphalt content of 5.40% is recommended to start this project.
Data shown in 5.41% column is interpolated from test data.

Comments: ______________________

Copies to: MANATTS INC DIST 1 MTLS DIST 1 LAB CITY OF AMES

Mix Designer & Cert.#: Signed ______________________

Dedham

Form 956 rev. 6/9x

Iowa Department of Transportation

Highway Division - Office of Materials

HMA Gyratory Mix Design

County:	Carroll	Project : FM -CO14(115)--55-14	Mix No. :
Mix Size (in.) :	1/2 Type A	Contractor : Manatt's Inc	Contract No. : 14-CO14-115
Mix Type:	HMA 1M	Design Life ESAL's : 1,000,000	Date Reported : 08/04/06
Intended Use:	Intermediate	Project Location : Various Locations throughout the County	

Aggregate	% in Mix	Source ID	Source Location	Beds	Gsb	%Abs	FAA
1/2" Asphalt Stone	30.0%	A94002	Martin Marietta (Fort Dodge Mine)	36-42	2.615	1.00	45.4
1/2 Washed Chips	10.0%	A94002	Martin Marietta (Fort Dodge Mine)	36-42	2.627	0.97	45.3
Manf Sand	5.0%	A94002	Martin Marietta (Fort Dodge Mine)	36-42	2.601	1.32	45.3
Gravel	55.0%	A14510	Tiefenthaler (Lanesboro)		2.599	1.30	41.0

Job Mix Formula - combined Gradation (Seve Size in.)

1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
Upper Tolerance										
100	100	100	94	74	60		34			5.7
100	100	96	87	67	55	43	30	13	5.2	3.7
100	100	89	80	60	50		26			1.7
Lower Tolerance										

Asphalt Binder Source and Grade: Bituminous Materials PG 58-28

Gyratory Data

% Asphalt Binder	5.5	5.76	5.8	6.5			Number of Gyrations
Corrected Gmb @ N-Des.	2.33	2.335	2.336	2.373			N-Initial
Max. Sp.Gr. (Gmm)	2.443	2.433	2.431	2.402			7
% Gmm @ N- Initial	89.5	90	90.1	91.1			N-Design
%Gmm @ N-Max	96.3	97.1	97.2	98.5			76
% Air Voids	4.6	4	3.9	2.5			N-Max
% VMA	1535	15.6	15.6	16			117
% VFA	70.2	74.3	74.9	84.6			Gsb for Angularity
Film Thickness	9	9.53	9.61	11.06			Method A
Filler Bit. Ratio	0.77	0.73	0.72	0.63			2.601
Gsb	2.604	2.607	2.607	2.607			Pba / %Abs Ratio
Gse	2.656	2.653	2.654	2.649			0.58
Pbe	4.81	5.1	5.14	5.92			Slope of Compaction
Pba	0.73	0.68	0.7	0.62			Curve
% New Asphalt Binder	100.0	100.0	100.0	100.0			17.4
Asphalt Binder Sp.Gr @ 25c	1.027	1.027	1.027	1.027			Mix Gmm Linearity
% Water Abs	1.18	1.18	1.18	1.18			Good
S.A. m^2 / Kg.	5.35	5.35	5.35	5.35			Pb Range Check
% + 4 Type 4 Agg. Or Better	100.0	100.0	100.0	100.0			1.0
% + 4 Type 2 or 3 Agg.	0.0	0.0	0.0	0.0			Specification Check
Angularity-method A	41	41	41	41			Comply
% Flat & Elongated	1.7	1.7	1.7	1.7			TSR Check
Sand Equivalent	72	72	72	72			

Disposition : An asphalt content of 5.80% is recommended to start this project.

Data shown in 5.76% column is interpolated from test data.

Comments :

Copies to :

Mix Designer & Cert. # : Brad Karsten CI 391 Signed :

Form 956 ver.5.0

Iowa Department of Transportation

Highway Division - Office of Materials

HMA Gyratory Mix Design

County :	STORY	Project : BR-810-0(83)--7A-85		Mix No. :	IBD3-008
Mix Size (in.) :	1/2	Contractor : MANATTS INC		Contract No. :	
Mix Type:	HMA 1M	Design Life ESAL's : 1,000,000		Date Reported :	05/26/03
Intended Use :	Surface	Project Location : 13TH STREET, NW			

Aggregate, Source IDs, Source Loc., Beds & % in Mix:					
	1/2 CR ASPH EC	A85006	MARTIN MARIETTA AMES	26,28-39	@ 45.0%
	1/4 CL CHIP GC	A85006	MARTIN MARIETTA AMES	19-25	@ 10.0%
	MANF SAND EC	A85006	MARTIN MARIETTA AMES	26,28-39	@ 20.0%
	SAND	A85510	HALLETT MTLS AMES S PIT		@ 25.0%

Job Mix Formula - Combined Gradation (Sieve Size in.)

	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
Upper Tolerance	100	100	100	95	69	52		24			6.2
	100	100	98	88	62	47	33	20	9.2	4.8	4.2
Lower Tolerance	100	100	91	81	55	42		16			2.2

Asphalt Binder Source and Grade: BITUMINOUS MTLS PG 64-22

	Gyratory Data				Interpolated	
% Asphalt Binder	5.15	5.65	6.15		5.55	
Corrected Gmb @ N-Des.	2.342	2.362	2.367		2.358	
Max. Sp.Gr. (Gmm)	2.466	2.454	2.426		2.456	Number of Gyrations
% Gmm @ N- Initial	87.6	88.7	89.6		88.5	N-Initial
%Gmm @ N-Max	96.1	97.4	98.8		97.1	7
% Air Voids	5.0	3.7	2.4		4.0	N-Design
% VMA	14.9	14.6	14.9		14.7	76
% VFA	66.2	74.4	83.7		72.8	N-Max
Film Thickness	9.2	10.1	11.6		9.9	117
Filler Bit Ratio	0.97	0.89	0.77		0.90	
Gsb	2.610	2.610	2.610		2.610	
Gse	2.668	2.675	2.662		2.668	Gsb for Angularity
Pbe	4.34	4.74	5.43		4.66	Method A
Pba	0.86	0.96	0.77		0.86	2.600
% New Asphalt Binder	100.0	100.0	100.0		100.0	
Asphalt Binder Sp.Gr. @ 25c	1.031	1.031	1.031		1.031	Pba / %Abs Ratio
% Water Abs	1.83	1.83	1.83		1.83	0.47
S.A. m^2 / Kg.	4.69	4.69	4.69		4.69	
% + 4 Type 4 Agg.	99	99	99		99	
% + 4 Type 2 or 3 Agg.	1	1	1		1	Slope of Compaction
Angularity-method A	43	43	43		43	Curve
% Flat & Elongated	0.3	0.3	0.3		0.3	14.1
Sand Equivalent	86	86	86		86	

Disposition : An asphalt content of 5.6% is recommended to start this project.

Data shown in 5.55% column is interpolated from test data.

Target change 8-10-06
#4 = 61-75 (68)
#8 = 45-55 (50)

Comments : Final approval based on plant produced mix.

Copies to : MANATTS INC DIST 1 MTLS DIST 1 LAB SNYDER & ASSOC. CHERYL BARTON

Signed : John M. Hart / Cheryl Barton

Form 955 ver 5.0

Iowa Department of Transportation

Highway Division-Office of Materials

Proportion & Production Limits For Aggregates

County : STORY | Project No.: BR-810-0(83)--7A-85 | Date: 05/28/03

Project Location: 13TH STREET | Mix Design No.: 1BD3-008

Contract Mix Tonnage: 3,000 | Course: Surface | Mix Size (in.): 1/2

Contractor: MANATTS INC | Mix Type: HMA 1M | Design Life ESAL's: 1,000,000

Material	Ident #	% in Mix	Producer & Location	Beds	Gsb	%Abs
1/2 CR ASPH EC	A85006	45.0%	MARTIN MARIETTA AMES	26,28-39	2.621	1.85
1/4 CL CHIP GC	A85006	10.0%	MARTIN MARIETTA AMES	19-25	2.600	1.80
MANF SAND EC	A85006	20.0%	MARTIN MARIETTA AMES	26,28-39	2.623	2.26
SAND	A85510	25.0%	HALLETT MTLS AMES S PIT		2.583	1.48

Type and Source of Asphalt Binder: PG 64-22 BITUMINOUS MTLS

Individual Aggregates Sieve Analysis - % Passing (Target)

Material	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
1/2 CR ASPH EC	100	100	95	73	31	21	15	13	10	8.4	8.0
1/4 CL CHIP GC	100	100	100	100	42	4.0	3.5	3.0	2.5	1.8	1.5
MANF SAND EC	100	100	100	100	98	72	43	23	11	5.6	2.0
SAND	100	100	100	100	98	89	69	37	9.1	0.4	0.2

Preliminary Job Mix Formula Target Gradation

	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
Upper Tolerance	100	100	100	95	69	52		24			6.2
Comb Grading	100	100	98	88	62	47	33	20	9.2	4.8	4.2
Lower Tolerance	100	100	91	81	55	42		16			2.2
S.A.sq. m/kg	Total	4.69		+0.41	0.27	0.39	0.62	0.77	0.80	1 00	2.23

Production Limits for Aggregates Approved by the Contractor & Producer

Sieve Size in.	45.0% of mix 1/2 CR ASPH EC		10.0% of mix 1/4 CL CHIP GC		20.0% of mix MANF SAND EC		25.0% of mix SAND	
	Min	Max	Min	Max	Min	Max	Min	Max
1"	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/4"	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1/2"	90.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/8"	67.0	79.0	98.0	100.0	98.0	100.0	98.0	100.0
#4	24.0	36.0	35.0	49.0	95.0	100.0	91.0	100.0
#8	16.0	26.0	0.0	7.0	66.0	80.0	84.0	94.0
#30	10.0	18.0	0.0	5.0	19.0	28.0	33.0	41.0
#200	6.0	10.0	0.0	2.5	0.0	3.0	0.0	2.2

Comments: Signatures on file in District 1 Materials Office

Copies to: MANATTS INC | DIST 1 MTLS | DIST 1 LAB | SNYDER & ASSOC. | CHERYL BARTON

The above target gradations and production limits have been discussed with and agreed to by an authorized representative of the aggregate producer.

Signed: ______________________ Producer

Signed: ______________________ Contractor

APPENDIX B DYNAMIC MODULUS TEST RESULTS

The results of the dynamic modulus test and phase angle for the control group are presented in Tables B-1 and B-2, respectively. The results for the conditioned group are presented in Tables B-3 and B-4

Table B-1 Dynamic Modulus Results for Control Mixes (GPa)

Mix Name	Sample Number	Temp	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
6N	Mean	4	12.47	12.26	10.66	10.97	10.43	9.07	8.33	7.78	6.55
6N	Mean	21	5.70	5.20	4.79	4.17	3.59	2.76	2.45	2.22	1.67
6N	Stdv	4	1.63	0.78	2.29	0.74	0.74	0.75	0.74	0.74	0.73
6N	Stdv	21	0.66	0.60	0.60	0.56	0.54	0.47	0.43	0.40	0.33
6N	CoV (%)	4	13.1	6.3	21.5	6.8	7.1	8.2	8.9	9.6	11.2
6N	CoV (%)	21	11.5	11.6	12.5	13.4	15.1	17.1	17.4	18.1	19.9
218	Mean	4	14.02	13.31	12.78	12.01	10.96	9.96	9.20	8.68	7.36
218	Mean	21	6.37	5.75	5.34	4.63	3.59	2.95	2.64	2.40	1.73
218	Stdv	4	1.31	1.14	1.01	0.91	0.99	0.82	0.78	0.65	0.50
218	Stdv	21	0.34	0.29	0.28	0.25	0.21	0.18	0.17	0.15	0.12
218	CoV (%)	4	9.3	8.6	7.9	7.6	9.0	8.2	8.5	7.5	6.7
218	CoV (%)	21	5.3	5.0	5.2	5.3	6.0	6.2	6.5	6.4	6.9
235I	Mean	4	14.13	13.35	12.62	11.67	11.04	9.37	8.50	7.86	6.43
235I	Mean	21	5.90	5.34	4.89	4.18	3.44	2.62	2.25	2.00	1.46
235I	Stdv	4	0.78	0.59	0.55	0.53	0.51	0.45	0.42	0.37	0.36
235I	Stdv	21	0.33	0.29	0.27	0.24	0.21	0.17	0.14	0.13	0.09
235I	CoV (%)	4	5.5	4.4	4.4	4.5	4.6	4.8	5.0	4.7	5.5
235I	CoV (%)	21	5.6	5.4	5.6	5.7	6.1	6.5	6.2	6.7	6.4
235s	Mean	4	13.83	13.02	12.30	11.40	10.32	9.22	8.49	7.92	6.62
235s	Mean	21	6.13	5.50	5.09	4.40	3.38	2.81	2.45	2.21	1.64
235s	Stdv	4	4.36	4.23	4.05	3.92	3.89	3.59	3.39	3.20	2.80
235s	Stdv	21	2.13	1.95	1.84	1.63	1.34	1.12	1.00	0.92	0.67
235s	CoV (%)	4	31.5	32.5	32.9	34.4	37.7	39.0	39.9	40.4	42.3
235s	CoV (%)	21	34.8	35.5	36.2	37.1	39.7	39.9	40.8	41.4	40.7

Table B-1 (continued)

Mix Name	Sample Number	Temp	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
330B	Mean	4	13.54	12.66	12.02	11.21	10.28	9.22	8.58	8.00	6.57
330B	Mean	21	5.56	4.99	4.58	3.93	2.96	2.40	2.12	1.90	1.32
330B	Stdv	4	1.02	0.85	0.78	0.74	0.75	0.66	0.61	0.58	0.49
330B	Stdv	21	0.48	0.39	0.37	0.33	0.26	0.22	0.18	0.18	0.13
330B	CoV (%)	4	7.6	6.7	6.5	6.6	7.2	7.1	7.1	7.2	7.4
330B	CoV (%)	21	8.6	7.9	8.0	8.4	8.8	9.0	8.7	9.4	9.8
330I	Mean	4	16.87	16.38	15.57	14.66	14.00	12.22	11.28	10.47	8.72
330I	Mean	21	7.57	6.77	6.24	5.42	4.63	3.54	3.10	2.76	1.96
330I	Stdv	4	0.93	0.47	0.39	0.37	0.35	0.34	0.32	0.27	0.26
330I	Stdv	21	0.29	0.25	0.24	0.19	0.18	0.14	0.12	0.10	0.08
330I	CoV (%)	4	5.5	2.9	2.5	2.5	2.5	2.8	2.8	2.6	2.9
330I	CoV (%)	21	3.8	3.7	3.9	3.5	3.8	3.9	3.9	3.7	3.9
330s	Mean	4	16.19	15.56	14.94	14.19	13.82	12.39	11.56	10.92	9.65
330s	Mean	21	9.83	9.08	8.47	7.45	6.71	5.22	4.38	3.82	2.79
330s	Stdv	4	1.17	1.16	1.11	1.12	1.11	1.10	1.05	0.98	1.04
330s	Stdv	21	0.34	0.32	0.30	0.26	0.24	0.22	0.21	0.22	0.19
330I	CoV (%)	4	7.2	7.4	7.4	7.9	8.0	8.9	9.1	9.0	10.8
330I	CoV (%)	21	10.4	11.1	11.5	12.0	14.4	17.6	20.2	23.4	28.3
ALT	Mean	4	20.66	19.64	19.35	18.32	17.61	15.69	14.62	13.79	11.96
ALT	Mean	21	10.70	9.60	8.95	7.96	6.98	5.57	4.88	4.45	3.35
ALT	Stdv	4	0.68	0.95	0.76	0.74	0.73	0.76	0.82	0.83	0.85
ALT	Stdv	21	0.75	0.65	0.61	0.62	0.57	0.55	0.53	0.52	0.46
ALT	CoV (%)	4	3.3	4.8	3.9	4.1	4.1	4.8	5.6	6.0	7.1
ALT	CoV (%)	21	7.0	6.8	6.9	7.8	8.1	9.8	10.8	11.8	13.8

Table B-1 (continued)

Mix Name	Sample Number	Temp	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
Ded	Mean	4	9.36	8.57	8.06	7.28	6.32	5.44	5.03	4.62	3.25
Ded	Mean	21	3.31	2.92	2.64	2.19	1.58	1.28	1.09	0.96	0.68
Ded	Stdv	4	0.62	0.51	0.53	0.51	0.43	0.40	0.35	0.35	0.79
Ded	Stdv	21	0.26	0.23	0.21	0.18	0.14	0.11	0.09	0.08	0.05
Ded	CoV (%)	4	6.6	6.0	6.5	7.0	6.8	7.3	7.0	7.5	24.3
Ded	CoV (%)	21	7.8	7.9	7.8	8.2	8.6	8.8	8.3	8.3	7.9
F52	Mean	4	12.71	11.76	11.16	10.23	9.50	7.91	7.15	6.64	5.32
F52	Mean	21	5.02	4.50	4.14	3.51	2.77	2.08	1.82	1.60	1.16
F52	Stdv	4	0.64	0.54	0.42	0.38	0.37	0.31	0.29	0.27	0.26
F52	Stdv	21	0.24	0.19	0.19	0.19	0.18	0.13	0.12	0.13	0.11
F52	CoV (%)	4	5.1	4.6	3.7	3.7	3.8	3.9	4.1	4.1	4.9
F52	CoV (%)	21	4.8	4.3	4.7	5.3	6.4	6.4	6.9	7.9	9.4
HW4	Mean	4	12.85	11.90	11.30	10.43	9.83	8.33	7.70	7.13	5.88
HW4	Mean	21	7.26	6.48	5.85	4.81	4.08	2.74	2.08	1.68	1.07
HW4	Stdv	4	1.85	2.01	1.96	1.95	2.04	2.03	1.86	1.78	1.81
HW4	Stdv	21	0.80	0.74	0.70	0.62	0.38	0.26	0.20	0.22	0.14
HW4	CoV (%)	4	14.4	16.9	17.3	18.7	20.8	24.3	24.2	25.0	30.8
HW4	CoV (%)	21	44.5	47.4	50.7	53.8	49.0	58.3	44.7	51.2	41.8
I80B	Mean	4	16.20	15.49	14.86	13.95	13.39	11.78	10.95	10.25	8.61
I80B	Mean	21	7.98	7.22	6.67	5.82	5.07	3.89	3.38	3.01	2.13
I80B	Stdv	4	0.35	0.42	0.40	0.31	0.41	0.40	0.39	0.35	0.32
I80B	Stdv	21	0.32	0.24	0.23	0.22	0.21	0.19	0.16	0.13	0.09
I80B	CoV (%)	4	2.2	2.7	2.7	2.2	3.1	3.4	3.6	3.4	3.7
I80B	CoV (%)	21	4.0	3.4	3.4	3.8	4.2	4.8	4.6	4.2	4.3

Table B-1 (continued)

Mix Name	Sample Number	Temp	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
I80s	Mean	4	17.74	17.16	16.41	15.57	14.56	13.51	12.51	11.84	10.43
I80s	Mean	21	9.08	8.26	7.71	6.88	5.76	4.89	4.42	4.04	3.09
I80s	Stdv	4	1.09	1.04	0.99	0.92	0.83	0.92	0.79	0.82	0.90
I80s	Stdv	21	0.85	0.77	0.72	0.69	0.68	0.63	0.59	0.54	0.49
I80s	CoV (%)	4	6.2	6.1	6.0	5.9	5.7	6.8	6.3	6.9	8.6
I80s	CoV (%)	21	9.3	9.3	9.4	10.1	11.8	12.8	13.3	13.4	15.9
Jewell	Mean	4	15.05	14.46	13.75	12.93	11.94	10.83	10.06	9.43	7.90
Jewell	Mean	21	6.75	6.11	5.67	4.92	3.84	3.18	2.84	2.57	1.83
Jewell	Stdv	4	0.64	0.67	0.64	0.60	0.62	0.64	0.60	0.58	0.51
Jewell	Stdv	21	0.39	0.34	0.35	0.33	0.29	0.26	0.24	0.24	0.20
Jewell	CoV (%)	4	4.3	4.6	4.6	4.7	5.2	5.9	5.9	6.1	6.5
Jewell	CoV (%)	21	5.8	5.6	6.1	6.7	7.5	8.2	8.5	9.3	10.7
NW	Mean	4	14.82	14.08	13.31	12.43	11.52	10.31	9.58	8.94	7.32
NW	Mean	21	6.17	5.50	5.05	4.33	3.31	2.70	2.39	2.14	1.48
NW	Stdv	4	0.64	0.76	0.70	0.71	0.71	0.69	0.63	0.58	0.52
NW	Stdv	21	0.43	0.36	0.34	0.30	0.26	0.22	0.19	0.18	0.13
NW	CoV (%)	4	4.3	5.4	5.3	5.7	6.2	6.7	6.6	6.5	7.1
NW	CoV (%)	21	6.9	6.6	6.8	7.0	7.7	8.1	8.1	8.3	8.8
Rose	Mean	4	16.39	16.34	15.65	14.96	14.47	13.07	12.29	11.66	10.33
Rose	Mean	21	8.86	8.13	7.60	6.83	6.21	5.09	4.55	4.18	3.30
Rose	Stdv	4	0.94	0.99	0.79	0.76	0.79	0.68	0.66	0.61	0.55
Rose	Stdv	21	0.49	0.47	0.44	0.48	0.54	0.55	0.50	0.47	0.44
Rose	CoV (%)	4	5.7	6.1	5.1	5.1	5.5	5.2	5.3	5.2	5.4
Rose	CoV (%)	21	5.5	5.8	5.8	7.0	8.7	10.7	10.9	11.2	13.3

Table B-2 Phase Angle Values for Control Mixes

Mix Name	Sample Number	Temp	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
6N	Mean	4	3.97	7.24	7.80	9.48	10.32	11.40	12.44	13.22	15.07
6N	Mean	21	14.38	16.26	17.44	19.56	21.39	24.18	26.14	28.87	31.92
6N	Stdv	4	2.18	0.81	1.20	0.83	1.12	1.05	1.02	1.43	1.43
6N	Stdv	21	1.34	1.28	1.28	1.46	2.12	2.10	1.87	2.55	1.86
6N	CoV (%)	4	54.9	11.2	15.4	8.8	10.9	9.3	8.2	10.8	9.5
6N	CoV (%)	21	9.3	7.9	7.3	7.4	9.9	8.7	7.2	8.8	5.8
218	Mean	4	5.23	6.95	7.81	9.23	9.85	10.99	12.25	13.62	15.60
218	Mean	21	14.68	16.55	17.85	20.28	23.45	25.39	27.17	32.60	35.79
218	Stdv	4	1.14	0.52	0.40	0.60	0.64	0.64	0.35	0.53	1.00
218	Stdv	21	0.67	0.43	0.39	0.47	2.04	0.76	0.85	1.16	1.38
218	CoV (%)	4	21.9	7.5	5.1	6.5	6.5	5.8	2.8	3.9	6.4
218	CoV (%)	21	4.6	2.6	2.2	2.3	8.7	3.0	3.1	3.5	3.9
235I	Mean	4	6.30	8.31	9.41	10.97	12.09	13.75	14.58	15.97	18.03
235I	Mean	21	16.23	18.08	19.40	21.69	24.98	26.97	30.61	32.54	33.28
235I	Stdv	4	0.31	0.32	0.27	0.26	0.69	0.39	0.38	0.51	0.58
235I	Stdv	21	0.40	0.21	0.23	0.33	1.56	1.04	2.09	1.67	1.91
235I	CoV (%)	4	4.9	3.9	2.9	2.4	5.7	2.8	2.6	3.2	3.2
235I	CoV (%)	21	2.4	1.2	1.2	1.5	6.2	3.9	6.8	5.1	5.7
235s	Mean	4	8.03	9.56	10.59	12.32	13.23	14.28	16.22	17.05	18.89
235s	Mean	21	16.00	17.80	18.84	20.92	23.97	26.00	29.01	30.60	32.50
235s	Stdv	4	3.71	3.91	4.08	4.49	5.21	5.47	7.33	7.58	6.79
235s	Stdv	21	3.21	3.10	2.73	2.39	3.91	2.77	4.08	2.52	1.67
235s	CoV (%)	4	46.2	40.9	38.5	36.4	39.4	38.3	45.2	44.5	36.0
235s	CoV (%)	21	20.1	17.4	14.5	11.4	16.3	10.7	14.1	8.2	5.1

Table B-2 (continued)

Mix Name	Sample Number	Temp	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
330B	Mean	4	6.29	6.86	8.02	9.56	10.44	11.69	12.75	14.05	16.73
330B	Mean	21	15.49	17.60	19.05	21.68	25.17	26.87	33.16	35.97	37.59
330B	Stdv	4	0.70	0.21	0.11	0.04	0.49	0.43	0.71	0.62	1.76
330B	Stdv	21	0.78	0.56	0.51	0.67	1.45	0.99	2.86	2.18	2.95
330B	CoV (%)	4	11.2	3.1	1.4	0.5	4.6	3.7	5.6	4.4	10.5
330B	CoV (%)	21	5.0	3.2	2.7	3.1	5.8	3.7	8.6	6.1	7.8
330I	Mean	4	4.81	6.45	7.33	8.68	9.65	11.10	11.64	12.46	14.29
330I	Mean	21	14.32	16.08	17.33	19.75	23.59	25.45	28.46	30.70	33.29
330I	Stdv	4	1.30	0.22	0.30	0.34	0.19	0.76	0.38	0.28	0.75
330I	Stdv	21	0.26	0.23	0.23	0.33	0.83	0.49	1.65	1.20	1.47
330I	CoV (%)	4	26.9	3.4	4.0	3.9	2.0	6.8	3.3	2.3	5.3
330I	CoV (%)	21	1.8	1.4	1.4	1.7	3.5	1.9	5.8	3.9	4.4
330s	Mean	4	4.51	5.58	6.26	7.27	7.69	8.71	8.88	9.39	10.33
330s	Mean	21	12.25	13.63	14.42	15.90	17.87	19.75	20.69	22.60	23.28
330s	Stdv	4	0.89	0.37	0.41	0.71	0.79	0.88	0.86	1.37	1.30
330s	Stdv	21	1.55	1.04	1.13	1.03	1.75	2.57	2.13	2.20	0.73
330I	CoV (%)	4	19.7	6.6	6.5	9.8	10.2	10.1	9.7	14.6	12.6
330I	CoV (%)	21	7.7	4.8	5.0	4.2	6.2	8.4	6.6	6.1	2.0
ALT	Mean	4	2.57	5.33	6.50	7.77	8.38	10.00	10.40	10.99	12.51
ALT	Mean	21	12.10	13.87	15.16	17.34	19.88	22.06	24.54	26.91	28.76
ALT	Stdv	4	2.39	1.09	0.46	0.69	0.90	0.54	0.91	0.94	0.98
ALT	Stdv	21	0.73	0.91	0.87	1.04	1.94	1.22	2.67	2.40	1.16
ALT	CoV (%)	4	92.9	20.5	7.1	8.9	10.8	5.4	8.7	8.6	7.8
ALT	CoV (%)	21	6.1	6.6	5.7	6.0	9.7	5.5	10.9	8.9	4.0

Table B-2 (continued)

Mix Name	Sample Number	Temp	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
Ded	Mean	4	9.21	11.11	12.23	14.21	15.51	16.86	18.58	21.03	25.66
Ded	Mean	21	19.82	21.93	23.18	25.36	28.18	30.15	33.05	35.28	38.25
Ded	Stdv	4	0.50	0.56	0.54	0.50	0.84	0.34	0.65	1.39	3.50
Ded	Stdv	21	0.45	0.71	0.58	0.62	1.29	0.65	0.78	1.20	1.06
Ded	CoV (%)	4	5.5	5.1	4.4	3.5	5.4	2.0	3.5	6.6	13.6
Ded	CoV (%)	21	2.3	3.3	2.5	2.5	4.6	2.2	2.3	3.4	2.8
F52	Mean	4	6.59	9.68	10.73	12.48	13.63	15.36	17.36	19.00	22.43
F52	Mean	21	18.90	20.39	21.56	23.96	28.59	29.57	31.78	33.86	35.11
F52	Stdv	4	2.28	0.37	0.41	0.50	0.99	0.55	1.02	1.17	0.74
F52	Stdv	21	0.87	0.84	0.74	0.79	1.69	1.38	0.85	0.82	1.71
F52	CoV (%)	4	34.6	3.9	3.8	4.0	7.2	3.6	5.9	6.2	3.3
F52	CoV (%)	21	4.6	4.1	3.4	3.3	5.9	4.7	2.7	2.4	4.9
HW4	Mean	4	7.01	8.58	9.82	11.22	12.28	13.83	14.84	16.90	20.07
HW4	Mean	21	16.48	17.85	18.52	19.53	22.57	22.78	23.31	25.12	25.60
HW4	Stdv	4	1.35	1.63	1.68	2.00	2.38	2.64	3.09	4.37	5.67
HW4	Stdv	21	4.55	3.78	3.58	2.70	1.97	1.19	1.75	2.61	3.68
HW4	CoV (%)	4	19.2	19.0	17.1	17.8	19.4	19.1	20.8	25.9	28.3
HW4	CoV (%)	21	17.5	13.9	13.1	9.7	6.0	3.7	5.5	7.8	11.8
I80B	Mean	4	4.27	6.08	7.36	8.61	9.24	10.82	11.97	12.92	15.19
I80B	Mean	21	13.26	15.54	16.87	19.26	21.70	24.49	27.78	29.53	32.50
I80B	Stdv	4	1.39	0.54	0.18	0.36	0.65	0.50	0.71	0.45	1.23
I80B	Stdv	21	0.72	0.50	0.51	0.50	1.06	0.82	1.61	0.92	1.92
I80B	CoV (%)	4	32.4	8.8	2.5	4.2	7.1	4.6	5.9	3.5	8.1
I80B	CoV (%)	21	5.4	3.2	3.0	2.6	4.9	3.3	5.8	3.1	5.9

Table B-2 (continued)

Mix Name	Sample Number	Temp	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
I80s	Mean	4	2.94	5.09	6.12	7.27	8.07	9.24	9.45	10.21	11.10
I80s	Mean	21	11.22	13.20	14.37	16.50	17.95	20.50	22.00	24.77	28.76
I80s	Stdv	4	0.79	0.61	0.45	0.50	0.84	0.86	0.74	0.76	0.91
I80s	Stdv	21	0.97	0.90	0.91	1.06	1.23	1.16	1.65	1.97	1.68
I80s	CoV (%)	4	26.9	12.1	7.4	6.9	10.4	9.3	7.8	7.5	8.2
I80s	CoV (%)	21	8.6	6.8	6.3	6.4	6.9	5.6	7.5	8.0	5.8
Jewell	Mean	4	5.08	6.40	7.63	8.96	9.53	10.99	11.81	12.53	14.92
Jewell	Mean	21	14.50	16.24	17.47	19.86	23.07	25.03	28.48	31.95	35.94
Jewell	Stdv	4	0.37	0.41	0.33	0.42	0.71	0.99	0.75	0.71	0.88
Jewell	Stdv	21	0.62	0.62	0.58	0.52	1.51	0.93	1.87	0.74	3.48
Jewell	CoV (%)	4	7.2	6.4	4.4	4.7	7.4	9.0	6.3	5.7	5.9
Jewell	CoV (%)	21	4.3	3.8	3.3	2.6	6.5	3.7	6.6	2.3	9.7
NW	Mean	4	5.63	7.00	8.01	9.62	10.38	12.19	12.95	13.60	16.53
NW	Mean	21	15.79	17.54	18.86	21.39	24.39	26.82	29.86	32.84	37.51
NW	Stdv	4	0.68	0.21	0.25	0.38	0.57	0.40	0.42	0.51	1.66
NW	Stdv	21	0.55	0.45	0.54	0.47	1.62	0.75	1.75	1.12	1.75
NW	CoV (%)	4	12.0	3.0	3.2	3.9	5.5	3.2	3.2	3.8	10.0
NW	CoV (%)	21	3.5	2.5	2.9	2.2	6.6	2.8	5.9	3.4	4.7
Rose	Mean	4	3.31	4.62	5.68	6.59	7.19	8.23	8.27	8.27	9.15
Rose	Mean	21	9.98	11.69	12.92	14.75	16.29	18.12	20.16	21.46	24.58
Rose	Stdv	4	1.30	0.72	0.66	0.66	0.81	0.96	0.97	1.41	1.65
Rose	Stdv	21	1.50	1.39	1.53	1.97	2.71	2.40	3.22	3.14	3.83
Rose	CoV (%)	4	39.2	15.6	11.7	10.0	11.3	11.7	11.8	17.1	18.0
Rose	CoV (%)	21	15.0	11.9	11.8	13.4	16.6	13.3	16.0	14.6	15.6

Table B-3 Dynamic Modulus Results for Moisture Conditioned Mixes (GPa)

Mix Name	Sample Number	Temp	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
6N	Mean	4	12.09	11.35	10.80	9.81	8.95	7.63	6.56	6.44	5.09
6N	Mean	21	5.84	5.21	4.77	4.04	3.37	2.57	2.21	1.94	1.35
6N	Stdv	4	1.72	1.37	1.24	1.11	1.35	1.20	1.27	1.01	1.31
6N	Stdv	21	0.62	0.55	0.45	0.41	0.37	0.29	0.26	0.21	0.14
6N	CoV (%)	4	14.2	12.0	11.5	11.3	15.1	15.7	19.4	15.6	25.9
6N	CoV (%)	21	10.6	10.5	9.4	10.0	11.0	11.4	11.7	10.9	10.1
218	Mean	4	14.65	13.62	13.17	12.30	11.55	10.09	9.28	8.75	7.33
218	Mean	21	7.41	6.65	6.07	5.22	4.41	3.32	2.82	2.52	1.62
218	Stdv	4	1.80	1.47	1.38	1.17	1.13	0.99	0.89	0.76	0.63
218	Stdv	21	0.84	0.69	0.60	0.50	0.45	0.34	0.38	0.30	0.41
218	CoV (%)	4	12.3	10.8	10.5	9.5	9.8	9.9	9.6	8.7	8.6
218	CoV (%)	21	11.3	10.4	9.9	9.6	10.3	10.3	13.4	12.1	25.3
235I	Mean	4	12.70	11.73	11.06	10.13	9.19	7.85	7.17	6.63	5.39
235I	Mean	21	5.34	4.81	4.38	3.70	2.99	2.24	1.90	1.70	1.20
235I	Stdv	4	2.13	1.87	1.84	1.79	2.12	1.74	1.55	1.45	1.33
235I	Stdv	21	0.52	0.53	0.54	0.46	0.41	0.33	0.27	0.27	0.20
235I	CoV (%)	4	16.8	16.0	16.7	17.6	23.1	22.2	21.6	21.9	24.8
235I	CoV (%)	21	9.7	11.1	12.3	12.5	13.6	14.7	14.3	15.7	16.2
235s	Mean	4	15.88	14.69	14.00	12.89	12.16	10.36	9.40	8.76	7.23
235s	Mean	21	7.40	6.62	6.07	5.22	4.38	3.40	2.88	2.65	1.81
235s	Stdv	4	1.82	2.09	1.80	1.77	1.80	1.58	1.47	1.30	1.12
235s	Stdv	21	0.75	0.67	0.61	0.56	0.54	0.42	0.36	0.43	0.28
235s	CoV (%)	4	11.5	14.2	12.9	13.8	14.8	15.2	15.7	14.8	15.5
235s	CoV (%)	21	10.1	10.2	10.0	10.7	12.2	12.2	12.6	16.0	15.4

Table B-3 (continued)

Mix Name	Sample Number	Temp	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
330B	Mean	4	12.59	11.63	11.42	10.48	9.89	8.42	7.82	7.41	6.14
330B	Mean	21	6.11	5.55	5.12	4.39	3.62	2.79	2.35	1.98	1.36
330B	Stdv	4	1.92	1.83	1.38	1.60	1.36	1.09	0.82	0.79	0.67
330B	Stdv	21	0.58	0.45	0.34	0.29	0.24	0.20	0.22	0.34	0.19
330B	CoV (%)	4	15.2	15.7	12.1	15.2	13.8	12.9	10.5	10.7	10.9
330B	CoV (%)	21	9.6	8.1	6.7	6.6	6.6	7.2	9.2	17.0	13.9
330I	Mean	4	18.05	16.96	16.18	15.13	14.38	12.44	11.18	10.73	8.85
330I	Mean	21	8.83	7.92	7.25	6.29	5.31	4.16	3.59	3.14	2.25
330I	Stdv	4	1.76	1.70	1.46	1.40	1.41	1.25	1.09	0.87	1.08
330I	Stdv	21	0.77	0.69	0.67	0.60	0.76	0.48	0.48	0.48	0.30
330I	CoV (%)	4	9.8	10.0	9.0	9.3	9.8	10.0	9.7	8.1	12.2
330I	CoV (%)	21	8.7	8.7	9.2	9.5	14.3	11.4	13.3	15.3	13.6
330s	Mean	4	16.08	15.39	14.69	13.89	13.30	11.62	10.71	10.07	8.61
330s	Mean	21	8.34	7.52	6.93	6.08	5.30	4.20	3.68	3.36	2.46
330s	Stdv	4	1.90	1.87	1.72	1.71	1.79	1.81	1.79	1.82	1.68
330s	Stdv	21	1.21	1.11	1.01	0.96	0.99	0.85	0.77	0.76	0.67
330I	CoV (%)	4	11.8	12.1	11.7	12.3	13.5	15.5	16.7	18.1	19.6
330I	CoV (%)	21	14.5	14.7	14.6	15.8	18.7	20.3	20.9	22.6	27.3
ALT	Mean	4	20.54	19.34	18.92	17.72	16.88	14.95	13.93	13.12	11.08
ALT	Mean	21	11.87	10.70	9.95	8.75	7.67	6.08	5.34	4.81	3.47
ALT	Stdv	4	1.08	0.95	1.40	1.33	1.21	1.18	1.12	1.12	1.41
ALT	Stdv	21	1.03	0.92	0.84	0.74	0.68	0.56	0.48	0.46	0.38
ALT	CoV (%)	4	5.3	4.9	7.4	7.5	7.2	7.9	8.1	8.6	12.8
ALT	CoV (%)	21	8.7	8.6	8.4	8.5	8.8	9.2	9.1	9.5	10.9

Table B-3 (continued)

Mix Name	Sample Number	Temp	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
Ded	Mean	4	8.42	7.73	7.33	6.72	5.94	4.62	4.43	3.99	3.12
Ded	Mean	21	3.70	3.25	2.95	2.43	1.97	1.38	1.15	0.89	0.58
Ded	Stdv	4	0.50	0.46	0.36	0.33	0.60	0.74	0.41	0.73	0.62
Ded	Stdv	21	0.36	0.31	0.28	0.23	0.20	0.20	0.21	0.24	0.20
Ded	CoV (%)	4	5.9	6.0	4.9	4.9	10.1	15.9	9.3	18.2	19.9
Ded	CoV (%)	21	9.6	9.6	9.4	9.5	10.3	14.5	18.6	26.6	34.7
F52	Mean	4	12.97	11.95	11.40	10.46	9.32	7.55	6.88	6.12	4.50
F52	Mean	21	5.55	4.89	4.42	3.67	2.92	2.12	1.72	1.37	0.94
F52	Stdv	4	0.98	0.66	0.58	0.49	0.62	0.65	0.64	1.04	1.34
F52	Stdv	21	0.34	0.28	0.27	0.25	0.19	0.17	0.17	0.15	0.11
F52	CoV (%)	4	7.6	5.5	5.1	4.7	6.6	8.6	9.2	16.9	29.7
F52	CoV (%)	21	6.2	5.7	6.1	6.7	6.7	7.9	9.7	10.9	11.8
HW4	Mean	4	11.81	10.90	10.26	9.33	8.54	7.22	6.62	6.07	5.21
HW4	Mean	21	4.86	4.28	3.88	3.26	2.61	1.95	1.68	1.47	0.96
HW4	Stdv	4	1.98	1.87	1.83	1.76	1.80	1.84	1.89	2.03	2.02
HW4	Stdv	21	0.95	0.87	0.81	0.75	0.68	0.54	0.49	0.48	0.34
HW4	CoV (%)	4	16.8	17.2	17.8	18.9	21.1	25.5	28.6	33.5	38.7
HW4	CoV (%)	21	19.5	20.3	21.0	23.1	26.1	27.9	29.1	32.6	35.2
I80B	Mean	4	16.33	15.71	15.16	14.13	13.45	11.87	10.89	10.00	8.65
I80B	Mean	21	7.83	7.40	6.88	6.02	5.22	4.06	3.58	3.01	2.14
I80B	Stdv	4	1.27	1.59	1.54	1.58	1.49	1.50	1.49	1.73	1.37
I80B	Stdv	21	1.35	1.69	1.60	1.44	1.31	1.06	0.98	0.66	0.54
I80B	CoV (%)	4	7.8	10.1	10.2	11.2	11.0	12.6	13.7	17.3	15.8
I80B	CoV (%)	21	17.2	22.8	23.3	23.9	25.1	26.2	27.5	21.8	25.0

Table B-3 (continued)

Mix Name	Sample Number	Temp	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
I80s	Mean	4	16.53	15.16	14.96	13.99	13.36	11.65	10.78	10.27	8.68
I80s	Mean	21	8.25	7.70	7.19	6.24	5.44	4.28	3.78	3.43	2.46
I80s	Stdv	4	2.35	2.44	2.10	2.02	2.07	1.89	1.87	1.67	1.50
I80s	Stdv	21	0.59	0.47	0.36	0.30	0.30	0.24	0.24	0.17	0.15
I80s	CoV (%)	4	14.2	16.1	14.0	14.4	15.5	16.3	17.4	16.2	17.3
I80s	CoV (%)	21	7.1	6.1	5.1	4.8	5.5	5.5	6.3	5.0	6.1
Jewell	Mean	4	15.88	14.95	14.29	13.01	12.67	10.86	9.98	9.45	7.77
Jewell	Mean	21	8.08	7.28	6.67	5.80	4.93	3.79	3.32	2.94	2.06
Jewell	Stdv	4	2.55	2.37	2.15	2.75	2.11	2.07	1.80	1.76	1.19
Jewell	Stdv	21	1.29	1.12	1.07	0.98	0.91	0.75	0.67	0.62	0.48
Jewell	CoV (%)	4	16.0	15.9	15.0	21.1	16.6	19.0	18.0	18.6	15.3
Jewell	CoV (%)	21	16.0	15.4	16.0	17.0	18.4	19.8	20.2	21.0	23.2
NW	Mean	4	13.45	12.56	11.94	11.15	10.58	9.14	8.33	7.86	6.41
NW	Mean	21	6.51	5.86	5.38	4.63	3.87	2.94	2.54	2.24	1.54
NW	Stdv	4	2.66	2.45	2.27	2.12	2.07	1.84	1.71	1.56	1.42
NW	Stdv	21	0.44	0.37	0.34	0.29	0.29	0.22	0.19	0.19	0.16
NW	CoV (%)	4	19.8	19.5	19.0	19.0	19.6	20.1	20.6	19.9	22.1
NW	CoV (%)	21	6.7	6.4	6.3	6.2	7.4	7.3	7.3	8.5	10.7
Rose	Mean	4	15.44	14.49	13.76	13.31	12.59	11.02	10.20	9.79	8.17
Rose	Mean	21	7.52	6.86	6.39	5.63	4.88	3.84	3.40	3.07	2.27
Rose	Stdv	4	2.50	2.58	1.76	2.46	2.43	2.04	2.00	1.96	1.43
Rose	Stdv	21	0.62	0.59	0.53	0.45	0.44	0.37	0.32	0.27	0.23
Rose	CoV (%)	4	16.2	17.8	12.8	18.4	19.3	18.6	19.6	20.0	17.6
Rose	CoV (%)	21	8.2	8.6	8.3	7.9	9.0	9.7	9.4	8.8	10.0

Table B-4 Phase Angle Values for Moisture Conditioned Mixes

Mix Name	Sample Number	Temp	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
6N	Mean	4	7.27	8.74	9.74	11.43	12.92	13.34	14.07	15.19	20.50
6N	Mean	21	16.33	18.19	19.54	22.02	24.07	27.09	29.71	33.13	34.43
6N	Stdv	4	1.18	0.89	0.96	1.10	1.59	1.52	3.02	3.42	3.24
6N	Stdv	21	0.88	0.57	0.57	0.62	0.93	1.35	1.25	2.16	1.45
6N	CoV (%)	4	16.2	10.2	9.9	9.6	12.3	11.4	21.5	22.5	15.8
6N	CoV (%)	21	5.4	3.1	2.9	2.8	3.9	5.0	4.2	6.5	4.2
218	Mean	4	6.22	7.03	8.48	9.87	10.46	12.07	13.03	14.48	19.31
218	Mean	21	15.15	16.82	18.24	20.62	22.94	25.56	28.05	33.21	35.73
218	Stdv	4	0.63	1.64	0.53	0.52	0.59	0.89	0.78	0.92	4.15
218	Stdv	21	0.97	0.74	0.63	0.65	0.78	1.69	1.63	3.40	4.46
218	CoV (%)	4	10.2	23.2	6.3	5.3	5.7	7.3	6.0	6.4	21.5
218	CoV (%)	21	6.4	4.4	3.5	3.1	3.4	6.6	5.8	10.2	12.5
235I	Mean	4	7.93	9.67	10.91	12.49	14.82	15.36	17.29	18.96	21.62
235I	Mean	21	17.54	19.62	20.96	23.31	26.10	28.55	31.32	34.08	34.32
235I	Stdv	4	1.16	1.12	1.25	1.39	3.80	1.77	2.45	2.94	2.80
235I	Stdv	21	1.25	0.93	0.88	0.72	1.02	0.48	1.27	1.95	1.52
235I	CoV (%)	4	14.7	11.5	11.5	11.1	25.6	11.6	14.1	15.5	12.9
235I	CoV (%)	21	7.1	4.7	4.2	3.1	3.9	1.7	4.1	5.7	4.4
235s	Mean	4	7.42	8.93	9.83	11.55	12.72	14.10	14.96	16.70	19.48
235s	Mean	21	15.91	17.64	18.88	20.99	22.95	26.13	27.86	31.16	32.16
235s	Stdv	4	0.78	0.87	0.96	0.77	0.75	1.14	1.10	1.56	2.02
235s	Stdv	21	1.47	0.70	0.81	0.69	1.03	2.14	1.24	2.44	2.45
235s	CoV (%)	4	10.6	9.7	9.8	6.7	5.9	8.1	7.3	9.3	10.4
235s	CoV (%)	21	9.3	4.0	4.3	3.3	4.5	8.2	4.5	7.8	7.6

Table B-4 (continued)

Mix Name	Sample Number	Temp	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
330B	Mean	4	6.18	7.47	8.61	9.93	10.90	11.56	13.29	15.74	21.42
330B	Mean	21	16.40	17.53	19.05	21.70	24.33	26.91	30.73	36.68	37.56
330B	Stdv	4	0.68	0.65	0.42	0.70	0.59	1.71	1.82	1.37	3.51
330B	Stdv	21	0.62	0.69	0.54	0.54	0.49	1.85	1.93	9.58	4.00
330B	CoV (%)	4	11.1	8.7	4.8	7.1	5.5	14.8	13.7	8.7	16.4
330B	CoV (%)	21	3.8	4.0	2.9	2.5	2.0	6.9	6.3	26.1	10.7
330I	Mean	4	5.90	7.24	8.06	9.53	10.27	11.68	12.34	13.64	19.25
330I	Mean	21	14.51	16.05	17.37	19.69	22.92	25.08	27.00	30.27	33.24
330I	Stdv	4	0.82	0.32	0.32	0.50	0.68	0.86	0.78	0.57	5.00
330I	Stdv	21	1.10	0.98	1.05	1.15	3.37	1.64	2.06	1.60	2.11
330I	CoV (%)	4	14.0	4.4	4.0	5.2	6.6	7.3	6.3	4.2	26.0
330I	CoV (%)	21	7.5	6.1	6.0	5.8	14.7	6.5	7.6	5.3	6.3
330s	Mean	4	5.40	6.51	7.59	9.21	10.15	11.13	11.63	12.75	15.84
330s	Mean	21	13.59	15.07	16.18	18.16	19.93	23.03	23.32	26.71	29.42
330s	Stdv	4	1.32	1.49	1.22	1.21	1.67	1.38	1.77	2.13	4.84
330s	Stdv	21	1.98	1.77	1.82	1.91	2.36	2.54	4.43	2.85	3.04
330I	CoV (%)	4	24.4	22.9	16.1	13.1	16.4	12.4	15.2	16.7	30.6
330I	CoV (%)	21	14.6	11.8	11.2	10.5	11.9	11.0	19.0	10.7	10.3
ALT	Mean	4	5.78	6.82	7.58	8.78	9.35	11.25	12.01	13.21	17.27
ALT	Mean	21	12.68	14.30	15.48	17.86	20.08	23.01	25.79	27.65	30.09
ALT	Stdv	4	1.50	0.69	0.63	0.66	0.64	0.80	0.77	0.90	5.56
ALT	Stdv	21	0.76	0.60	0.54	0.48	0.82	1.01	1.21	0.75	0.97
ALT	CoV (%)	4	26.0	10.1	8.3	7.5	6.8	7.2	6.4	6.8	32.2
ALT	CoV (%)	21	6.0	4.2	3.5	2.7	4.1	4.4	4.7	2.7	3.2

Table B-4 (continued)

Mix Name	Sample Number	Temp	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
Ded	Mean	4	10.35	11.68	12.94	14.59	16.63	16.33	17.83	22.01	31.94
Ded	Mean	21	20.25	21.65	22.79	25.13	27.85	30.58	33.11	36.06	42.01
Ded	Stdv	4	1.26	1.39	1.39	1.56	2.40	2.90	2.75	2.57	11.78
Ded	Stdv	21	1.49	0.61	0.75	0.58	1.10	1.79	2.75	2.81	12.15
Ded	CoV (%)	4	12.2	11.9	10.8	10.7	14.4	17.8	15.4	11.7	36.9
Ded	CoV (%)	21	7.4	2.8	3.3	2.3	3.9	5.9	8.3	7.8	28.9
F52	Mean	4	9.08	10.69	11.68	13.70	15.43	16.10	18.61	20.25	37.36
F52	Mean	21	19.85	21.50	23.07	25.35	28.63	31.02	34.38	37.22	36.88
F52	Stdv	4	0.88	0.72	0.73	1.09	1.34	2.13	2.20	2.99	30.68
F52	Stdv	21	1.01	0.97	0.95	1.10	1.58	1.51	2.92	3.64	2.84
F52	CoV (%)	4	9.7	6.7	6.2	7.9	8.7	13.3	11.8	14.8	82.1
F52	CoV (%)	21	5.1	4.5	4.1	4.3	5.5	4.9	8.5	9.8	7.7
HW4	Mean	4	8.55	10.32	11.33	13.05	15.29	15.38	17.07	18.43	21.92
HW4	Mean	21	18.96	20.85	22.47	24.77	28.17	30.10	32.32	34.94	37.15
HW4	Stdv	4	1.53	1.32	1.45	1.71	2.83	2.37	3.05	3.18	3.96
HW4	Stdv	21	2.57	2.61	2.85	2.71	2.93	3.40	2.86	2.96	2.25
HW4	CoV (%)	4	17.9	12.8	12.8	13.1	18.5	15.4	17.9	17.3	18.1
HW4	CoV (%)	21	13.5	12.5	12.7	11.0	10.4	11.3	8.9	8.5	6.1
I80B	Mean	4	5.22	7.19	8.22	9.44	10.28	11.77	12.32	12.89	15.69
I80B	Mean	21	12.91	15.33	17.06	19.57	22.02	24.43	26.84	29.37	33.93
I80B	Stdv	4	0.85	0.75	0.93	0.90	1.12	1.06	1.59	3.26	2.85
I80B	Stdv	21	2.52	1.20	1.50	1.74	1.65	1.88	2.10	2.48	3.27
I80B	CoV (%)	4	16.2	10.4	11.3	9.5	10.9	9.0	12.9	25.3	18.2
I80B	CoV (%)	21	19.5	7.8	8.8	8.9	7.5	7.7	7.8	8.4	9.6

Table B-4 (continued)

Mix Name	Sample Number	Temp	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
I80s	Mean	4	5.08	6.59	7.81	9.00	9.72	10.74	11.08	12.90	16.64
I80s	Mean	21	12.80	15.03	16.24	18.64	20.72	23.04	25.40	28.65	34.16
I80s	Stdv	4	1.56	0.66	0.54	0.61	0.61	0.86	2.69	1.89	4.13
I80s	Stdv	21	3.43	0.38	0.41	0.67	0.97	0.79	1.05	2.81	5.29
I80s	CoV (%)	4	30.7	10.1	6.9	6.8	6.2	8.0	24.3	14.7	24.8
I80s	CoV (%)	21	26.8	2.5	2.5	3.6	4.7	3.4	4.1	9.8	15.5
Jewell	Mean	4	5.95	7.00	8.51	9.85	10.97	11.61	12.13	13.27	18.78
Jewell	Mean	21	15.03	16.63	18.00	20.48	23.06	25.39	28.59	30.94	33.28
Jewell	Stdv	4	1.08	1.98	1.08	1.22	1.53	1.86	2.17	2.23	4.43
Jewell	Stdv	21	0.70	0.72	0.65	0.75	0.93	1.31	2.17	1.86	1.59
Jewell	CoV (%)	4	18.2	28.3	12.7	12.3	13.9	16.1	17.9	16.8	23.6
Jewell	CoV (%)	21	4.7	4.3	3.6	3.6	4.0	5.2	7.6	6.0	4.8
NW	Mean	4	7.06	8.17	9.06	10.70	11.43	13.04	14.15	14.94	19.36
NW	Mean	21	15.31	17.33	18.58	21.10	23.83	25.98	29.17	32.09	34.57
NW	Stdv	4	1.29	1.07	0.98	1.04	1.17	1.63	1.47	1.95	3.04
NW	Stdv	21	1.05	0.69	0.85	0.60	1.20	0.86	1.36	1.64	1.10
NW	CoV (%)	4	18.2	13.1	10.8	9.7	10.2	12.5	10.4	13.0	15.7
NW	CoV (%)	21	6.9	4.0	4.6	2.8	5.0	3.3	4.7	5.1	3.2
Rose	Mean	4	4.79	6.22	6.92	8.83	9.63	10.57	11.56	13.15	16.44
Rose	Mean	21	13.00	14.91	16.33	18.47	20.37	22.64	25.04	28.37	30.89
Rose	Stdv	4	1.14	1.21	1.92	0.74	0.85	0.81	1.51	0.73	1.93
Rose	Stdv	21	1.28	1.04	1.41	1.09	1.39	1.93	2.40	2.11	2.66
Rose	CoV (%)	4	23.7	19.5	27.8	8.3	8.8	7.7	13.1	5.6	11.7
Rose	CoV (%)	21	9.8	7.0	8.6	5.9	6.8	8.5	9.6	7.4	8.6

APPENDIX C INDIRECT TENSILE STRENGTH RESULTS

Table C-1 Indirect Tensile Strength Test Results

Mix	Control				Moisture Conditioned			
	Sample	Thickness (mm)	Force (kN)	Stress (kPa)	Sample	Thickness (mm)	Force (kN)	Stress (kPa)
6N	3	62.48	9.37	955.1	1	62.95	8.43	853.0
6N	4	62.45	9.74	993.3	2	62.64	7.29	740.6
6N	6	62.38	10.06	1026.3	5	62.60	8.58	872.1
6N	8	62.49	9.83	1001.0	7	62.81	9.16	928.7
6N	10	62.47	9.79	998.2	9	62.72	8.67	880.4
6N	Mean	62.45	9.76	994.8	Mean	62.74	8.43	854.9
6N	Stdev	0.04	0.25	25.6	Stdev	0.14	0.69	69.7
6N	COV	0.07	2.52	2.6	COV	0.22	8.23	8.2
218	1	62.40	12.36	1260.7	2	62.70	7.14	724.6
218	5	62.39	12.10	1234.7	3	62.57	8.44	858.3
218	7	62.67	11.95	1214.1	4	62.50	8.57	873.3
218	8	63.24	10.79	1085.9	6	62.64	9.03	917.7
218	10	62.64	12.16	1236.3	9	62.60	9.07	922.4
218	Mean	62.67	11.87	1206.3	Mean	62.60	8.45	859.2
218	Stdev	0.35	0.62	69.3	Stdev	0.07	0.78	80.2
218	COV	0.55	5.26	5.7	COV	0.12	9.28	9.3
235I	4	62.50	12.10	1232.2	1	62.65	10.92	1109.9
235I	6	62.32	12.01	1227.3	2	62.45	11.51	1172.9
235I	8	62.37	11.98	1222.3	3	62.38	11.75	1199.6
235I	9	62.38	11.41	1164.9	5	62.37	11.48	1171.3
235I	10	62.38	11.51	1175.0	7	62.40	11.75	1198.7
235I	Mean	62.39	11.80	1204.3	Mean	62.45	11.48	1170.5
235I	Stdev	0.07	0.31	31.8	Stdev	0.12	0.34	36.5
235I	COV	0.11	2.67	2.6	COV	0.19	2.95	3.1
235S	3	62.40	12.10	1234.2	1	62.48	12.24	1246.8
235S	5	62.74	10.90	1106.5	2	62.60	12.45	1266.4
235S	6	62.41	11.51	1173.9	4	62.57	12.18	1239.0
235S	9	62.62	11.68	1187.6	7	62.74	11.81	1198.6
235S	10	62.84	11.56	1171.2	8	63.02	10.72	1083.0
235S	Mean	62.60	11.55	1174.7	Mean	62.68	11.88	1206.8
235S	Stdev	0.20	0.43	45.8	Stdev	0.21	0.69	73.4
235S	COV	0.31	3.71	3.9	COV	0.34	5.79	6.1

Table C-1 (continued)

Mix	Control				Moisture Conditioned			
	Sample	Thickness (mm)	Force (kN)	Stress (kPa)	Sample	Thickness (mm)	Force (kN)	Stress (kPa)
330B	1	62.30	9.14	934.3	2	62.51	7.66	780.1
330B	5	62.43	10.35	1055.7	3	62.34	7.47	762.4
330B	6	62.31	10.47	1069.5	4	62.50	7.86	800.3
330B	9	62.41	9.29	947.2	7	62.56	7.16	728.7
330B	10	62.40	10.45	1065.9	8	62.59	8.04	817.6
330B	Mean	62.37	9.94	1014.5	Mean	62.50	7.64	777.8
330B	Stdev	0.06	0.67	67.7	Stdev	0.10	0.34	34.4
330B	COV	0.10	6.69	6.7	COV	0.15	4.47	4.4
330I	2	62.50	12.02	1224.8	1	62.54	11.05	1124.5
330I	4	62.44	12.02	1225.6	3	62.68	11.11	1128.0
330I	5	62.39	12.06	1230.5	7	62.53	11.58	1178.8
330I	6	62.09	12.00	1230.8	8	62.62	11.23	1141.5
330I	9	62.51	10.83	1102.6	10	62.55	11.36	1155.9
330I	Mean	62.39	11.79	1202.9	Mean	62.58	11.26	1145.7
330I	Stdev	0.17	0.54	56.1	Stdev	0.06	0.21	22.2
330I	COV	0.28	4.56	4.7	COV	0.10	1.89	1.9
330S	1	62.46	12.56	1280.0	2	62.52	12.33	1255.5
330S	3	62.51	12.24	1246.3	4	62.40	12.28	1252.9
330S	6	62.34	12.33	1259.4	5	62.21	12.16	1244.5
330S	8	62.26	12.42	1270.1	7	62.24	12.10	1237.9
330S	9	62.31	12.50	1277.5	10	62.44	12.29	1253.0
330S	Mean	62.38	12.41	1266.6	Mean	62.36	12.23	1248.8
330S	Stdev	0.11	0.13	13.9	Stdev	0.13	0.10	7.3
330S	COV	0.17	1.04	1.1	COV	0.21	0.78	0.6
ALT	1	62.43	13.23	1349.3	2	62.48	13.20	1345.1
ALT	5	62.40	13.14	1341.0	3	62.44	13.17	1343.3
ALT	6	62.42	13.22	1347.8	4	62.46	13.07	1332.1
ALT	7	62.28	13.07	1336.3	9	62.50	13.16	1340.8
ALT	8	62.34	13.14	1341.9	10	62.47	13.12	1336.9
ALT	Mean	62.37	13.16	1343.3	Mean	62.47	13.15	1339.6
ALT	Stdev	0.06	0.06	5.3	Stdev	0.02	0.05	5.2
ALT	COV	0.10	0.49	0.4	COV	0.04	0.39	0.4
DED	1	62.34	12.21	1247.2	2	62.54	8.81	896.5
DED	3	62.47	11.30	1151.8	4	62.66	8.71	885.4
DED	7	62.35	11.66	1190.8	5	62.46	8.65	882.1
DED	9	62.39	11.32	1155.3	6	62.57	8.66	881.3
DED	10	62.29	10.90	1114.1	8	62.59	8.06	819.9

Table C-1 (continued)

Mix	Control				Moisture Conditioned			
	Sample	Thickness (mm)	Force (kN)	Stress (kPa)	Sample	Thickness (mm)	Force (kN)	Stress (kPa)
DED	Mean	62.37	11.48	1171.8	Mean	62.56	8.58	873.0
DED	Stdev	0.07	0.49	50.1	Stdev	0.07	0.30	30.3
DED	COV	0.11	4.27	4.3	COV	0.12	3.45	3.5
F52	2	62.56	8.55	870.0	1	62.75	7.98	809.7
F52	3	62.58	6.34	644.9	4	62.49	8.21	836.0
F52	4	62.40	9.01	919.5	7	62.67	6.80	691.2
F52	5	62.47	8.89	905.5	8	62.95	7.51	759.6
F52	6	62.46	8.41	856.8	10	62.89	8.01	810.5
F52	Mean	62.49	8.24	839.3	Mean	62.75	7.70	781.4
F52	Stdev	0.07	1.09	111.6	Stdev	0.18	0.56	57.5
F52	COV	0.12	13.23	13.3	COV	0.29	7.31	7.4
HW4	2	63.50	8.46	847.9	1	64.31	7.61	753.2
HW4	4	62.37	12.06	1231.0	3	64.25	7.63	756.1
HW4	6	62.40	12.15	1239.4	5	62.77	11.23	1138.5
HW4	7	62.42	11.84	1208.0	8	62.77	10.52	1067.4
HW4	9	62.38	11.30	1153.3	10	62.47	8.21	836.2
HW4	Mean	62.61	11.16	1135.9	Mean	63.31	9.04	910.3
HW4	Stdev	0.50	1.55	164.5	Stdev	0.89	1.71	180.8
HW4	COV	0.79	13.86	14.5	COV	1.41	18.93	19.9
I80B	2	62.50	12.84	1307.5	1	62.78	12.15	1231.7
I80B	3	62.55	12.60	1282.5	4	62.67	12.31	1250.6
I80B	5	62.05	12.61	1293.6	6	62.65	12.20	1239.8
I80B	7	62.06	12.56	1288.1	8	62.94	12.23	1236.6
I80B	9	62.02	12.50	1282.8	10	62.61	12.57	1278.2
I80B	Mean	62.24	12.62	1290.9	Mean	62.73	12.29	1247.4
I80B	Stdev	0.26	0.13	10.3	Stdev	0.13	0.17	18.5
I80B	COV	0.43	1.02	0.8	COV	0.21	1.36	1.5
I80S	5	62.72	12.26	1244.6	1	62.98	9.89	1000.0
I80S	6	62.55	12.16	1238.0	2	62.87	9.82	994.2
I80S	7	62.69	12.28	1247.1	3	63.26	9.13	918.7
I80S	8	62.61	12.04	1224.5	4	62.88	10.18	1030.4
I80S	10	62.58	12.39	1260.8	9	63.45	9.59	962.1
I80S	Mean	62.63	12.23	1243.0	Mean	63.09	9.72	981.1
I80S	Stdev	0.07	0.13	13.3	Stdev	0.26	0.39	42.5
I80S	COV	0.12	1.08	1.1	COV	0.41	4.04	4.3
Jewell	2	62.56	11.26	1146.1	1	62.54	11.02	1122.1
Jewell	6	62.49	11.91	1213.5	3	62.67	9.32	947.2

Table C-1 (continued)

Mix	Control				Moisture Conditioned			
	Sample	Thickness (mm)	Force (kN)	Stress (kPa)	Sample	Thickness (mm)	Force (kN)	Stress (kPa)
Jewell	7	62.48	11.51	1173.1	4	62.88	11.05	1119.1
Jewell	9	62.45	11.55	1176.9	5	62.76	11.54	1170.7
Jewell	10	62.46	11.56	1178.0	8	62.75	11.59	1175.6
Jewell	Mean	62.49	11.56	1177.5	Mean	62.72	10.91	1107.0
Jewell	Stdev	0.04	0.23	24.0	Stdev	0.13	0.92	93.1
Jewell	COV	0.07	2.00	2.0	COV	0.20	8.46	8.4
NW	2	62.55	8.90	906.0	1	63.46	7.61	763.7
NW	4	62.72	8.73	886.1	3	62.66	8.50	863.7
NW	5	62.62	9.07	921.9	6	62.77	6.97	706.8
NW	7	62.51	9.20	936.8	8	62.65	7.18	729.7
NW	10	62.43	9.03	920.4	9	62.58	8.68	882.6
NW	Mean	62.57	8.98	914.3	Mean	62.82	7.79	789.3
NW	Stdev	0.11	0.18	19.1	Stdev	0.36	0.77	79.5
NW	COV	0.18	1.98	2.1	COV	0.58	9.88	10.1
Rose	2	62.42	11.43	1166.2	1	62.53	12.11	1233.2
Rose	3	62.48	12.13	1236.0	6	62.40	12.09	1233.8
Rose	4	62.34	12.09	1235.1	8	62.32	11.86	1211.9
Rose	5	62.39	12.14	1238.7	9	62.45	12.06	1229.2
Rose	7	62.33	12.02	1228.0	10	62.47	11.77	1199.7
Rose	Mean	62.39	11.96	1220.8	Mean	62.43	11.98	1221.6
Rose	Stdev	0.06	0.30	30.8	Stdev	0.08	0.15	15.1
Rose	COV	0.10	2.51	2.5	COV	0.13	1.28	1.2