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Effect of Cement Content on Concrete Performance

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Effect of Cement Content on Concrete Performance

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Civil Engineering

by

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University of Arkansas
Bachelor of Science in Civil Engineering, 2017

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University of Arkansas

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Abstract

Of all the traditional concrete materials, portland cement has the greatest impact on mixture cost and the environment. Cement is in many ways the glue holding concrete together (Weiss, 1999), and as such, it plays a major role in fresh and hardened concrete properties. Without the proper range of cement in the mixture, low strength development or excessive shrinkage may occur leading to premature deterioration. The Arkansas Department of Transportation (ARDOT) recognizes two types of concrete for use in bridge construction, Class S and Class S(AE). This paper focuses on the findings from testing of Class S(AE) concrete, short for Class S air entrained, as it is the primary concrete used in the construction of bridge decks within the state. The goal of this project is to investigate the possibility of reducing cement content in Class S(AE) mix designs while maintaining required ARDOT specifications for fresh and hardened concrete. The testing program included varying cementitious material content, Class C fly ash percentage, and water to cementitious material ratio (w/cm).

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1. Chapter 1: Introduction

1.1. Need for Research

Concrete is one of the most heavily used construction materials around the world today, however this is not without a price (Mehta and Monteiro, 2006). One of the main elements in concrete is portland cement. Cement is not only more expensive than most other components in a traditional concrete mixture, but it also has major environmental impact. Approximately 7% of the carbon dioxide (CO₂) production worldwide is created in association with the production of cement (Mehta, 2004). In addition, the Environmental Protection Agency (EPA) designated the cement industry as the 3rd largest contributor to pollution in the world (EPA, 2003). Thus, the findings detailed within this report have potential to offer substantial monetary and financial savings.

The focus on cement reduction is not backed only by cost and green initiatives, but also by its relationship to many fresh and hardened concrete properties. Arguably the most important concrete property is compressive strength, since compressive strength affects so many properties of concrete. Compressive strength often increases as cement content increases. While this may seem positive, past research has shown links between increased concrete strength and increased drying shrinkage and cracking density (Darwin, Browning, and Lindquist, 2004). As cement content increases beyond what is necessary for design strength, issues with workability and durability may result, which must be accounted for via the use of admixtures (Wasserman, Katz, and Bentur, 2009). This decrease in workability and increase in heat of reacting cement often result in increased early age cracking. Through mixing and batching, concrete is as much an art as it is a science, there are evident ties between cement content and cracking (Aktan, Fu, Dekelbab, and Attanayaka , 2003).

When higher cement contents lead to strengths much higher than the minimum required by ARDOT for Class S(AE) concrete, early age cracking can occur decreasing the useful lifespan of bridges. Past research has shown the average compressive strength of bridge decks in Arkansas exceed the required 28-day compressive strength of 4000 psi (Reed and Hale, 2013). This study showed that even mixtures with higher w/cm still achieve 4000 psi by 7 days. Strengths exceeding the minimum requirements have been found to cause increased shrinkage that was likely partially related to the early strength gain due to increased hydration product formation in the first 1 to 7 days (Almutairi, 2017). Arkansas is not alone in experiencing this type of early cracking. Of the 30 states polled by Aktan et al. (2003), approximately 70% experienced the same sort of cracking within the first few months of the concrete’s life, as provided in Figure 1.1 (Aktan et al., 2003). The standards for Class S(AE) bridge deck concrete are provided in Table 1.1. The overall need for this project can be summed up by stating that reduction in cement content for concrete bridge decks can: reduce cracking, reduce cost, and reduce environmental impact.

Table 1.1. Class S (AE) ARDOT Concrete Mix Requirements

Properties	Class S (AE)
Minimum 28-day compressive strength (psi)	4000
Minimum cementitious content (lb/yd ³)	611
Maximum fly ash content (Class C or F) (%)	20
Maximum slag cement content (%)	25
Maximum w/cm	0.44
Slump range (in.)	1 – 4
Air content (%)	6 ± 2

Note. Adapted from ARDOT division 800. (2014).



Figure 1.1. States polled for early age concrete cracking (Aktan et al., 2003)

1.2. Goal of Research

Past research has provided data on the effect of cementitious material content on concrete properties. Cement content can affect Class S(AE) bridge deck concrete. This study looks at furthering these findings through additional testing of fresh and hardened properties of Class S(AE) concrete, to better determine how the mix proportions can change concrete properties. 36 different mixture designs were tested with 4 different w/cms, 3 different fly ash contents, and 3 different amounts of cementitious material. The principal goal was to provide evidence that mixtures can be proportioned to meet or exceed ARDOT requirements with a reduced cement content below current minimum design standards.

2. Chapter 2: Literature Review

This literature review will take an in depth look at past research that has shown correlations between fresh and hardened properties of concrete and cement content.

2.1. Mix Proportioning

In the most basic of terms concrete is made up of water, aggregate, and cementitious materials. Portland cement reacts with water to become the binder holding the mixture together. When additional admixtures, like high range water reducer (HRWR), or supplementary cementitious materials (SCMs) are added, their effects must be considered as all materials affect the concrete differently. For example, the addition of fly ash has been found to affect both compressive strength and shrinkage of concrete, and this must be accounted for when designing the mix (Thomas, 2007).

When designing a mix, engineers typically start by aiming for a specified 28-day concrete strength specified for the job, as shown in the ACI 211.1 *Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete* (Qasrawi, 2016). If using this standard, the engineer first selects the desired slump for the project. Then after taking into account the nominal maximum aggregate size, mixing water required can be determined. Next, the w/cm is chosen being chiefly dependent on the desired compressive strength, but also considering the exposure conditions of the concrete. Exposure also plays a role in selection of the type of cement as certain cement types work better under specific environmental conditions. Once all of this has been selected, the engineer can determine the weights of coarse aggregate, water, and cement to be used. Then using the absolute volume method and the different material weights and specific gravities, it is possible to determine the necessary amount of fine aggregate, while considering air voids.

2.2. Cement

Cement plays a major role within a concrete mixture and affects most important aspects of the mix, such as: workability, compressive strength, drying shrinkage, and durability. Through the process of hydration, cement particles react with water, binding the aggregate, and the strength matrix develops (Weiss, 1999). Around the world, many standards and specifications call for the overdesign of the concrete elements under the assumption that this creates another factor of safety (Taylor, Yurdakul, and Brink, 2015). However, recent research has shed light on the relationship between cement content and cracking and how overdesigning may be detrimental to concrete. As cement content in a mix increases, the compressive strength usually increases as well. However, costs also increase due to the high cost of cement relative to other concrete ingredients and long-term effects caused by crack maintenance. This cracking is likely a result of increased drying shrinkage and heat of hydration in the early age concrete with higher cement content (Aktan et.al, 2003).

2.2.1. Cement Content and Workability

Cement content and cement fineness play crucial roles in affecting the workability of concrete. If a mix has too much cement in relation to its water content, the mix will likely be difficult to place. However, with too much water the mixture will segregate, making it equally difficult to use for the intended purpose on the job. Thus, selecting the required amount of cement for a mix is integral to the concrete mixture design, affecting workability and overall construction costs. Finer cement requires increased water contents to hydrate a larger surface area and generally causes higher temperature during hydration (Mardani-Aghabaglou, Son, Felekoglu, Ramya, 2017). Thus, adjusting cement quantities and fineness within mixes prior to placement can help to improve workability protects the concrete from additional cracking within

its interfacial transition zone due to excessive heat and drying strain created during the curing process.

2.2.2. Cement Content and Compressive Strength

Increasing cement content typically results in an increase in compressive strength, particularly early age strength, however with all other factors kept standard the w/cm has the greater effect on strength. (Wasserman et al., 2009). There are limits to the linear relationship between compressive strength and cement content as provided in Figure 2.1. Taylor et al. (2015) found there was effectively a minimum cement content required to meet the 28-day strength. Once this value was met, the addition of cement beyond this amount did not significantly increase the compressive strength.

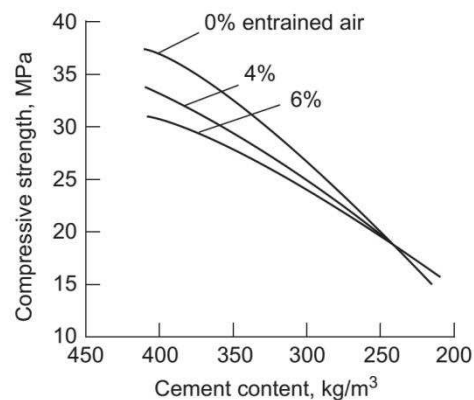


Figure 2.1. Relationship of concrete compressive strength and cementitious content (Mehta and Monteiro, 2006).

2.2.3. Cement Content and Drying Shrinkage

Drying shrinkage is the change in the volume of concrete from the loss of water by the concrete as the cement hydrates (Zhang, Han, and Gao, 2014). Increasing cement content will often increase the heat of hydration and the amount of water required to hydrate the cement, causing cracking (Weiss, 1999). This additional water can be an issue since adding extra water

increases drying shrinkage as more water is available within the mix to evaporate. Additionally, when concrete is restrained either with rebar or by other structural elements, any strain over 400×10^{-6} results in cracking (Babaei and Fouladga, 1997). Cracking can occur easily and is often very detrimental to the lifespan of concrete, so it is important to guard against it in as many ways as possible. Therefore, it is generally recommended to use a minimum cement content while still meeting 28-day compressive strength requirements, to better reduce early age cracking.

2.2.4. Cement Content and Durability

Cement also plays a major role in the durability of a concrete mix. Durability is the way the concrete resists weathering and deterioration while retaining its form, quality, and properties when under exposure (ACI Committee 201, *Durability of Concrete*). Cracks are a problem for durability and can decrease service life. An increase in cement can lead to an increase in cracking density, which can ultimately lower the durability of concrete substantially (Darwin et al., 2004). Additionally, increased cement often leads to more paste which has been shown to increase shrinkage and permeability (Fowler and Rached, 2011). It has also been seen that the use of fly ash or slag cement in mixes can reduce permeability (Salem and Burdett, 2004). Permeability can be better understood through rapid chloride ion permeability tests which are discussed in Section 4.4.

2.3. Prior Research

During hydration, greater heat causes greater stresses due to temperature. This leads to tensile stresses, which cause cracking as the concrete begins to hydrate. The heat of hydration and the subsequent cracking it causes were found to be primarily dependent on cement: type, content, and fineness (Aktan et al., 2003).

Past studies have also shown the amount of drying shrinkage present in concrete is a function of the amount of aggregate, type of aggregate, and cement paste content of the

concrete (ElSafty, 2013). Salem and Burdette (2004) found that shrinkage decreased with decreases in cement paste via the use of SCMs, as these often decrease the overall concrete porosity or amount of void spaces within the concrete. In addition, findings from this study showed an increase in shrinkage over the first 5 weeks, with reduced shrinkage over the subsequent 11 weeks on average. With all other factors held constant, an increase in cement will increase the amount of paste. This results in an increased rate of hydration and evaporation, leading to additional shrinkage. Shrinkage cracking in reinforced concrete not only reduces compressive strength of the concrete, but also decreases durability of the concrete by creating channels for water and chemicals to penetrate the concrete. Penetration of the concrete by various harmful chemicals can then do further damage via freeze-thaw cycles and deterioration of reinforcing steel.

It was found prior that an increased cement content often leads to an increase in cracking density (Darwin et al., 2004). Darwin also suggested setting upper bounds for compressive strength values to help negate the cracking caused by the increase in strength. Additionally, Yurdukul (2010) found that the use of cementitious materials at the lower end of a range from 500 to 600 lb/yd³ was best overall for the mix when evaluating both fresh and hardened properties of concrete. Wasserman et al. (2009) found workability decreased with reductions in cement. The decreased cement content created a harsh mix, with little lubrication for the aggregates. However, this study noted that the replacement of the reduced cement with SCMs was helpful in restoring workability. This factor can likely be attributed to the ability of SCMs, such as the fly ash used in this study, to act as additional lubrication within the mix.

The replacement of cement with SCMs like Class C fly ash have been shown to offer equal to or slightly greater long-term strengths than similar mixes made with only cement (Salem and Burdette, 2004). In a study performed by Yurdakul (2013), the introduction of fly ash at 15% and 30% was found to produce similar compressive strength to mixtures containing

only portland cement. Class C fly ash has cementitious and pozzolanic properties of, with the pozzolanic reaction contributing to greater strength gain later in life (Thomas, 2007).

Economically speaking, fly ash is a byproduct of the coal industry and is generally less expensive than cement (Aktan et al., 2003). Regarding shrinkage, Class C fly ash has shown to cause equal or less shrinkage than plain cement, due to the reduction in paste (Seo, Ohno, and Nakagawa, 2007).

2.4. Summary

Cement content plays a chief role in concrete mixtures and effects both fresh and hardened properties. Past research has shown, in most cases, cement content can be decreased while maintaining strength requirements and decreasing drying shrinkage, permeability, and cracking. Additionally, the replacement of cement by SCMs can be helpful in reducing cracking and permeability while maintaining workability. The addition of fly ash can reduce the required cement content while still meeting design standards.

3. Chapter 3: Investigation

3.1. Scope

This study was conducted to examine whether the cement content in Class S(AE) concrete can be reduced while still meeting ARDOT standards for both fresh and hardened concrete properties. This testing program was conducted in two parts. In part one, 36 mixes were batched (shown in Table 3.1). The development of the mixes and the testing matrix is further discussed in section 3.3. All mixes were held to the same standards for slump, air content, and temperature.

Table 3.1. Mix proportioning

Properties	Values
Cementitious Material Contents (lb/yd ³)	611, 564, 517
Water Cement Ratio	0.40, 0.42, 0.44, 0.50
Class C Fly Ash Replacement (%)	0, 20, 30
Number of Mixes	36
Cylinders (per mix)	12
Compressive Strength Tested (days)	1, 7, 28, 56
Shrinkage Prisms (per mix)	3
Shrinkage Strain Tested (per week/16 weeks)	1

Part two of this program developed worst case scenarios based on the results of part one. Nine additional batches were developed based on the mixtures that had the highest w/cm and lowest cementitious material. The same testing in part one was performed but additionally the rapid chloride ion permeability (RCIP) was measured along with modulus of elasticity (MOE). To better complete the project, which included similar testing for Class S and portland cement concrete pavement (PCCP) concrete, a mix from Class S, S(AE), and PCCP were each chosen for these tests. Each batch was performed once using three of coarse aggregates: sandstone, river gravel, and limestone.

3.2. Materials

The material properties of the aggregates used in the study are shown in Table 3.2. The principal coarse aggregate used was crushed limestone from Springdale, AR. The primary fine aggregate used was river sand from the Arkansas River in Van Buren, AR. The coarse and fine aggregate properties of absorption and specific gravity (ASTM C127 and ASTM C128), as well as dry rodded unit weight (ASTM C29) are listed in Table 3.2.

Table 3.2. Coarse and fine aggregate properties

Properties	Fine Aggregate	Coarse Aggregate
Maximum Size Aggregate (in.)	-	1.00
Nominal Maximum Size Aggregate (in.)	-	0.75
Dry Rodded Unit Weight (lb/ft ³)	-	100
Specific Gravity	2.63	2.61
Absorption Capacity (%)	0.48	2.10
Fineness Modulus	2.99	-

The primary coarse aggregate used was #57 crushed limestone. Sieving per ASTM C33 was performed on both types of aggregate to ensure the gradations met the ARDOT requirements as well. The fine aggregate and the coarse aggregate gradations are listed in Tables 3.3 and 3.4. The fine aggregate met the ARDOT standards though the coarse aggregate did not as the percent passing the 1/2in and #4 sieves were both beyond the specifications in two separate tests.

Table 3.3. Fine aggregate sieve analysis

Sieve	Fine Aggregate % Passing	ARDOT Specification % Passing
3/8"	100	100
# 4	99	95-100
# 8	95	70-95
# 16	83	45-85
# 30	61	20-65
# 50	17	5-30
# 100	2	0-5

Table 3.4. Coarse aggregate sieve analysis

Sieve	Coarse Aggregate % Passing	ARDOT Specification % Passing	AASHTO M43 #57
1½"	100	100	100
1"	100	60-100	95-100
¾"	75	35-75	-
½"	25	-	25-60
⅜"	12	10-30	-
#4	2	0.5	0-10
#8	1	-	0-5

Ash Grove Type I/II cement was used throughout the study, along with Class C fly ash from Boral Resources. The fly ash was produced at the White Bluff generating plant in Redfield, AR. Properties of the cement and fly ash are listed in Tables 3.5 and 3.6. Additional admixtures such as, air entertainer (AE) and HRWR were also used as needed to meet requirements for air content and slump. The AE used was Terapave AEA and the HRWR was a carboxylate-based admixture, Grace ADVA Cast 575.

Table 3.5. Fly Ash properties

Item	Description
SiO ₂	36.73%
Al ₂ O ₃	21.49
Fe ₂ O ₃	5.68%
CaO	22.70%
Na ₂ O	1.48%
K ₂ O	0.57%
MgO	4.30%
∑ Oxides	63.90%
∑ Alkalis	29.05%

Table 3.6. Cement properties

Item	Description
Chemical	
SiO ₂	20.11%
Al ₂ O ₃	5.07%
Fe ₂ O ₃	3.80%
CaO	64.15%
MgO	0.98%
SO ₃	3.23%
Loss on ignition	2.39%
Na ₂ O	0.18%
K ₂ O	0.56%
Insoluble Residue	0.40%
CO ₂	1.09%
Limestone	2.80%
CaCO ₃	88.23%
Potential compounds	
C ₃ S	55%
C ₂ S	14%
C ₃ A	7%
C ₄ AF	11%
C ₃ S + 4.75 C ₃ A	88%
Physical	
Air content of mortar (volume)	8%
Fineness	4.5 m ² /g
Autoclave expansion	-0.01%
Mortar Bar Expansion	0.00%

3.3. Procedure

3.3.1. Mix Proportions and Testing

Table 3.7 shows representative mixes for Class S(AE) concrete, as reported by ARDOT from various bridge deck projects in AR. From Table 3.7, it is clear that concrete producers typically used the minimum amount of cementitious material, and generally the max w/cm. Additionally, 5 of the 8 cases below included a water reducer or retarder, and nearly all added varying amounts of fly ash ranging from 18 to 25%. The coarse aggregate content used in this

study was 1800 lb/yd³, which was chosen based on consultation with ARDOT and was quite similar to the range of coarse aggregate contents shown in Table 3.7.

Table 3.7. Class S(AE) Contractor Mixes

Material or Property	Concrete Producers							
	ACC	CMTS	CMTS	MTA	RCC	MTA	Tune	Near
Cement (lb/yd ³)	611	520	489	519	489	519	516	489
Fly ash (lb/yd ³)	0	91	122	91	122	91	95	122
Rock (lb/yd ³)	1760	1740	1745	1687	1731	1629	1720	1720
WR/Retarder	D17	D17	Yes	Recover	-	-	D17	-
w/cm	0.44	0.40	0.42	0.44	0.44	0.44	0.44	0.42

As previously described, testing in this study largely involved varying the cementitious content, w/cm, and fly ash content. The different mix proportions that followed from these variations can be seen in Table 3.8. All mixes were designed to meet ARDOT minimum standards of 28-day compressive strength, air content, and slump. For cementitious material, the ARDOT minimum is 611 lb/yd³. To check the reduction not only of cement but also of total cementitious material, this was tested at the current minimum standard of 611, as well as lower values of 564 and 517 lb/yd³, to further evaluate the effect of further reductions in cementitious material content. Regarding w/cm, the current maximum w/cm that ARDOT allows for Class S(AE) is 0.44. Thus, testing was performed at the maximum value, as well as at two lower w/cm. This was done to compare reductions in shrinkage due to lessened water contents. The w/cm was also tested at 0.50, as a worst case scenario for field concrete. Finally, the current maximum ARDOT standard for fly ash replacement is 20%. For tests in this study, 0, 20 and 30% fly ash replacement values were used. The mixes batched with 0% fly ash were treated as the control while the 20 and then 30% mixes were evaluated to determine shrinkage effects when reducing cement through replacement with fly ash.

Table 3.8. Class S(AE) Batching Plan

Cementitious Material content (lb/yd ³)	w/cm			
	0.40	0.42	0.44	0.50
	Mixtures ID			
611(100% portland cement)	1-A	1-D	1-G	1-J
611(20% Class C fly ash)	1-B	1-E	1-H	1-K
611(30% Class C fly ash)	1-C	1-F	1-I	1-L
564(100% portland cement)	2-A	2-D	2-G	2-J
564(20% Class C fly ash)	2-B	2-E	2-H	2-K
564(30% Class C fly ash)	2-C	2-F	2-I	2-L
517(100% portland cement)	3-A	3-D	3-G	3-J
517(20% Class C fly ash)	3-B	3-E	3-H	3-K
517(30% Class C fly ash)	3-C	3-F	3-I	3-L

3.3.2. Batching

The batching procedure for each mix occurred as follows. One day prior to batching, coarse and fine aggregates were obtained from stockpiles at the Engineering Research Center (ENRC) at the University of Arkansas (UA). A small representative sample of each was placed in an oven for 24 hours to measure moisture content per ASTM C566. Then larger samples of each aggregate type, approximately 5 gallons, were collected and used for batching the following day. Each bucket was sealed upon collection. The following day the samples were removed from the oven and moisture contents measured.

Once the moisture contents of the aggregates were determined, the quantities of all the materials were measured and the concrete was mixed in accordance with ASTM C192. The coarse aggregate and approximately half of the mixing water were first added to the mixer. The mixer was then started, sand and more water added, and finally the cementitious materials along with the remaining water containing the admixtures were added. Upon addition of all the

materials to the mixer, the mixer was started and the materials were mixed for three minutes, then allowed to rest for three minutes (with the mixer off), and then mixed for another two minutes. For each of the initial 36 mixes the batch size was 1.8 ft³, which was sufficient concrete to measure slump, unit weight, and air tests. If the mixtures passed the ARDOT requirements for slump and air content, 12 cylinders and 3 shrinkage prisms were cast according to the ASTM C192. For the 9 additional mixes, an extra 14 cylinders were cast to perform RCIP (ASTM C1202) and MOE (ASTM C469) at 28 and 56 days. The batch size for these mixes was 2.6 ft³.

3.3.3. Curing

All specimens were cured in similar manner per ASTM C192. After batching, all cylinders and prisms were placed into the environmental chamber at the ENRC, which is held at approximately 73.5 °F (±3.5 °F) with a relative humidity of 50%. Cylinders and prisms were both demolded at approximately 24 hours, at which point the cylinders were cured in a lime saturated water bath as shown in Figure 3.2. The prisms were placed onto shelves atop small pieces of cylindrical plastic which allowed them to shrink without restraint as is visible in Figure 3.1.



Figure 3.1. Drying Shrinkage specimen



Figure 3.2. Compressive Strength specimen

3.3.4. Fresh and Hardened Property Tests

The fresh concrete tests were performed to ensure the mix met the standard specifications for slump (ASTM C143), temperature (ASTM C1064), unit weight and air content (ASTM C138), so further testing could be performed. Compressive strength was measured primarily to determine if concrete mix met the requirements for 28-day strength. 4 inch by 8 inch cylinders were cast, with three cylinders tested at 1, 7, 28, and 56 days. An

example of this testing can be seen in Figure 3.3. Cylinders were ground plane on both ends using an end grinder prior to testing.



Figure 3.3. Compressive Strength Testing

After casting and 24 hours of curing, the specimens were demolded and the hardened properties were measured; compressive strength (ASTM C39), MOE (ASTM C469), RCIP (ASTM C1202), and drying shrinkage (ASTM C157). Drying shrinkage was tested to evaluate how mix proportioning affected the dimensional stability of the mix. In theory, the shrinkage should decrease as cement content was reduced. From each mix, three 4-in by 4-in by 11.25-in prisms were crafted with dimensions of. The initial length of each prism was measured upon demolding and then changes were measured once per week for 16 weeks. The shrinkage testing apparatus can be seen in Figure 3.4.



Figure 3.4. Shrinkage Prism Testing

Next, MOE was tested in the hardened concrete, as shown in Figure 3.5. Like RCIP, MOE was only tested for the additional 9 mixtures with higher w/c. For each test, three cylinders were tested to determine compressive strength, and then three additional cylinders were tested for MOE. The results of these 9 additional mixes and their MOEs were analyzed and compared to determine the effect of aggregate type on MOE. These values were compared with the ACI/AASHTO prediction equations.



Figure 3.5. Modulus of Elasticity testing

RCIP testing followed the procedure outlined in ASTM C1202. An example of the RCIP test setup can be seen in Figure 3.6. Prior to testing, the specimens went through the preparation outlined in ASTM 1202. The test involves running a 60V current through the specimens with an NaCl and BaOH solution on either side to measure the concrete's permeability to chloride ions. This data gives a numerical measure of how well the concrete mixture can protect the steel reinforcement inside it from chemical attack. The ability of the different mixes to resist the current can be seen in Figure 4.17.



Figure 3.6. Rapid Chloride Ion Permeability testing

4. Chapter 4: Results

4.1. Goal

This study was completed with the overarching goal of providing evidence that there could be reduction to the ARDOT minimum cement content while still meeting the standard specifications for other concrete properties. Testing of this hypothesis involved varying cementitious material, w/cm, and fly ash percentage. Below are the results from the testing of the different mix designs, and how the fresh and hardened concrete properties changed in accordance.

4.2. Fresh Properties

The fresh concrete properties tested in this study were slump, unit weight, and air content. The results of these tests are shown in Tables 4.1 and 4.2 below. These tables also show mixtures containing HRWR. It should be noted that admixtures were added, when needed, to increase workability and to meet ARDOT standards. In regards to air content, there were no direct correlations noted in this study between air content and slump or air content and cementitious material contents. When looking at unit weight, it was seen that as the w/cm decreased from 0.50 to 0.40, unit weight generally increased by approximately 2.5 lb/yd³. This was likely caused by the reduction of water because, with all other factors held constant, reducing water in the mix will require a slight increase in the amount of fine aggregate, which is heavier than the water. Besides this however, there were no direct correlations between unit weight and cement content or fly ash percentage.

In the case of slump, the w/cm and the overall amount and type of cementitious material are both vital. Whenever the w/cm increased, it often resulted in an increase in the slump of the mix. When dealing with cementitious material quantities, it was noted that reducing the overall

quantity of cementitious material made the mix become less workable. This is due primarily to the overall decrease in water quantity as the quantity of cementitious materials decreased. This factor is key when recommending a lower minimum value to ARDOT, especially since some of the lower w/cm mixtures with 517 lb/yd³ of cementitious material had lower slumps than those of the other mixtures in this study and were more difficult to work. Though all mixes met the required strength at 28 days, workability is still a major factor in mixture design to ensure the concrete can be placed and consolidated efficiently. In addition to overall content, the type of cementitious material is also important. It was found that when using fly ash contents of 20 or 30%, the workability would increase compared to mixtures containing cement only. This is due to the increased lubrication effect of fly ash, as its particles are smaller and act like “ball bearings” in the mixture. This isn’t obvious in the data from every mix due the impact of air entertainer, but as an example, the slump values for the 20 and 30% fly ash mixes for 0.5 w/cm, were relatively high with no addition the HRWR.

Table 4.1. Cement only Slump and Unit weight mixes

Cementitious Content (lb/yd ³)	% Class C Fly Ash	w/cm	Slump (in.)	Unit weight (lb/yd ³)	Air Content (%)	HRWR (mL)	AEA (mL)
611	0	0.40	1.25*	144.5	5.5	20	10
		0.42	2.25*	143.3	6.1	20	9
		0.44	1.25	144.6	4.8	0	10
		0.50	6.50**	138.1	6.9	0	2
564	0	0.40	2.00*	141.3	8.0	35	10
		0.42	2.00*	141.4	7.0	10	6.5
		0.44	1.00	143.8	5.2	0	10
		0.50	5.25**	141.4	6.0	0	2
517	0	0.40	1.00*	145.4	5.2	20	4
		0.42	4.00*	142.6	7.1	20	4
		0.44	1.00*	142.2	7.2	15	7
		0.50	1.75	145.2	4.4	0	1.5

*Slump was achieved with HRWR

**Slump could not be reduced due to high water content

Table 4.2. Fly ash Slump and Unit weight mixes

Cementitious Content (lb/yd ³)	% Class C Fly Ash	w/cm	Slump (in.)	Unit weight (lb/yd ³)	Air Content (%)	HRWR (mL)	AEA (mL)
611	20	0.40	2.00*	139.8	7.5	15	20
		0.42	2.00*	142.4	6.1	10	15
		0.44	3.75	138.7	5.9	0	24
		0.50	8.00**	141.6	4.2	0	9
	30	0.40	2.00*	140.1	7.4	15	25
		0.42	1.75	145.4	4.0	0	18
		0.44	4.25	140.6	6.0	0	27
		0.50	7.75**	137.7	7.0	0	15
564	20	0.40	1.00*	143.0	6.8	10	13.5
		0.42	2.25*	141.9	7.2	10	11
		0.44	1.75	142.4	5.6	0	22
		0.50	6.50**	141.7	5.4	0	9
	30	0.40	1.25*	144.1	5.6	10	16
		0.42	1.50*	143.5	6.5	29.6	13.5
		0.44	2.50	144.3	4.1	0	25
		0.50	7.50**	142.0	4.6	0	13
517	20	0.40	1.25*	140.7	8.0	25	8.5
		0.42	1.00*	144.0	6.0	35	8
		0.44	1.50*	142.0	6.6	10	22
		0.50	2.50	144.2	4.7	0	8.5
	30	0.40	2.00*	140.6	8.0	20	8
		0.42	1.00*	143.5	7.0	30	11
		0.44	2.75*	139.4	7.8	15	17
		0.50	6.75**	141.2	7.0	0	13

*Slump was achieved with HRWR

**Slump could not be reduced due to high water content

Overall, reducing the cementitious material content had little effect on the air content or unit weight. The replacement of cement with fly ash also had little effect in these areas, though it increased slump. Values for air were within the ARDOT standards (shown in Table 1.1). Slump was affected by the reduction in cementitious materials, as the lower cementitious content mixes

were often more difficult to work with. That said, several mixes ranging from the upper limit of 611 to the lower limit of 517 lb/yd³ required the addition of HRWR to meet the slump standards of 1 to 4 inches, so this correlation between slump and reduced cementitious values is likely not quite as exact as it may seem.

Using these tables, it is recommended that ARDOT consider using cementitious material values of 564 and 517 lb/yd³ on a more regular basis, as batches that utilize these amounts can still meet the requirements for slump, air, and unit weight without requiring substantially different amounts of admixtures or effort from that of currently approved mixes. It may also be worth considering increasing the limits of fly ash contents to 30%, as these would have a positive impact on slump.

4.3. Hardened Properties

4.3.1. Compressive Strength

For Class S(AE) concrete, ARDOT requires a minimum 28-day compressive strength of 4000 psi, which was achieved by all mixes. Compressive strengths were measured using three cylinders tested at 1, 7, 28, and 56 days. The strength values referenced in this report represent the average of 3 specimens.

4.3.1.1. Cement Content and Strength

As specified prior, an increase in cement content is often related to an increase in compressive strength. However, in this study, an increase of cementitious material from 517 to 564 to 611 lb/yd³ produced near equivalent compressive strength values, as shown in Figure 4.2. Roughly 78% of the mixtures reached the specified compressive strength of 4000 psi within 7 days. The remainder of the mixtures achieved 4000 psi by 28 days.” Additionally, it is important to note that the weakest mixture (0.50 w/cm, 517 lb/yd³, 30% FA) met the required strength by 28 days. Based on this data, even if only 517 lb.yd³ of cementitious materials are used, and the

w/cm exceeds the 0.44 minimum set by ARDOT, the mixture was still capable of exceeding the minimum 28-day strength of 4000 psi. Additionally, decreases in w/cm and increases in unit weight were found to increase in compressive strength. Higher slump mixtures had lower compressive strengths as well. Higher air content mixtures generally had lower strengths, which is likely a partial cause of some of the compressive strength values in the graphs below.

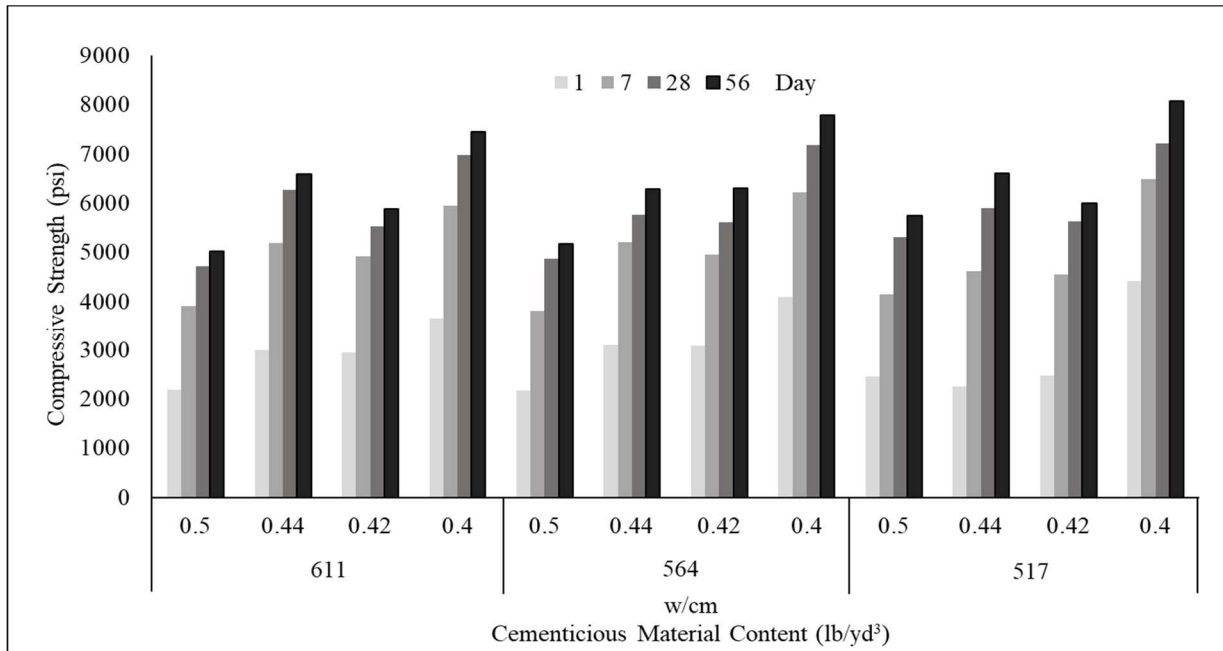


Figure 4.1. Cement only compressive strength

4.3.1.2. Fly Ash Content and Compressive Strength

Fly ash plays a role in the ultimate compressive strength, but for this study it is more valuable to look at how it effects strength gain. Due to the pozzolanic reaction, many fly ash mixes gain strength more slowly than non-fly ash mixes and have reduced early age strength development, but gain slightly greater ultimate strength due to the continued reactions (Thomas, 2007) Thus, when comparing it to a cement only mix, the comparable fly ash mix often had lower 1 and 7 day strengths , as shown in Figures 4.2, 4.3, and 4.4. This is especially true for lower cementitious contents, such as the 517 lb/yd³ mix, as these mixes already have

reduced cement and portions of the mixes are replaced with a less reactive material.

Conversely, fly ash replacement often resulted in slightly greater strength than mixes with little to no fly ash at similar water cement ratios. Overall, the data provided little reason to be concerned with the strength mixtures with w/cm up to 0.5 or high fly ash contents, as even the mixture with the highest w/cm and lowest cementitious content achieved 4000 psi by 28 days with over 3000 psi at 7 days and 1000 psi at 1 day. Again, this data can be seen in Figures 4.2, 4.3, and 4.4.

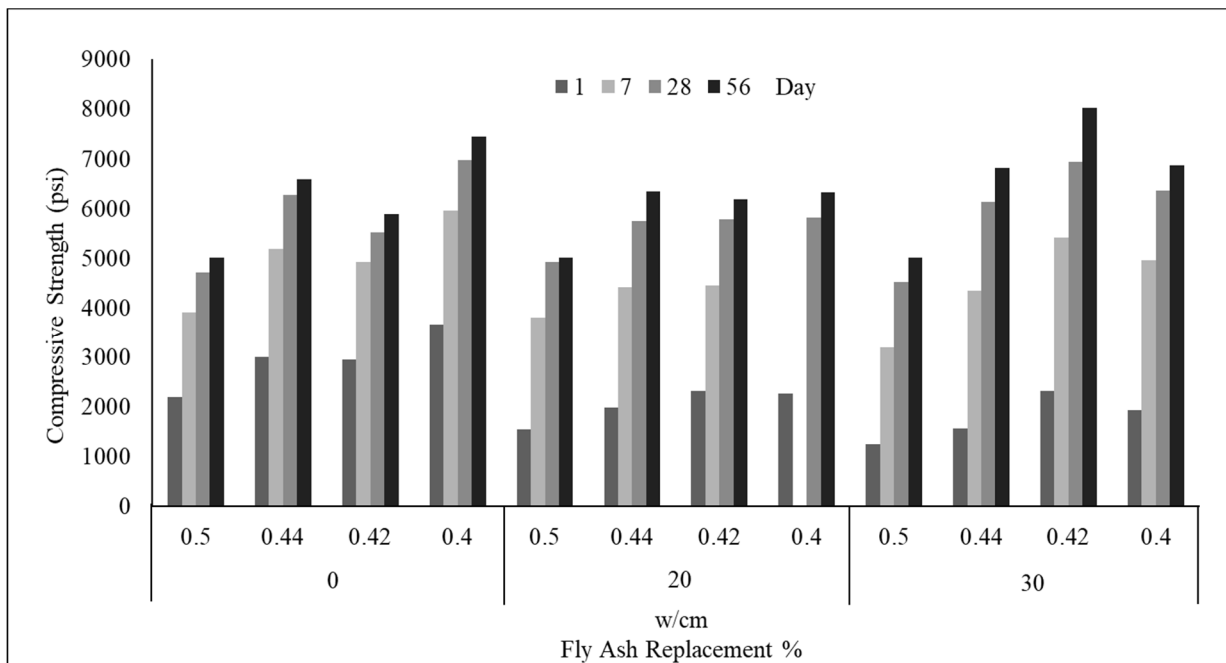


Figure 4.2. Mixes with 611 lb/yd³ compressive strengths

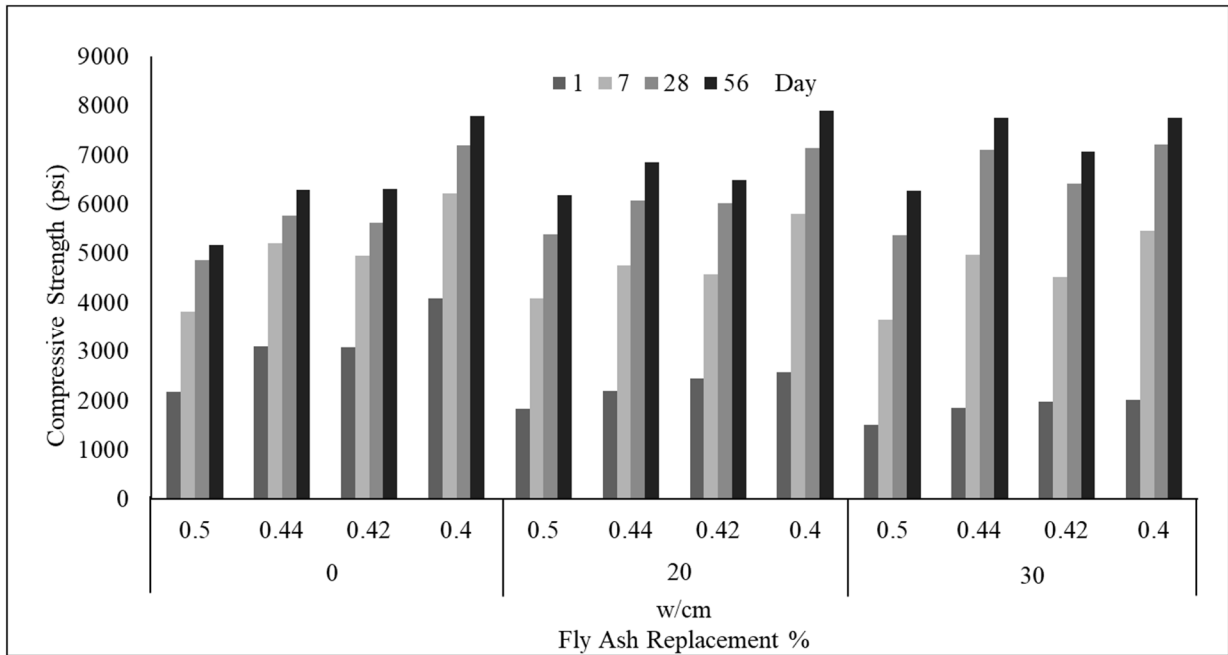


Figure 4.3. Mixes with 564 lb/yd³ compressive strengths

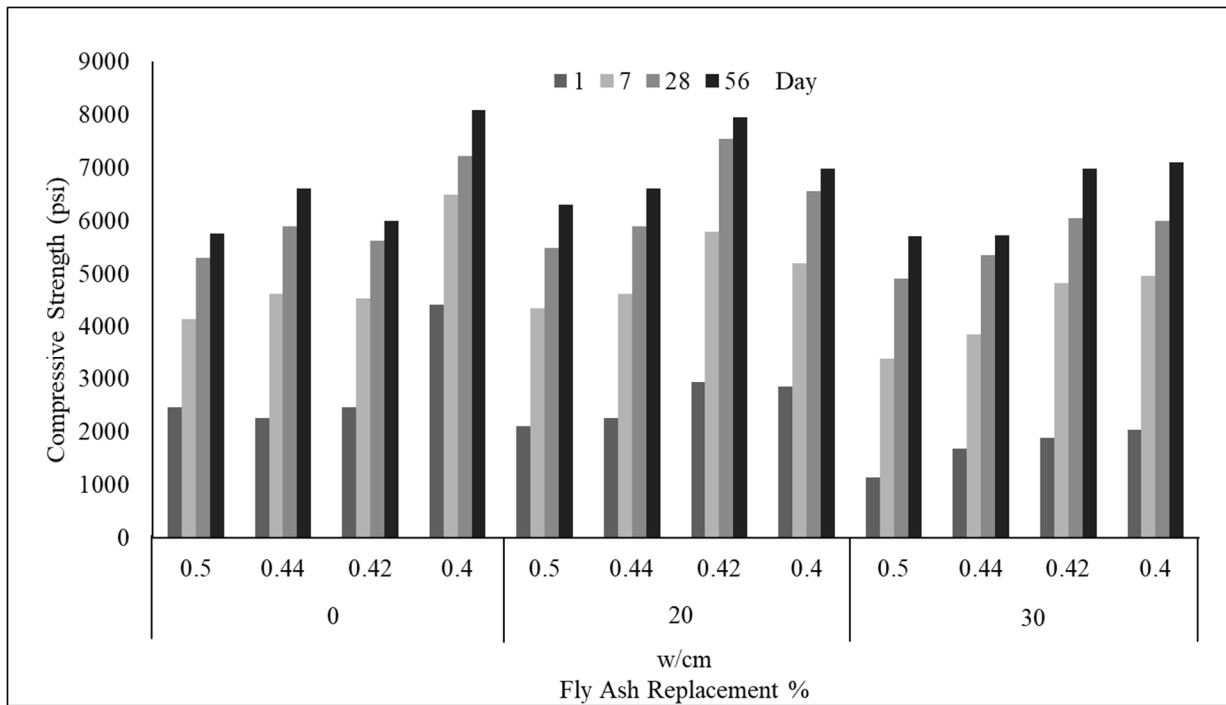


Figure 4.4. Mixes with 517 lb/yd³ compressive strengths

4.3.1.3. Compressive Strength Results

Based on the compressive strength data, the ARDOT standard of 611 lb/yd³ of cementitious material could be reduced substantially, as all the mixes met the minimum compressive strength of 4000 psi by 28 days. This includes the mixes where the fly ash contents were 20 and 30%. Though the mixes with higher fly ash contents did show lower early strength, by 28 days they developed sufficient strength. Considering this, the ARDOT maximum of 20% fly ash replacement could be increased to 30% without a detrimental effect on 28-day compressive strength. Additionally, it is important to note that even in the case of a w/cm of 0.50, well above the ARDOT max of 0.44, all mixes still met the requirements. In the end, strength data shows that in many cases current standards result in overdesign, and reduction of cement is both plausible and helpful monetarily and environmentally.

4.3.2. **Drying Shrinkage**

Three shrinkage prisms were cast from each batch to test drying shrinkage in accordance with ASTM C157. These prisms were measured once per week for 16 weeks and the values noted for each week are the average of the measurements for the 3 prisms. These findings are another major aspect to this study to supplement the strength results. The goal with shrinkage was to look for equal to or lesser drying shrinkage as cementitious materials was reduced or replaced, ultimately resulting in decreased cracking.

4.3.2.1. Cement Content and Drying Shrinkage

Figures 4.5, 4.6, and 4.7 represent findings for the cement only mixtures for all w/cm tested. In both mixtures with and without fly ash, findings were generally similar. It was noted that reducing cementitious material from 611 to 517 lb/yd³ decreased shrinkage by 100×10^{-6} microstrains. As the w/cm decreased from the max of 0.50 to the minimum of 0.40, there was an approximate decrease of 50×10^{-6} microstrains. The similarity in strain is likely attributed to the high amount of coarse aggregate, 1800 lb/yd³, in each mix. By the end of 16 weeks, many of the

measurements for these mixes were near 500×10^{-6} microstrain. Overlapping strain values for different w/cm within mixes can be seen in Figures 4.5 through 4.13. It seems reasonable that mixes with a higher w/cm would develop greater strains throughout the testing as the increased amounts of water within these mixes lead to additional evaporation and shrinkage. However, minor deviations due to time of batching and changes in humidity caused several of the shrinkage values to rise and fall below those of subsequent w/cm tested. The data showed that the more significant factor in controlling strain was cementitious content, as this caused the greater differences.

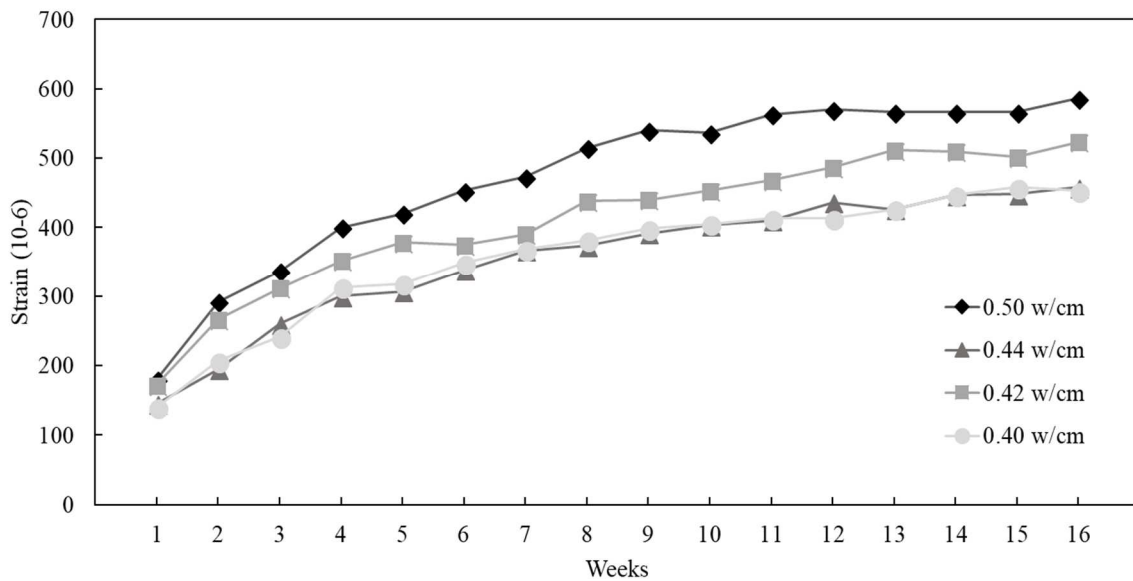


Figure 4.5. Concrete mixture with 611 lb/yd³ and 0% fly ash

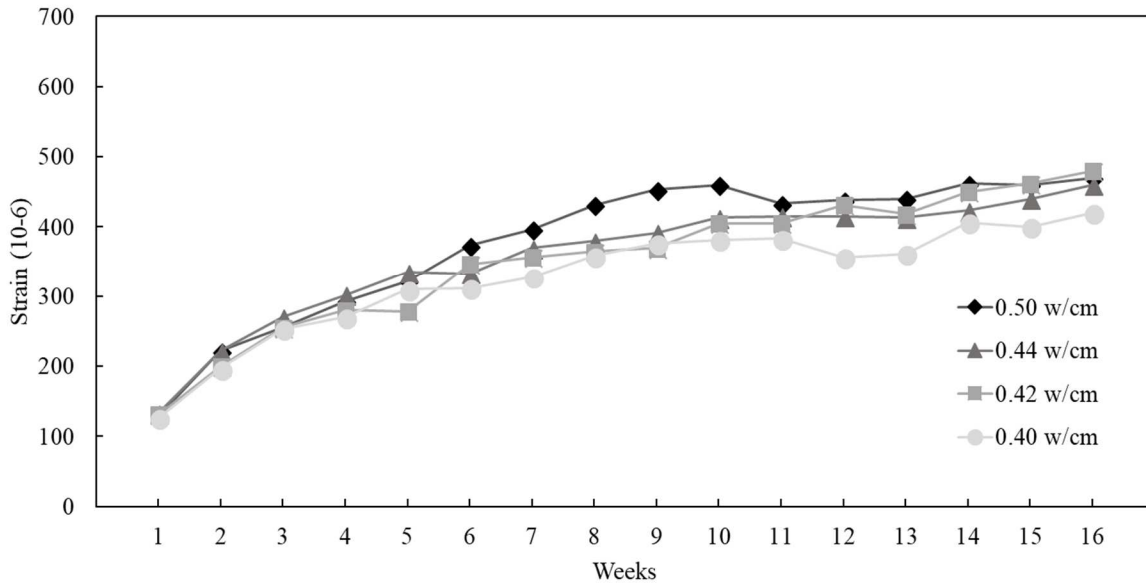


Figure 4.6. Concrete mixture with 564 lb/yd3 and 0% fly ash

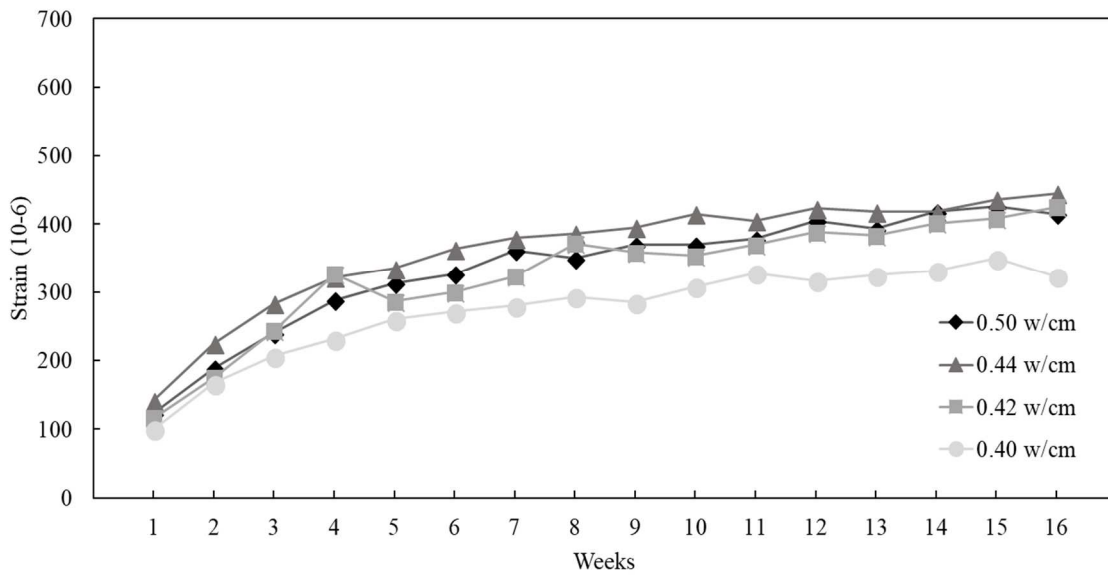


Figure 4.7. Concrete mixture with 517 lb/yd3 and 0% fly ash

4.3.2.2. Fly Ash and Drying Shrinkage

The contribution of fly ash to drying shrinkage was minimal. Overall, fly ash affected the shrinkage in a very similar manner as it affected strength. Mixes with 20 or 30% fly ash showed approximately equivalent strain at 16 weeks. The difference in strain between the 20

and 30% replacement amounts was minimal and no direct approximation of value can be denoted for the difference, as data values often overlapped for similar mixes. Similar trends for drops in microstrain as cementitious material and w/cm decreased were noted and still applied to fly ash mixes. All of this can be seen in Figures 4.8 through 4.13. It is important to note that little to no change in shrinkage occurred between these same mixes of similar w/cm. Likely, this can be all be related back to one of the main culprits for loss in strength, the ITZ. Since the ITZ is the weak link in concrete, it is valuable to think about how the addition of fly ash can affect it. In most cases, adding fly ash has shown to decrease the heat of hydration. This lower heat not only helps better protect the ITZ from early age thermal cracking, but it can also help reduce potential for evaporation and drying shrinkage. These lower temperatures often help reduce microcracks which would only propagate further during drying and cause more cracking (Aktan et al., 2003).

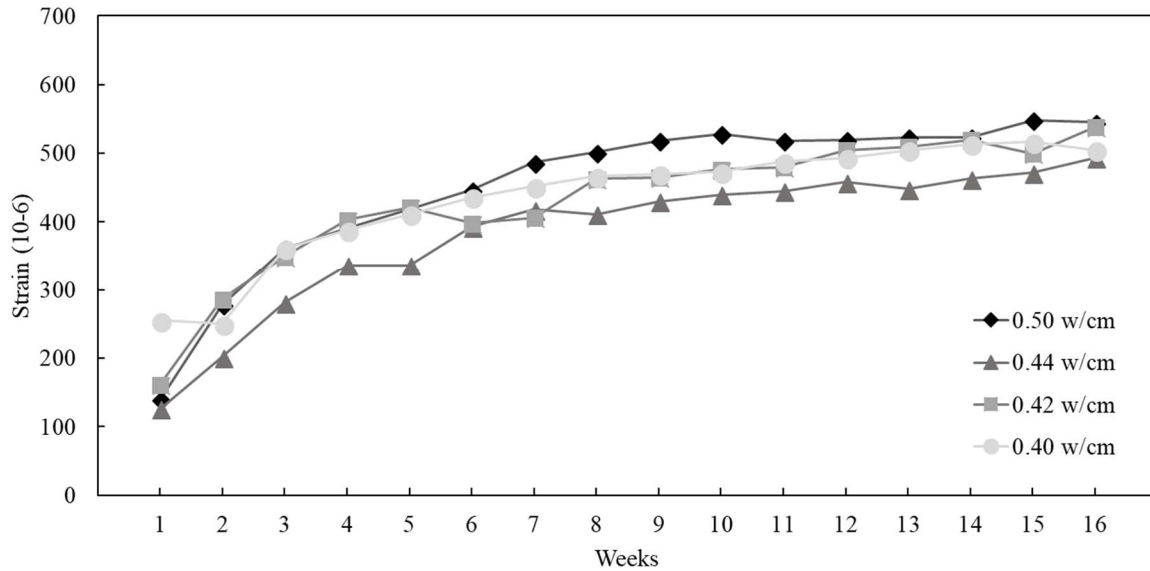


Figure 4.8. Concrete mixture with 611 lb/yd³ and 20% fly ash

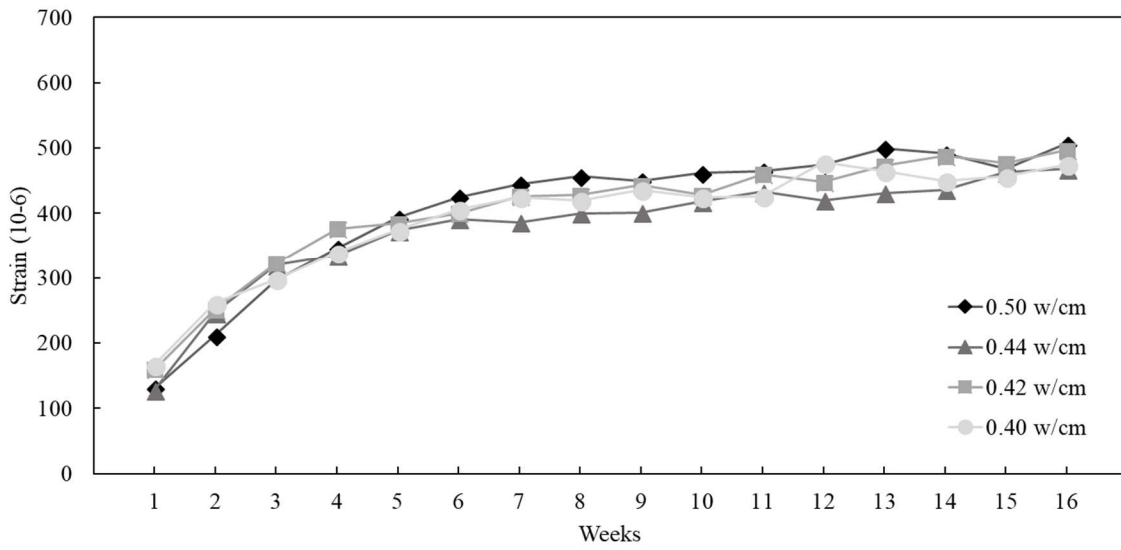


Figure 4.9. Concrete mixture with 564 lb/yd3 and 20% fly ash

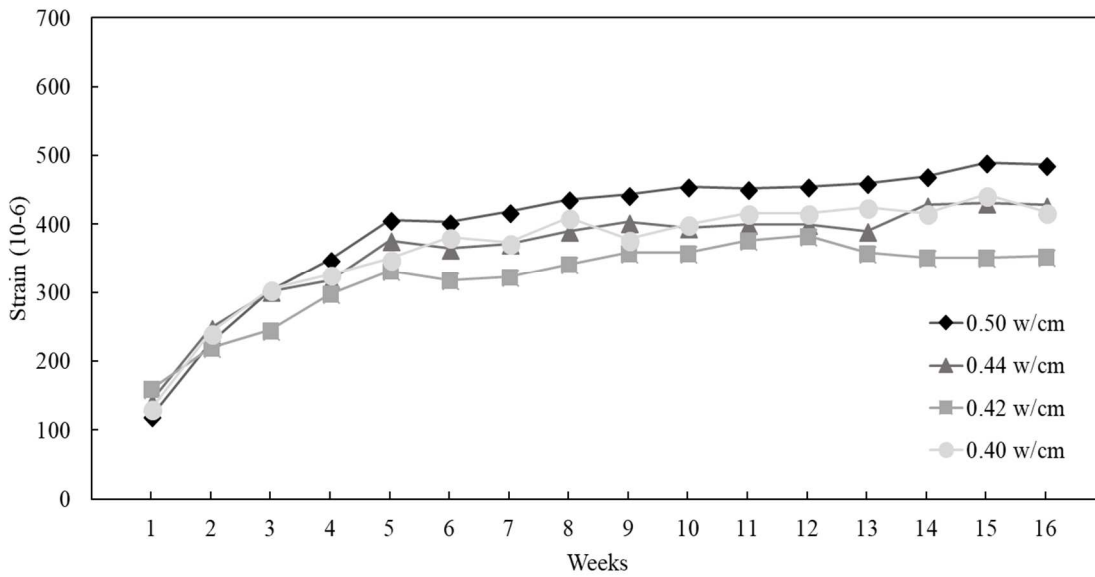


Figure 4.10. Concrete mixture with 517 lb/yd3 and 20% fly ash

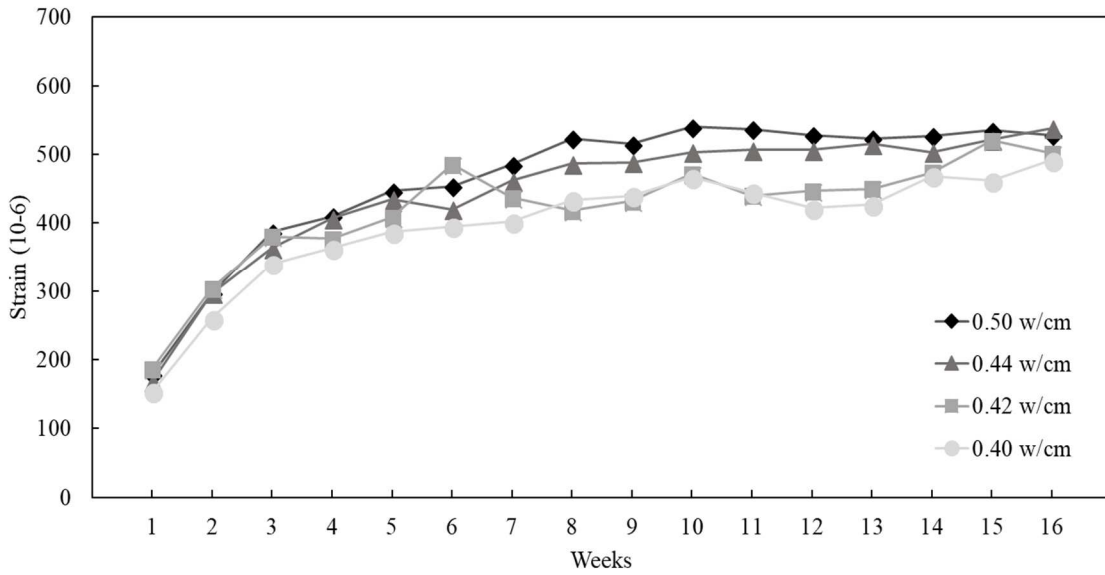


Figure 4.11. Concrete mixture with 611 lb/yd3 and 30% fly ash

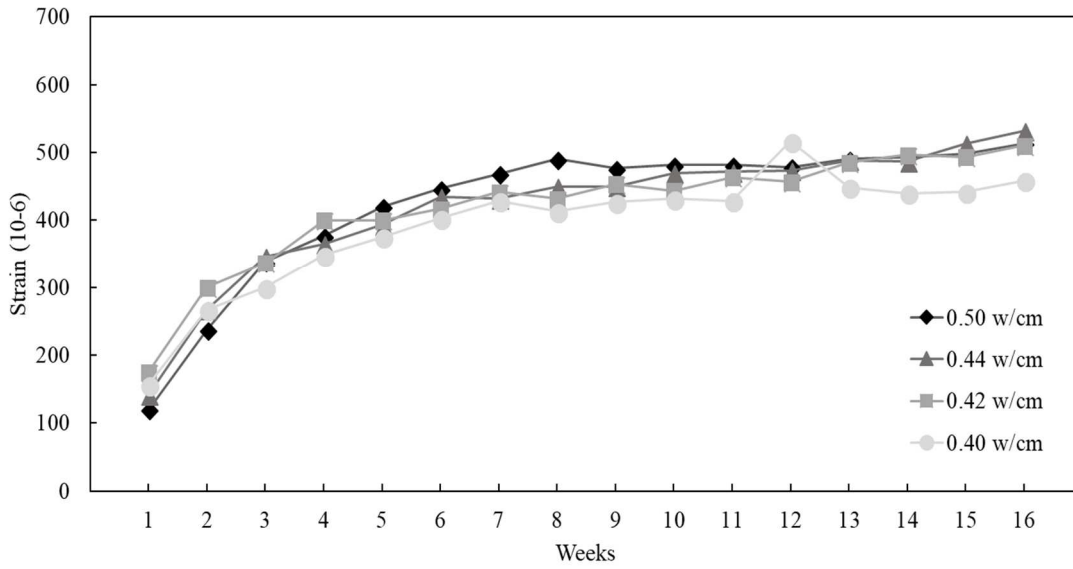


Figure 4.12. Concrete mixture with 564 lb/yd3 and 30% fly ash

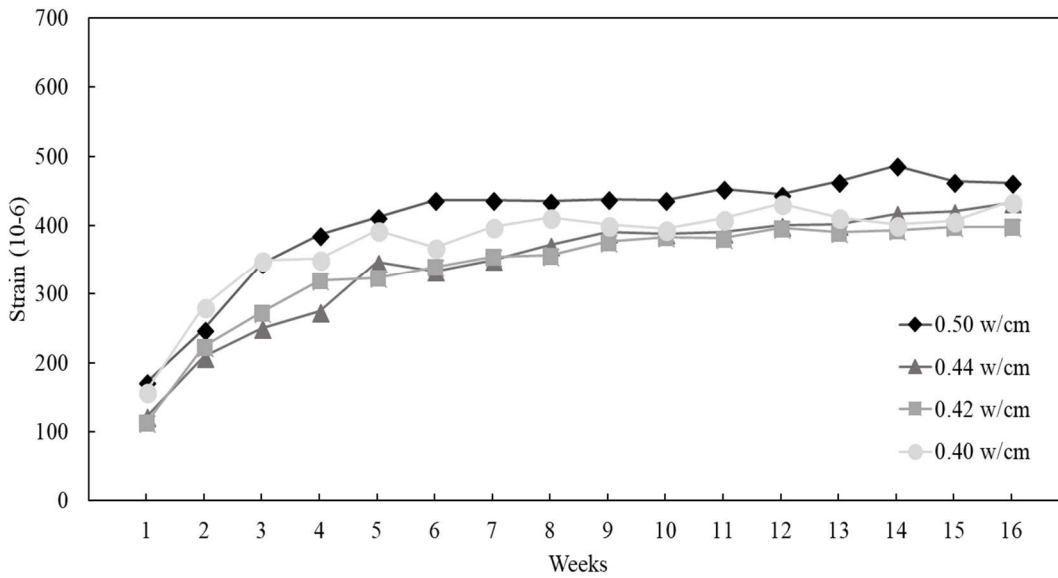


Figure 4.13. Concrete mixture with 517 lb/yd³ and 30% fly ash

4.3.2.3. Drying Shrinkage Results

From the shrinkage data shown in the previous figures, the reduction in cement content reduces the strain associated with drying shrinkage. In addition, it appears the addition of fly ash is of little to no consequence in regard to drying shrinkage, as it causes near equivalent strain to those mixes with no fly ash. In all 36 cases, no mix exceeded a drying shrinkage of 600×10^{-6} microstrain, meaning max shrinkage values were not far above the initial values for cracking in restrained conditions. Additionally, it was noted that as w/cm decreased the strain showed a slight drop on average. Thus, overall it was found that reduction of cement and replacement of fly ash reduced the drying shrinkage of some mixtures and little effect on others. This was most likely due to the constant coarse aggregate content of 1800 lb/yd³ that was used in all the mixtures.

4.3.3. Additional Testing

Both MOE and RCIP testing were performed for the last 9 high w/cm low cementitious material mixes. These mixes represented not just Class S(AE) concrete, but

also Class S and PCCP, to better fulfill the entirety of the study which focused on multiple ARDOT approved concrete types. The goal was to determine the differences in MOE, RCIP, compressive strength, and shrinkage between the mixtures tested for these three classes. The 3 mixes tested used no fly ash and were: Class S(AE) with 517 lb/yd³ of cement at a w/cm of 0.50, Class S with 517 lb/yd³ of cement at a w/cm of 0.55, and Class PCCP with 470 lb/yd³ of cement at a w/cm of 0.50. Each batch was performed once with sandstone, river gravel, and limestone as the coarse aggregate. Mixes were tested at 28 and 56 days.

The goal of the MOE testing performed in this study was to determine if the standard prediction equations for MOE given below could be used to predict MOE based on concrete compressive strength. To test this, the mixtures that had the lowest 28-day compressive strength were used. Additionally, since MOE effectively provides stiffness and stiffness is affected by coarse aggregate content, three different coarse aggregates from around the state were chosen after consultation with ARDOT research personnel. For the MOE data, Equation 1 and 2 below give the standard MOE equations so they can be plotted and compared to the data in Figure 4.14. In the case of equation 2 below, it was plotted with an upper bound using the highest density of limestone in the equation, and lower bound using the lowest density of the river gravel.

$$E_c = 57000\sqrt{f'_c} \quad \text{Eq. 1}$$

$$E_c = 33w_c^{1.5}\sqrt{f'_c} \quad \text{Eq. 2}$$

There is little change in MOE values from 28 to 56 days. Though it had the lowest specific gravity, the river gravel provided the highest MOE values. The river gravel was followed by the limestone and then the sandstone, both at 28 and 56 days. Additionally, it appears the river gravel and limestone both behave better than the predictions from the ACI

and AASHTO equations. However, the sandstone failed to meet expectations at either 28 or 56 days. From these results, it was determined that the standard equations above could be used to predict MOE for river gravel and limestone mixtures containing a high w/cm and low cement content, however they would overpredict for sandstone

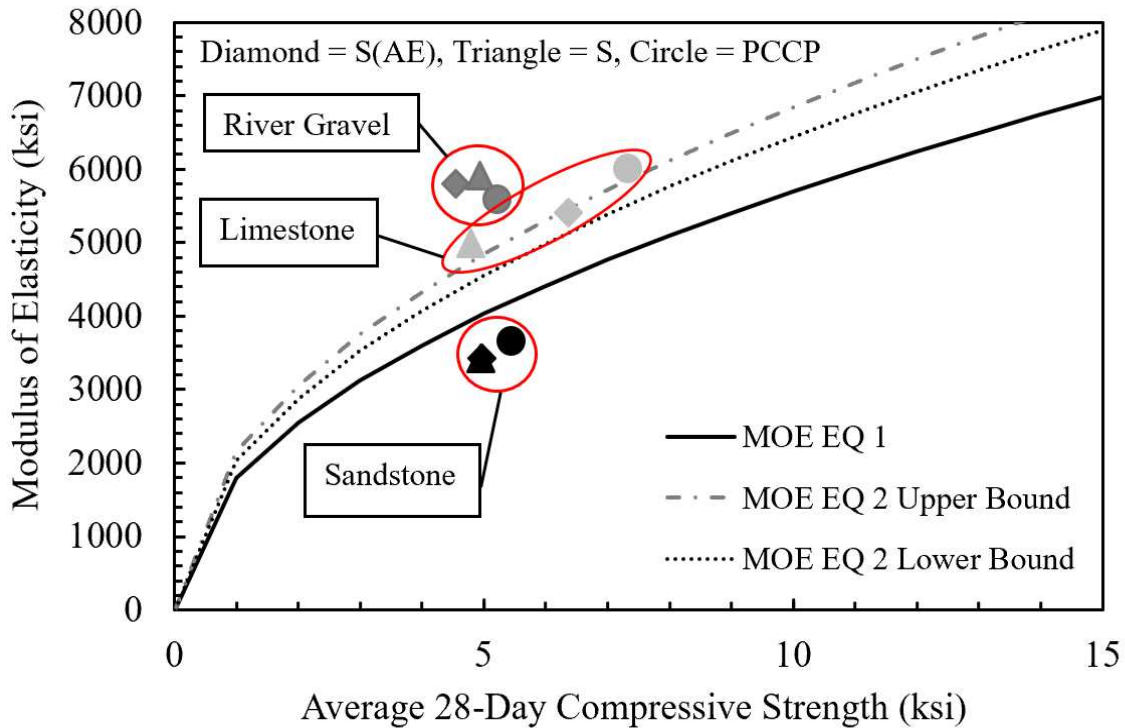


Figure 4.14. Measured Modulus of Elasticity versus prediction equations

Table 4.3. Modulus of elasticity data

Class	Sandstone	River Gravel	Limestone
	28 Day – Average Modulus of Elasticity (ksi)		
S(AE)	3430	5800	5410
S	3430	5920	4990
PCCP	3670	5590	6010
Class	Sandstone	River Gravel	Limestone
	56 Day – Average Modulus of Elasticity (ksi)		
S(AE)	3520	6070	5552
S	3490	5870	5079
PCCP	3820	6260	6147

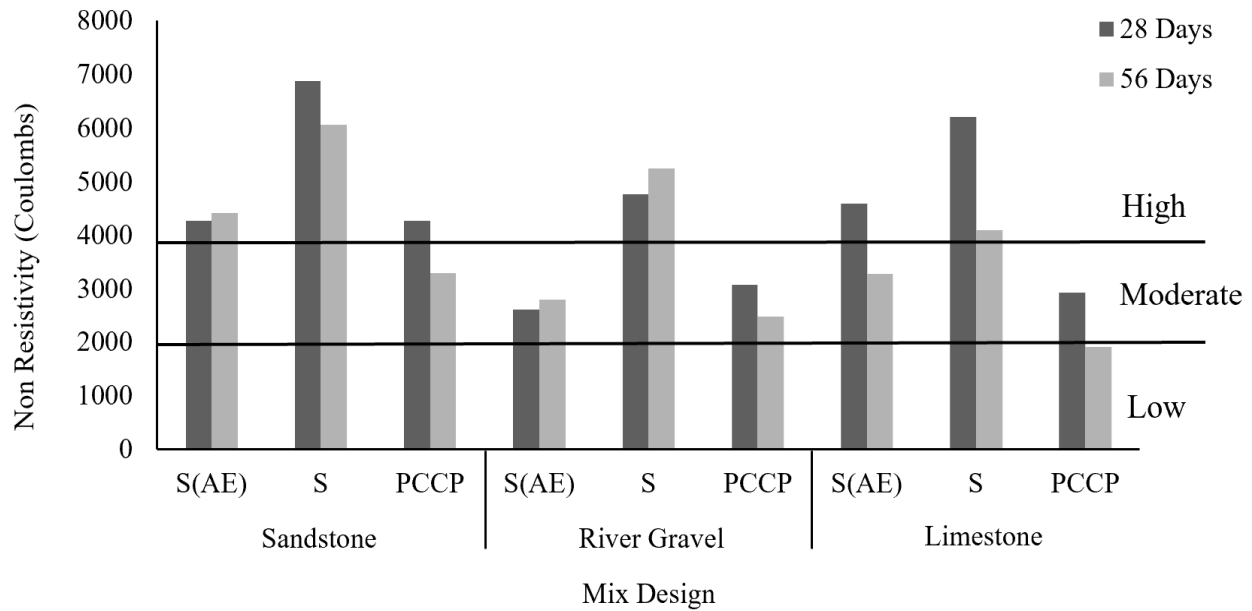


Figure 4.15. Measured Non Resistivity compared to standards

Figure 4.15 represents the findings for RCIP and shows the standards for chloride ion permeability (low, moderate, and high) as defined by ASTM C1202. The data shown in this section represents the average of the tested specimens. However, due to imperfections in the systems and specimens, not all four of the specimens could be fully tested each time. Thus, some of the data is averaged for fewer specimens. It should be noted in Figure 4.15 that higher numbers of coulombs passing through the specimen equate to less resistive and theoretically more permeable concrete. This was best seen in the case of the Class S mix which had the highest w/cm of 0.55 and produced higher permeability values in every aggregate case. While changes were small between the values of the different mixes as the aggregate was changed, it seemed evident that the most resistant aggregate was the river gravel, followed by the limestone and then sandstone. These results point to a difference in the classification of the three types of concrete tested here, with class S(AE) and PCCP concrete having moderate permeability, and class S concrete having high permeability likely due to its increased water content.

Additionally, based on these results it is evident that the type of coarse aggregate used and a

lower cement content can both decrease the permeability of the concrete, though the w/cm has the greatest ability to cause change.

4.4. Potential Savings

Below is a cost evaluation of some common Class S(AE) mixes batched at minimum and lower cementitious material contents, with an increased fly ash replacement percentage. The average material cost received from ARDOT in June of 2018 are listed in Table 4.4. From 2013 to 2015, 76,469 yd³ of Class S(AE) bridge deck concrete was used by ARDOT for state projects. Based on this quantity and the average cost values, potential savings were calculated and compared for traditional and non-traditional mixes.

Table 4.4. Material cost estimates

Material	Price (\$)*
Cement	280
Fly Ash	35
Rock	18
Sand	17

* Prices listed above are per 2000 lbs

For a w/cm of 0.44, the least expensive mix that meets ARDOT standards contained 611 lb/yd³ of cementitious material with a 20% fly ash content. Using the cost estimates in Table 4.4 this mix costs approximately \$96/yd³, though it only includes cost of materials and not transportation or labor. However, using the same w/cm while reducing the cementitious content to 517 lb/yd³ and increasing the fly ash content to 30%, the mix cost decreases to approximately \$81/yd³, while still meeting all the ARDOT requirements for fresh and hardened concrete. This amounts to a difference of \$15/yd³ and based on the total quantity of Class S(AE) concrete cast from 2013 through 2015, the cost savings could have been over 1 million dollars, as shown in Table 4.5. As can be seen from this table, substantial economic savings can be attained through the reduction of cement and increase of fly ash within mixes.

Table 4.5. Approximate potential savings

Year	Quantity (yd ³)	Cost (\$)	
		611 lb/yd ³ - 20% FA	517 lb/yd ³ - 30% FA
2013	31129	2,988,384	2,521,449
2014	36088	3,464,448	2,923,128
2015	9252	888192	749,412
Sum	147577	7,341,024	6,193,989
Σ Savings		\$1,147,035	

5. Chapter 5: Conclusion

The goal of this study was to show that ARDOT can reduce cement content in Class S(AE) concrete while still meeting all the necessary requirements for fresh and hardened concrete. The primary variables were cementitious material content, fly ash percentage, and w/cm. The most important conclusions and findings of this study are listed below in bullet form.

- ARDOT can allow their minimum required cementitious material content for Class S(AE) concrete to be reduced from 611 to 517 lb/yd³ while still meeting requirements for fresh and hardened properties.
- Class C fly ash content can be increased to a max of 30% while still meeting ARDOT requirements for compressive strength, air content, and slump.
- At the highest w/cm of 0.50 with the lowest cementitious material value of 517 lb/yd³ and 30% replacement of cement with fly ash, the mix still developed the required 28-day strength and showed a level of shrinkage not significantly different from that of lower w/cm mixes.
- All mixes achieved the ARDOT standard compressive strength for Class S(AE) concrete of 4000 psi by 28 days, with most exceeding this value by 7 days.
- Mixes batched with 20 or 30 % Class C fly ash had equivalent or slightly greater drying shrinkage strain and compressive strength at 28 day and 56 days, compared to mixtures with no fly ash.
- Drying shrinkage was found to have minimal change overall, with approximate decreases of 100 microstrain from 611 to 517 lb/yd³ and of 50 microstrain from 0.50 to 0.40 w/cm.

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