ArDOT TRC TRANSPORTATION RESEARCH COMMITTEE

TRC1602

Examining the Required Cement Content

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Final Report

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16. Abstract

Portland cement is a significant component in a concrete mixture. For concrete used in portland cement concrete pavement (PCCP), Class S, and Class S(AE) concrete, the Arkansas Department of Transportation specifies a minimum cementitious material content of 564 lb/yd^3 and 611 lb/yd^3, respectively. Prior research conducted at the University of Arkansas, TRC 0603, indicated concrete mixtures used in five bridge decks throughout Arkansas achieved the required 28-day strength at seven days, and the measured compressive strength at 28 days was 30% greater than required. The use of high strength concrete in may increase cracking and consequently reduce the durability of the pavement, structure, or bridge deck. Therefore, a reduction of the current cementitious content to a minimum level at which the concrete can meet the requirements of workability, compressive strength, and durability is an essential assignment. In addition, a reduction of the cementitious content can partially reduce construction costs, because cement is the most expensive ingredient in concrete. Using less cement within the concrete mixtures also lessens the negative impact on the environment due to the production of cement accounting for a large portion of total greenhouse gases generated by the production of concrete and its ingredients. This project will examine reducing the required cement content for PCCP, Class S, and Class S(AE) concrete.

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Cement content, drying shrinkage, compressive strength

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic	m^3
		meters NOTE: volumes greater than 1000 L shall be		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^{o}C	Celsius	1.8C+32	Fahrenheit	^{o}F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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1. Introduction

1.1. Research Motivation

Deterioration of the infrastructure in the United States of America is a problem which is in critical need of address. According to the American Society of Civil Engineers' Infrastructure Report Card, the United States scores a D in the roads category due to many roadways being in poor condition and responsible agencies being chronically underfunded (ASCE, 2017). The Arkansas Section of ASCE graded the state's roads as a D+ in their 2014 report. According to the report, Arkansas has the 12th largest state highway system in the nation with over 16,000 miles of highway, but lack of funding has placed projects on hold, and the long-term funding solutions are not immediate clear (ASCE, 2014). These burdens have placed a strain on the Arkansas Department of Transportation (ARDOT), which is tasked with maintaining and adding to the growing network of state highways in Arkansas. There is a need to find practical ways to effectively use materials and funds.

A portion of the over 16,000 miles of highway in Arkansas is portland cement concrete pavement (PCCP). Between 2006 and 2016, ARDOT spent $566 million for over 4.2 million cubic yards of PCCP. A large component of this cost is cement. Cement is the most expensive material found in typical PCCP mixtures. From information provided by ARDOT, the cost of cement is $95.42/ton. Not only is cement the most expensive material found in typical PCCP mixtures, but it is also the most pollutant. Among industrial emissions, cement production is the third largest source of greenhouse gases contributing 39.9 MMT CO_2 equivalent, which accounts for 10.6% of industrial emissions (EPA 2017). Additionally, it is estimated cement production accounts for 5% of total global anthropogenic carbon emissions (Humphreys and Mahasenan 2002, Worrell, et al. 2001). By reducing the cement content in PCCP mixtures, both economic and environmental benefits would be realized.

In addition to examining PCCP mixtures, the research program will also investigate the minimum cement content in Class S and Class S(AE) concrete. Class S mixtures are used for the structural elements of bridges, such as retaining walls, box culverts, footings, piers, and abutments cast in Arkansas. Class S(AE) is Class S, structural concrete, that is air entrained (AE). Class S(AE) is used in bridge decks and in other structural concrete that requires air entrainment. Table 1.1 shows the required fresh and hardened concrete properties for Class S, Class S(AE), and PCCP concrete.

Table 1.1. Class S, Class S (AE), and PCCP Concrete Mixture Requirements

Properties	Class S	Class S(AE)	PCCP
Minimum 28-day compressive strength (psi)	3500	4000	4000
Minimum cementitious content (lb/yd^3)	611	611	564
Maximum fly ash content (Class C or F) (%)	20	20	20
Maximum slag cement content (%)	25	25	25
Maximum w/cm	0.49	0.44	0.45
Slump range (in.)	1 – 4	1 – 4	≤ 2
Air content (%)	-	6 ± 2	6 ± 2

1.2. Research Goals

The goal of this research is to investigate the effects of reducing the current ARDOT minimum cementitious content on the compressive strength, unrestrained drying shrinkage, and modulus of elasticity for the three type of mixtures, Class S, Class S(AE), and PCCP. Unique mixture designs incorporating up to four cementitious material contents, three fly ash replacement percentages, and four water to cementitious material ratios (w/cm) will be tested for compressive strength and unrestrained drying shrinkage. Sample mixtures from the initial tests will be chosen and subjected to a static modulus of elasticity test, and the effect of coarse aggregate source will be examined on selective mixtures. The goal of this research program is to determine if the minimum specified cement content for PCCP, Class S, and Class S(AE) can be reduced and determine what this reduction in cement content may have on concrete performance.

2. Literature Review

This literature review will take an in depth look at past research that has examined the relationship between mixture characteristics and the fresh and hardened properties of concrete. These characteristics include w/cm, cement content, aggregate content, supplementary cementitious material content, and fly ash content and will be discussed in detail.

2.1. Water to Cementitious Material Ratio

Research in the early 1900s by Abrams produced a relationship between water-cementitious material ratio (w/cm) and concrete strength (Mehta and Monteiro 2006). This relationship is illustrated in Figure 2.1. As w/cm increases, compressive strengths decrease at all ages for moist cured concrete due to an increase in capillary porosity (Wassermann, Katz and Bentur 2009, Dhir, et al. 2004, Mehta and Monteiro 2006, Taylor, et al. 2012).

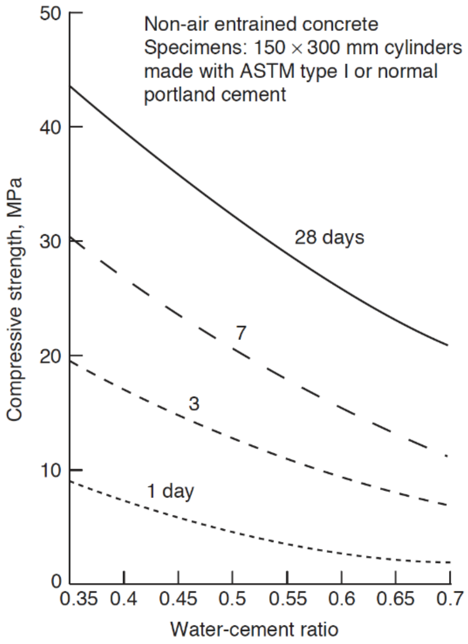


Figure 2.1 – Influence of Water-Cement Ratio and Moist Curing Age on Concrete Strength (Mehta and Monteiro 2006)

Studies have shown strength is directly correlated to w/cm and independent of cement content at a given w/cm (Wassermann, Katz and Bentur 2009). How the w/cm is changed is also of importance. Popovics concluded changing the cement content while keeping the water content constant caused greater changes in strength, while changing the water content and maintaining the cement content resulted in lower strength changes (Popovics 1990, Obla, Hong and Lobo 2017).

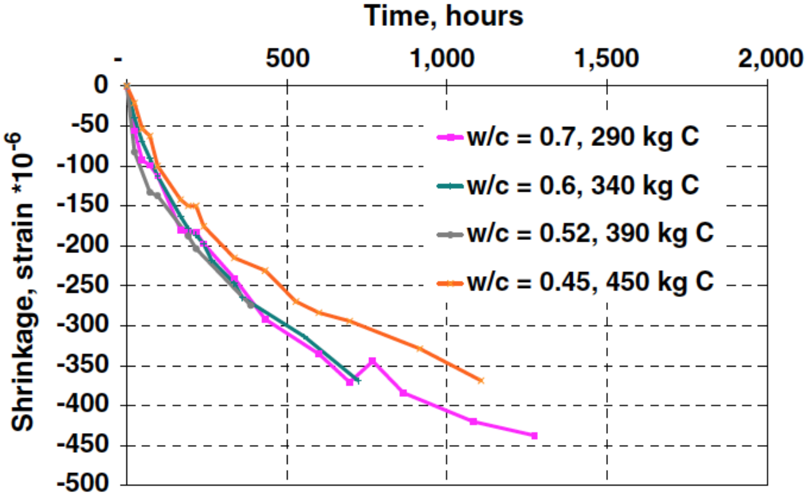


Figure 2.2 – Effect of w/c on Shrinkage (Wassermann, Katz and Bentur 2009)

While w/cm has a measureable effect on the compressive strength of concrete, a correlation between w/cm and drying shrinkage is not as pronounced. Research conducted by Wassermann (2009) and shown in Figure 2.2, indicates increasing the w/cm from 0.45 to 0.70 results in only an increase in shrinkage of the test specimens of 100 microstrains. For the mixtures tested, water content was held at approximately 200 kg/m^3. Additionally, this decrease in shrinkage is potentially attributed to the use of a chemical admixture in the mixture with a w/cm of 0.45 which was not used in the remaining three mixtures.

2.2. Cement Content

As mentioned previously, changes in cement content for a given w/cm have little to no effect on concrete strength. Cement content has a greater effect on total absorption and capillary absorption coefficient, due to increasing the paste content, which does increase strength, but the increase is not in large magnitude (Wassermann, Katz and Bentur 2009). Research has also suggested once the required cement content is reached, additional cement can decrease 28-day compressive strength by up to 15% (Yurdakul 2010).

A consensus is difficult to be reached concerning how and to what degree cement content effects drying shrinkage. Research conducted by Wassermann (2009) suggests the impact of cement content on drying shrinkage is minor, and changes in drying shrinkage due to increasing or decreasing cement content have no clear pattern. However, other researchers suggest a decrease in cement content provides less opportunity for concrete shrinkage due to an increase of aggregate to compensate for the lowered w/cm (Kosmatka, Kerkhoff and Panarese 2003, Mehta and Monteiro 2006, Mindess, Young and Darwin 2003). Research focused on cracking in decks observed a nearly 500% increase in crack density from 0.05 ft/ft^2 to 0.23 ft/ft^2 when the cement content was increased from 605 lb/yd^3 to 639 lb/yd^3 in field studies involving bridge decks (Schmitt and Darwin 1999). It is important to note, due to this data being conducted in the field, the opportunity for outside factors to contribute to the increase in crack density is higher.

Similar to the effect of overall cement content on drying shrinkage, the effects of cement fineness is also a topic not fully understood. According to ACI 224.R-01 (ACI Committee 224 2001), the properties of cement, including fineness, directly affect concrete shrinkage. However, several other researchers have concluded the effect of fineness and other cement properties cause little to no change in the overall performance of the concrete mixture (Li, Qi and Ma 1999, Neville 1995, Mehta and Monteiro 2006).

2.3. Aggregate Content

In normal strength concrete, aggregates rarely fracture and cause the failure of the specimen. Instead, factors affected by aggregate properties are typically the cause of failure. Aggregate size, shape, gradation, surface texture, and mineralogy can all affect strength. Large aggregates tend to form weak bonds with the cement matrix in the interfacial transition zone, leading to increased microcracks. However, smaller aggregates increase water demand due high surface area to volume ratios (Mehta and Monteiro 2006, Cordon and Gillespie 1963, Ley and Cook, Aggregate Gradations for Concrete Pavement Mixtures 2014).

Figure 2.3 shows the increasing strength benefit of using smaller maximum aggregate size as w/cm decreases. Use of microfines (material passing the #200 sieve) in concrete mixtures has shown increased strength when compared to baseline mixtures (Rached, Fowler and Koehler 2010). Additionally, the use of rough aggregates has shown improved early-age strength, but the benefits decrease at later ages due to chemical interactions between the aggregate and hydrated cement particles increasing in influence (Mehta and Monteiro 2006, Rached, Fowler and Koehler 2010).

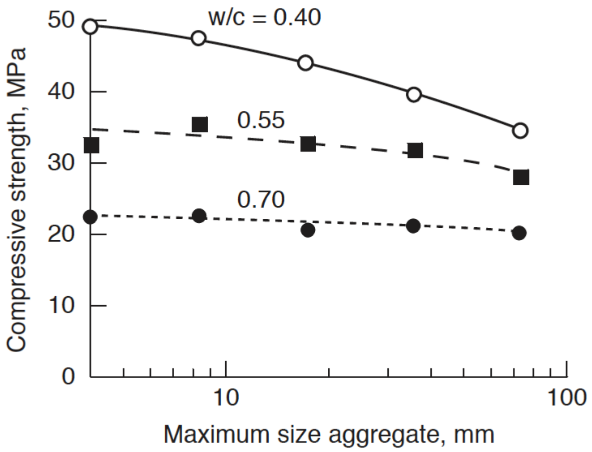


Figure 2.3 – Influence of Aggregate Size and w/cm on Strength (Cordon and Gillespie 1963)

Mehta (2006) suggests the most important factor affecting drying shrinkage in concrete is the aggregate content of the mixture. Shown in Figure 2.4, concrete mixtures with varying w/cm followed a similar, decreasing trend in shrinkage as percent content of aggregate was increased. Pure cement paste is susceptible to large changes in volume due to moisture loss and lack of mechanical restraint. Aggregates in concrete serve as a physical restraint for the cement paste. Therefore, increasing the amount of aggregate within a mixture will decrease drying shrinkage. Additionally, increasing the modulus of elasticity of the coarse aggregate will result in greater shrinkage resistance due to the coarse aggregate experiencing lower strain values for the same amount of stress exerted by the contracting cement paste (Kosmatka, Kerkhoff and Panarese 2003, Mehta and Monteiro 2006, Mindess, Young and Darwin 2003). While increasing coarse aggregate content generally has positive effects on shrinkage, an increase in the percentage of microfines of greater than four percent within a gradation can increase drying shrinkage due to an increase in water demand of the mixture. With additional water required to maintain fresh concrete properties, excess water is introduced into the mixture which is eventually expelled during curing causing drying shrinkage (Hanna 2003).

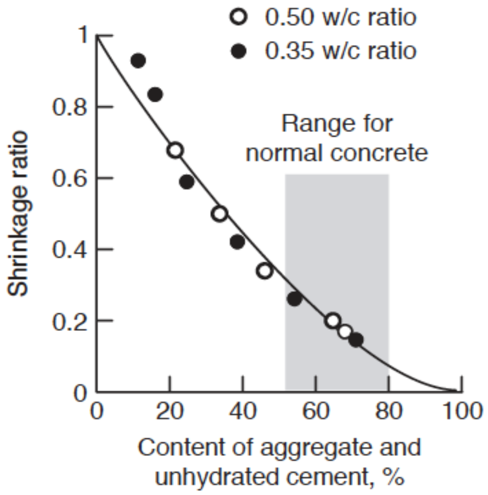


Figure 2.4 – Influence of Aggregate Content on Shrinkage (Mehta and Monteiro 2006)

2.4. Supplementary Cementitious Material Content

Use of pozzolanic mineral admixtures also known as supplementary cementitious materials, such as fly ash, can improve ultimate strength of concrete by causing chemical reactions which lead to additional calcium silica hydrate formation (Mehta and Monteiro 2006). While the ultimate strength of a concrete mixture may be improved by the usage of supplementary cementitious materials, early age strength is typically reduced. Low early age strength is attributed to lower heat of hydration of the pozzolanic reactions. The rate of pozzolanic hydration is slower than the rate of cement hydration which means concrete incorporating fly ash must be properly cured for an appropriate length of time for the strength benefits of fly ash to be realized (Thomas 2007).

Figure 2.5 shows the affects incorporating fly ash into concrete mixtures has on early and late age strengths. For the mixtures shown in Figure 2.5, fly ash replacement was 30%. When standard curing methods are used, concrete with fly ash experiences a delay in strength gain initially, as shown in the graph on the left of Figure 2.5. At approximately 56 days of age, the mixture incorporating fly ash surpassed the mixture containing only portland cement.

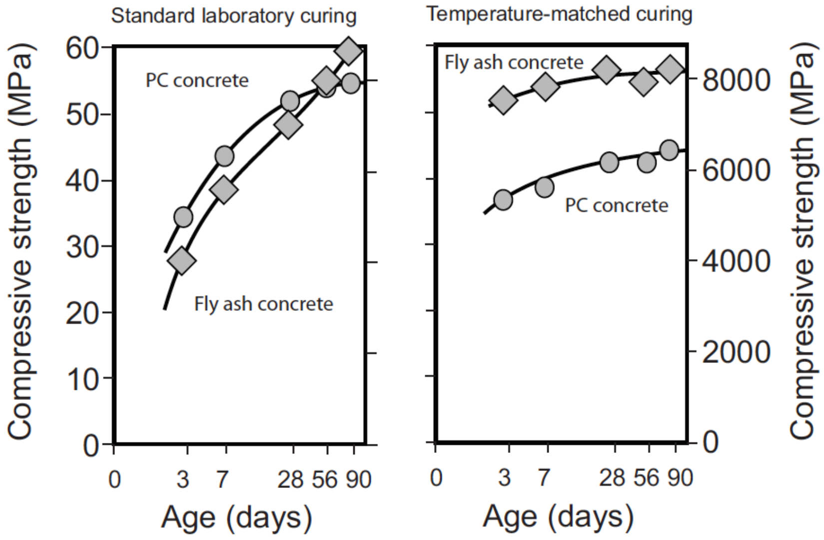


Figure 2.5 – Effects of Fly Ash on Concrete Strength (Bamforth 1980)

2.5. **Summary**

Cement content effects both fresh and hardened properties. Past research has shown, in most cases, cement content can be decreased while maintaining strength requirements and helping to decrease 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, along with high range water reducer and air entertainer, can reduce the required cement content while still meeting design standards.

3. Materials and Methods

3.1. Introduction

This research program consisted of five primary tasks: design of concrete mixtures based on data provided by ARDOT, batching of concrete mixtures, casting of concrete test specimens, testing of concrete specimens at predetermined intervals, and analysis of collected data. All casting and testing of samples occurred at the University of Arkansas Engineering Research Center (ERC) in Fayetteville, Arkansas. Materials used in this research program were locally available. The goal of the research program was to determine if the minimum cement content for Class S, Class S(AE), and/or PCCP mixtures can be reduced while achieving the specified fresh and hardened concrete properties.

3.2. Mixture Design

3.2.1. Overview

As stated previously, the goal of this research program was to determine if the minimum cementitious content for PCCP, Class S, and Class S(AE) concrete as defined in ARDOT specifications can be reduced but still achieve the required fresh and hardened properties. Current ARDOT specifications for the three types of concrete are shown below in Table 3.1. The specifications prescribe the minimum cementitious material content, maximum fly ash replacement percentage, minimum 28-day compressive strength, slump range, air content range, and maximum w/cm. A summary of these specifications is provided in Table 3.1. These specifications served as a base point for the design of concrete mixtures tested. Additionally, ARDOT provided representative PCCP, Class S, and Class S(AE) mixtures from various concrete producers in Arkansas. A summary of these eight PCCP mixtures is provided in Table 3. with the names of the companies redacted. As shown in Table 3., all PCCP mixture providers designed mixtures using the minimum cementitious material amount, 546 lb/yd^3. Of the eight representative mixtures, two provided mixtures with 0% fly ash replacement, four provided mixtures with 15% fly ash replacement, and two provided mixtures with 20% fly ash replacement – the maximum allowed by ARDOT specifications. Coarse aggregate content varied from 1747 to 1899 lb/yd^3, and all providers used #57 gradation for the coarse aggregate. Finally, the w/cm varied from 0.38 to 0.45 for the provided representative mixtures.

Table 3.1 – Class S, Class S (AE), and PCCP Concrete Mixture Requirements

Properties	Class S	Class S(AE)	PCCP
Minimum 28-day compressive strength (psi)	3500	4000	4000
Minimum cementitious content (lb/yd^3)	611	611	564
Maximum fly ash content (class C or F) (%)	20	20	20
Maximum slag cement content (%)	25	25	25
Maximum w/cm	0.49	0.44	0.45
Slump range (in.)	1 – 4	1 – 4	≤ 2
Air content (%)	-	6 ± 2	6 ± 2

Table 3.2 – Representative PCCP Mixture Designs

Material	Concrete Mixture Designs from Various Companies							
	A	B	C	D	E	F	G	H
Cement (lb/yd^3)	451	479	479	564	479	564	479	451
Fly Ash (lb/yd^3)	113	85	85	0	85	0	85	113
Coarse Aggregate (lb/yd^3)	1851	1747	1747	1756	1893	1770	1774	1899
w/cm	0.40	0.38	0.38	0.38	0.44	0.44	0.38	0.45

ARDOT also provided the data shown below in Table 3.3. This table shows the typical mixtures proportions for the Class S used in Arkansas with the names of the concrete producers redacted. The table shows that there are many commonalities among the mixtures. For the Class S mixtures, all producers used the minimum amount of cementitious material (564 lb/yd^3). Six of the eight producers used an ASTM Type B/D admixture. The w/cm ranged from 0.38 to 0.49, and the coarse aggregate content ranged from 1640 to 2028 lb/yd^3. Class C fly ash was the only supplementary cementitious material used, and its replacement rate was 15 or 20 percent. All mixtures contained #57 coarse aggregate.

Table 3.3 – Representative Class S Mixture Designs

Material	Concrete Producers							
	I	J	K	L	M	N	O	P
Cement (lb/yd^3)	611	611	611	489	489	489	489	516
Fly ash (lb/yd^3)	0	0	0	122	122	122	122	95
Coarse Aggregate (lb/yd^3)	1887	1757	1737	1909	1830	1640	2028	1775
WR/Retarder	D17	Recover	Recover	Recover	-	MB900	D17	-
w/cm	0.49	0.45	0.48	0.41	0.44	0.45	0.38	0.49

Shown below in Table 3.4 are the typical mixtures proportions for the Class S(AE) used in Arkansas which was provided by ARDOT. The table shows that there are many commonalities among the mixtures. For the Class S(AE) mixtures, all producers used the minimum amount of cementitious material (611 lb/yd^3). Five of the eight producers used an ASTM Type B/D admixture. The w/cm ranged from 0.40 to 0.44, and the coarse aggregate content ranged from 1629 to 1760 lb/yd^3. Class C fly ash was the only supplementary cementitious material used, and its replacement rate was 15 or 20 percent. All mixtures contained #57 coarse aggregate.

Table 3.4 – Representative Class S(AE) Mixture Designs

Material	Concrete Producers							
	Q	R	S	T	U	V	W	X
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
Coarse Aggregate (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

3.2.2. Mixture Proportions

Utilizing the representative PCCP mixture designs in Table 3. as a reference, a batching matrix was developed with the goal of reducing cement content and cementitious material content. The batching matrix consisting of 36 unique concrete mixtures is shown in Table 3.. Cementitious material contents were decided to be 470, 517, and 564 lb/yd^3. These values incorporate current ARDOT specifications and provided representative mixture designs for the maximum cementitious material content tested. Cementitious material contents of 517 and 470 lb/yd^3 represent removing a half and a whole standard bag of cement per cubic yard, respectively. Fly ash replacement percentages were chosen to be 0, 20, and 30 percent of cementitious material content to best represent current specification allowances and observe effects of increasing the current maximum fly ash replacement percentage of 20. The lowest three w/cms, 0.38, 0.42, and 0.45, best represent current PCCP mixture designs from providers. A w/cm of 0.50 was added to observe the performance effects of excess water incorporated into mixtures on job sites. For all mixtures, a coarse aggregate of #57 gradation and content of 1750 lb/yd^3 were chosen, because this combination best represents the gradation and various coarse aggregate contents in Table 3.. This was the only consistent batch weight property for all mixtures.

Table 3.5 – PCCP Batching Matrix

Cementitious Material Content (lb/yd^3)	w/cm			
	0.38	0.42	0.45	0.50
564 (0% Class C Fly Ash)	X	X	X	X
564 (20% Class C Fly Ash)	X	X	X	X
564 (30% Class C Fly Ash)	X	X	X	X
517 (0% Class C Fly Ash)	X	X	X	X
517 (20% Class C Fly Ash)	X	X	X	X
517 (30% Class C Fly Ash)	X	X	X	X
470 (0% Class C Fly Ash)	X	X	X	X
470 (20% Class C Fly Ash)	X	X	X	X
470 (30% Class C Fly Ash)	X	X	X	X

Using the representative Class S mixture designs in Table 3. as a reference, a batching matrix was developed with the goal of reducing cement content and cementitious material content. The batching matrix consisting of 36 unique concrete mixtures is shown in Table 3.. The cementitious material content ranged from 517 to 611 lb/yd^3. This included the current ARDOT minimum of 611 lb/yd^3 but then included 517 and 564 lb/yd3. This represents a “1/2 bag” and full bag of cement less than the ARDOT minimum. The w/cm range was 0.38, 0.45, 0.49, and 0.55. This also represents the range of w/cm used in the 9 districts along with the w/cm of 0.55 which represents a mixture in which water was added in the field. For each cementitious material content and w/cm, Class C fly ash replaced 0, 20, or 30 % of the cement. The coarse aggregate content used in all mixtures was 1800 lb/yd^3 which was chosen based on consultation with ARDOT.

Table 3.6 – Class S Batching Matrix

Cementitious Material content (lb/yd^3)	w/cm			
	0.38	0.45	0.49	0.55
611 0% Class C Fly Ash)	X	X	X	X
611 (20% Class C Fly Ash)	X	X	X	X
611 (30% Class C Fly Ash)	X	X	X	X
564 (0% Class C Fly Ash)	X	X	X	X
564 (20% Class C fly ash)	X	X	X	X
564 (30% Class C fly ash)	X	X	X	X
517 (0% Class C Fly Ash)	X	X	X	X
517 (20% Class C fly ash)	X	X	X	X
517 (30% Class C fly ash)	X	X	X	X

Utilizing the representative Class S(AE) mixture designs in Table 3. as a reference, a batching matrix was developed with the goal of reducing cement content and cementitious material content. The batching matrix consisting of 36 unique concrete mixtures is shown in Table 3.. For cementitious material, the ARDOT minimum is 611 lb/yd^3. To check the reduction not only of cement but also of total cementitious material, this was tested at the current minimum standard of 611 lb/yd^3, as well as lower values of 564 and 517 lb/yd^3, to further evaluate the potential waste of materials in pursuit of unneeded strength. Regarding w/cm ratio, the current max w/cm that ARDOT allows for class S(AE) is 0.44. Thus, testing was performed at the max, as well as at two lower w/cm ratios to compare reductions in shrinkage due to lessened water contents. The w/cm ratio 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 by SCMs. The coarse aggregate content used in all mixtures was 1800 lb/yd^3, which was chosen based on consultation with ARDOT. The only difference between the Class S(AE) mixtures and the Class S mixtures is the total air content and the fine aggregate content. All Class S(AE) mixtures had a total air content of 6±2 %, and because of the additional air, the fine aggregate content was less in the Class S(AE) mixtures.

Table 3.7 – Class S(AE) Batching Matrix

Cementitious Material content (lb/yd^3)	w/cm			
	0.38	0.45	0.49	0.55
611 0% Class C Fly Ash)	X	X	X	X
611 (20% Class C Fly Ash)	X	X	X	X
611 (30% Class C Fly Ash)	X	X	X	X
564 (0% Class C Fly Ash)	X	X	X	X
564 (20% Class C fly ash)	X	X	X	X
564 (30% Class C fly ash)	X	X	X	X
517 (0% Class C Fly Ash)	X	X	X	X
517 (20% Class C fly ash)	X	X	X	X
517 (30% Class C fly ash)	X	X	X	X

3.3. Materials

All mixtures tested used the same source of cement, fly ash, coarse aggregate, and fine aggregate. Type I/II portland cement from Ash Grove Packaging Group meeting ASTM C150 specifications (ASTM 2017) was selected due to its ease of availability in Northwest Arkansas. Class C fly ash meeting ASTM C618 specifications (ASTM 2015) was sourced from Pine Bluff, Arkansas, and supplied by Boral Resources. Both materials were kept in a storage building at to provide protection from moisture and contamination. The cement and fly ash used in this project were tested to determine chemical composition and other properties. The results of these tests are summarized in Table 3.8 and Table 3.9, respectively.

Table 3.8 – Cement Properties

Property	Composition
	Chemical Compounds
SiO_2	20.1%
Al_2O_3	5.1%
Fe_2O_3	3.8%
CaO	64.2%
MgO	1.0%
SO_3	3.2%
Loss on Ignition	2.4%
Na_2O	0.2%
K_2O	0.6%
Insoluble Residue	0.4%
CO_2	1.1%
Limestone	2.8%
$CaCO_3$	88.2%
Potential Compounds	
C_3S	55.0%
C_2S	14.0%
C_3A	7.0%
C_4AF	11.0%
$C_3S + 4.75\ C_3A$	88.0%
Physical	
Air Content of Mortar (Volume)	8.0%
Fineness	4.5 m^2/g
Autoclave Expansion	-0.01%
Mortar Bar Expansion	0.00%

Table 3.9 – Fly Ash Properties

Chemical Compounds	Composition
SiO_2	36.7%
Al_2O_3	21.5%
Fe_2O_3	5.7%
CaO	22.7%
Na_2O	1.5%
K_2O	0.6%
MgO	4.3%
∑ Oxides	63.9%
∑ Alkalis	29.1%

Coarse aggregate used for this project was a crushed limestone sourced from Sharp's Quarry in Springdale, Arkansas. A sieve analysis was performed on the aggregate to ensure the gradation met ARDOT specifications. The results of this sieve analysis are shown against ARDOT specifications in Figure 3.. Additionally, specific gravity and absorption capacity of 2.68 and 1.2%, respectively, were used for proportion calculations. Fine aggregate used in this project was sourced from the Arkansas River in Van Buren, Arkansas. A sieve analysis was also performed on the fine aggregate. The results from this analysis are shown in Figure 3.2. A specific gravity of 2.63 and absorption capacity of 0.8% were used for mixture proportioning. The calculated fineness modulus for the sand was 2.22. Coarse and fine aggregate stock piles were stored in uncovered aggregate bins at the Engineering Research Center (ENRC) at the University of Arkansas, shown in Figure 3.3. The sieve analysis of both coarse and fine aggregates followed specifications found in AASHTO T27 (AASHTO 2014).

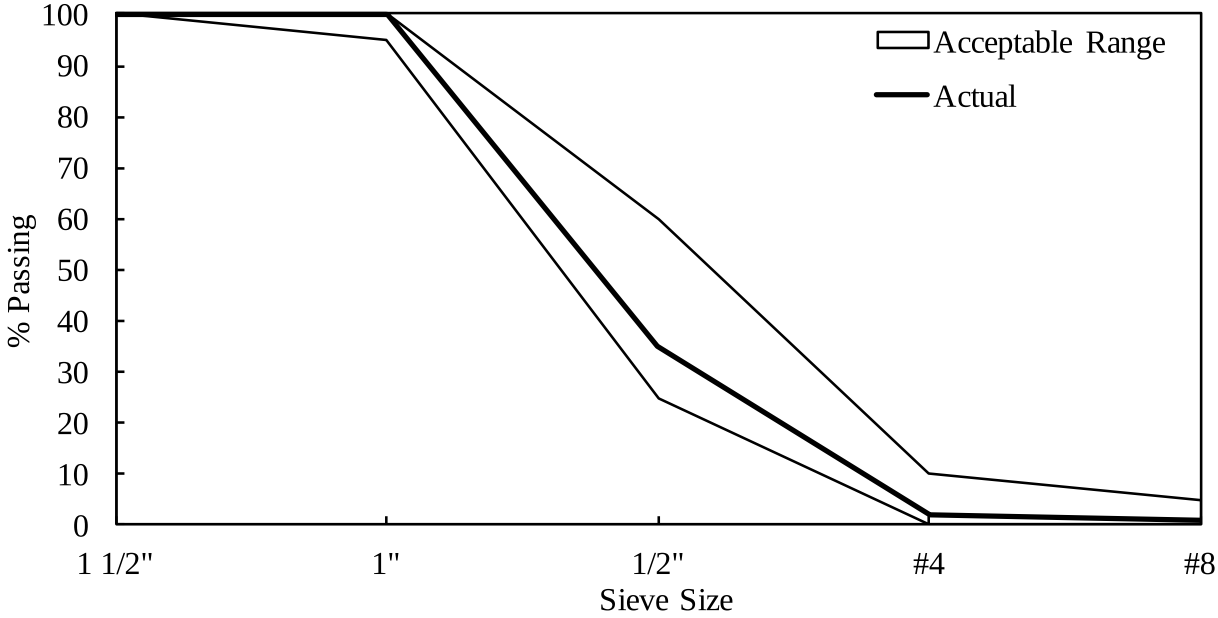


Figure 3.1 – Coarse Aggregate Gradation

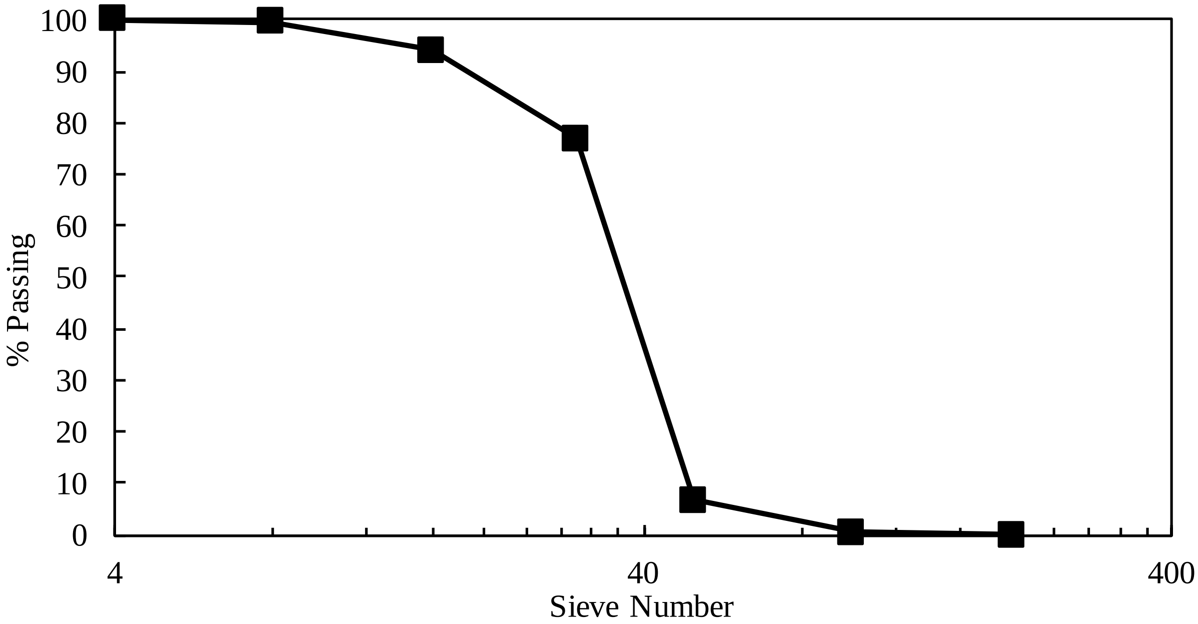


Figure 3.2 – Fine Aggregate Gradation

Figure 3.3 – Aggregate Storage Bins

Chemical admixtures used for this project were supplied by GCP Applied Technologies. The admixtures were ADVA® Cast 575, Daravair® 1000, and Terapave® AEA. ADVA® Cast 575 is a high-range water reducing Type A/F admixture which meets ASTM C494 specifications for chemical admixture use in concrete (ASTM 2016). Daravair® 1000 and Terapave® AEA are air-entraining admixtures which both meet ASTM C260 specifications (ASTM 2016). Daravair® 1000 was used in initial concrete mixtures, however the low slump benefits of Terapave® AEA led to Terapave® AEA being used primarily. All chemical admixtures were introduced to mixtures according to manufacturer's recommendations.

3.4. Test Specimens

After final batch weights were calculated, material was weighed and mixed according to standard mixing procedures found in ASTM C192 (ASTM 2016). Immediately following removal from a rotating drum mixer, several tests were performed to determine fresh properties of concrete including, slump, air content and unit weight. The process of measuring slump and the pressure meter used for unit weight and air content are shown in Figure 3.4. Slump, unit weight, and air content were measured according to specifications found in AASHTO T119, T121, and T152, respectively (AASHTO 2014, AASHTO 2015, AASHTO n.d.).

Figure 3.4 – Sump, Unit Weight, and Air Content Measurements

For all mixtures, two hardened concrete properties were measured – compressive strength and unrestrained drying shrinkage. To complete this task, 12 cylinders, four inches in diameter by eight inches in height, were fabricated and cured according to AASHTO T23 and ASTM C192 specifications (AASHTO 2014, ASTM 2016). Additionally, three prisms, four inches square by 11.25 inches in length were fabricated and stored for each mixture according to ASTM C157 (ASTM 2016). However, due to limited water bath storage space, initial water curing of prisms was not performed. All test specimens were stored in an enclosed environmental chamber which was kept at 72ºF through use of an air conditioning system and 50% humidity through use of a dehumidifier. Following compressive strength testing, an additional 12 cylinders were fabricated from the mixtures which averaged the three highest and three lowest compressive strength values for modulus of elasticity testing.

3.5. Test Methods

All compressive strength tests were performed at the ERC using a 400-kip capacity Forney compression machine with an ADMET GB2 digital display. Compressive strengths of all mixtures were measured at 1 day, 7 days, 28 days, and 56 days following procedures found in AASHTO T22 (AASHTO 2014). Three cylinders were tested to failure at each age, and the average of the three calculated compressive strengths was recorded as mixture's compressive strength. Cylinder ends were placed within aluminum caps with neoprene pads prior to loading. Some cylinder ends were ground using an end-grinding machine on site, because the compressive strength of the cylinders exceeded the limits of the neoprene pads.

For each mixture, unrestrained drying shrinkage of three prisms was measured weekly for 16 weeks following measurement procedures found in ASTM C157 (ASTM 2016). An initial length was measured following demolding at 24 hours of age for each prism. As shown in Figure 3.5, prisms were placed on rollers to allow free movement in the plane of measurement. Length changed was measured using a Humboldt length comparator with a digital gauge and precision to the nearest ten-thousandth of an inch.

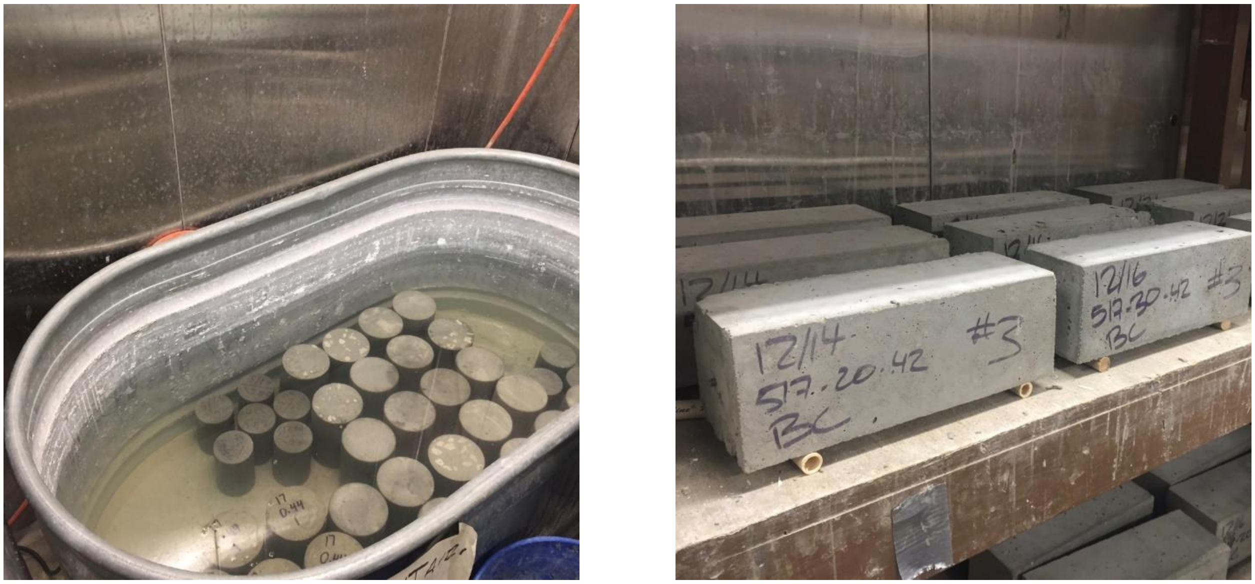


Figure 3.5 – Compressive Cylinder and Unrestrained Drying Shrinkage Prism Storage

Static modulus of elasticity was measured at seven and 28 days for the three mixtures with the highest compressive strength and the three mixtures with the lowest compressive strength following the guidance of ASTM C469 (ASTM 2014). The test was performed on three cylinders within a collar with dial gauge using the Forney for loading. All cylinders used for static modulus of elasticity testing were ground to a smooth, plane finish on the ends. Figure 3. shows the length comparator, Forney with static modulus of elasticity specimen loaded, and end-grinding machine. Raw data from these tests were analyzed using Microsoft Excel.

Figure 3.6 – Laboratory Equipment

4. Results and Discussion

4.1. Introduction

This chapter will cover the three hardened concrete properties of primary concern – compressive strength, unrestrained drying shrinkage, and static modulus of elasticity. The results will be shown in as concise manner possible to provide the reader with a clear understanding of the results. The results are also divided into three sections based on the type of mixture, PCCP, Class S, and then Class S(AE).

4.2. Results for the PCCP Mixtures

The results for the PCCP mixtures are presented and discussed in the following sections. The testing matrix and the mixture proportions for the PCCP mixtures were discussed in Chapter 3.

4.2.1. Compressive Strength

Compressive strength data are condensed to three figures based upon cementitious material content. Figure 4.1 shows compressive strength data for mixtures with a cementitious material content of 564 lb/yd^3 at 1 day, 7 days, 28 days, and 56 days of age. The data presented in this figure – along will all following compressive strength figures – is grouped by fly ash replacement percentages, increasing from left to right, and by w/cm within those groups, also increasing from left to right. A horizontal line was added at 4,000 psi to represent the current ARDOT compressive strength specification of 4,000 psi at 28 days.

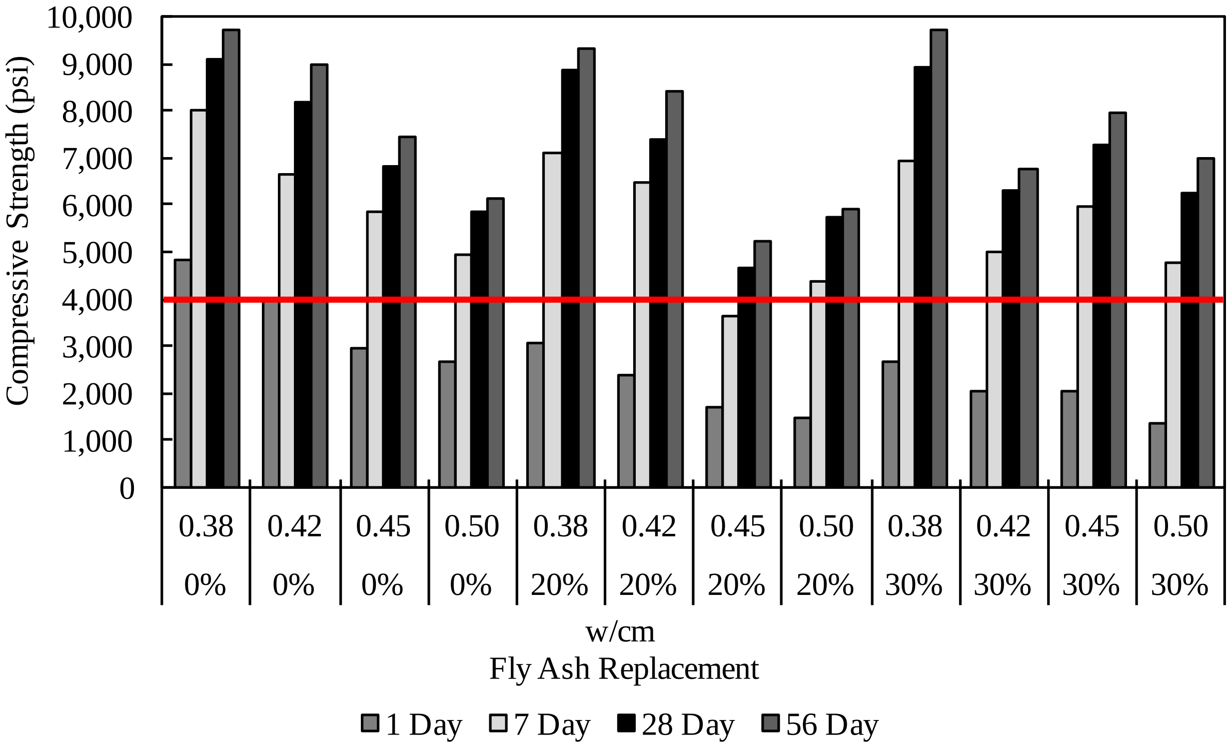


Figure 4.1 – Compressive Strengths of 564 lb/yd^3 Cementitious Material PCCP Mixtures

As shown by Figure 4.1, all mixtures containing a cementitious material content of 564 lb/yd^3 achieved the specified 28-day strength of 4,000 psi. All but one mixture achieved the specified strength by 7 days of age. Several trends are evident in this figure. First, a positive effect on compressive strength caused by decreasing the w/cm is evident by decreasing compressive strength values within each fly ash replacement percentage group as w/cm increase from left to right.

There are two exceptions to this trend. The mixture with a fly ash replacement percentage of 20 and w/cm of 0.45 along with the mixture with a fly ash replacement percentage of 30 and w/cm of 0.42 both had lower compressive strengths than mixtures with the same fly ash replacement percentage and higher w/cm. A possible explanation for this is air content. The two lower compressive strength mixtures had measured air contents of 8.0% and 7.5%, respectively, while the two higher compressive strength mixtures had measured air contents of

6.5% and 5.8%, respectively. Second, while 28-day and 56-day compressive strengths are comparable between mixtures with a w/cm 0.38 and different fly ash replacement percentages, a slight increase in late-age compressive strengths of 30% fly ash replacement mixtures can been seen when comparing to mixtures with 0% and 20% fly ash replacement. This trend would be expected to continue if compressive strength tests were performed at later ages than this project. A delay in strength gain as fly ash replacement percentage increases is seen when comparing 1-day and 7-day compressive strengths. The difference in early-age compressive strengths between 20% fly ash replacement and 30% fly ash replacement is not as pronounced as the difference between mixtures containing zero fly ash and mixtures those containing any amount of fly ash. Third, without decreasing current ARDOT specifications for cementitious material content, the results in Figure 4.1 show the quantity of cement can be reduced by increasing the maximum allowable fly ash replacement percentage to 30. While early-age strengths may not be comparable to PCCP mixtures with a lower fly ash replacement percentage, 4,000 psi at 28 days is the only compressive strength requirement and a majority of mixtures achieved this requirement by 7 days of age.

Next, Figure 4.2 shows compressive strength data for all mixtures with a cementitious material content of 517 lb/yd^3. The format of this graph is the same as Figure 4.1. Again, a horizontal line representing the current ARDOT 28-day compressive strength specification of 4,000 psi was added. This group of data contains the first mixture which was unable to be completely mixed which was the mixtures at a w/cm of 0.38. This mixture lacked the workability needed to cast test cylinders. Mixtures with higher fly ash replacement percentages benefited from the increase in workability when fly ash is used.

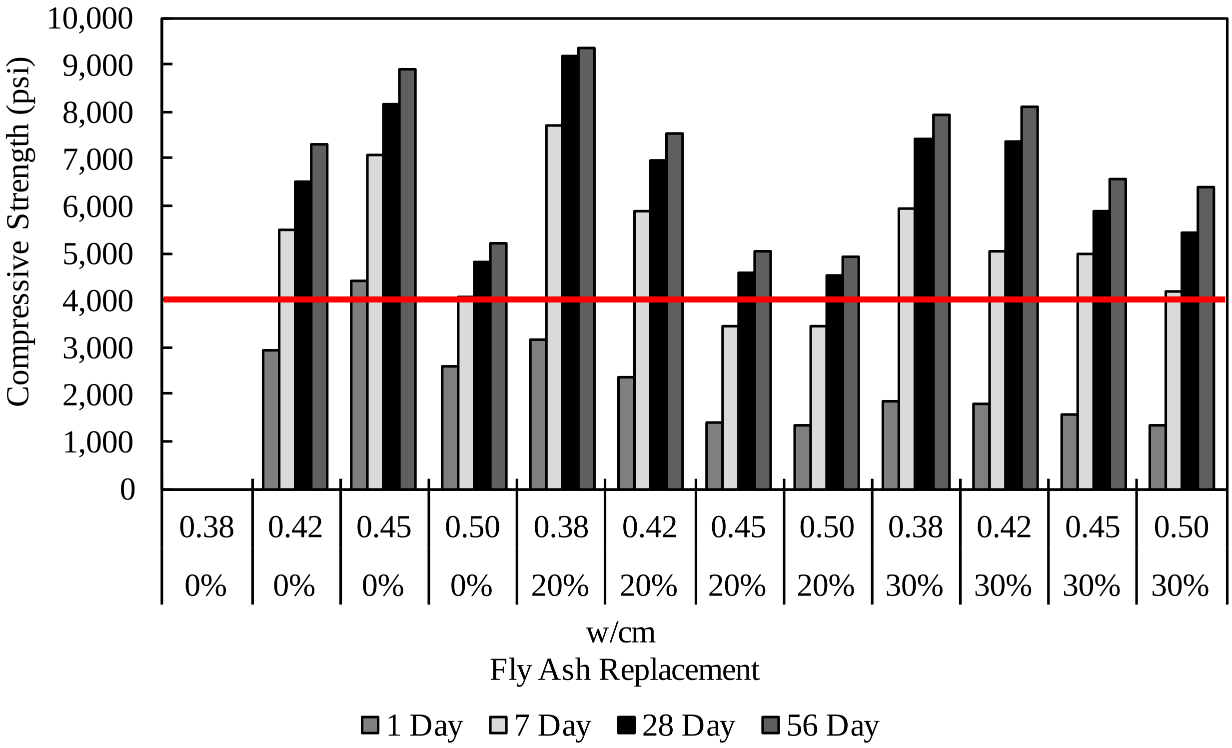


Figure 4.2 – Compressive Strengths of 517 lb/yd^3 Cementitious Material PCCP Mixtures

Despite the mixtures with a w/cm of 0.38 being unmixable, all other mixtures represented in Figure 4.2 exceeded the 28-day compressive strength specification. Similar to Figure 4.1, all but two mixtures achieved 4,000 psi by 7 days of age. Several trends again are present in Figure 4.2, but not as clear as data from mixtures with 564 lb/yd^3 cementitious material contents. First, the positive trend in compressive strength as w/cm decreases is again present in this data, especially among the mixtures with 20% and 30% fly ash replacement. An exception to this trend is evident among the mixtures containing zero fly ash. The mixture within this group with a w/cm of 0.42 had a lower compressive strength than a mixture with a w/cm of 0.45. Once again, air content could be the cause of this discrepancy. The air contents of these two mixtures was 6.0% and 4.0%, respectively. Second, compressive strengths at 28 days and 56 days of age between mixtures with the same w/cm and different fly ash replacement percentages exhibit increased variability compared to the differences in late-age strengths of mixtures containing 564 lb/yd^3 with 30% fly ash replacement mixtures showing increased late age strength only over zero fly ash mixtures with a e/cm of 0.50 and 20% fly ash replacement mixtures with a w/cm of 0.45 and 0.50. However, the pattern of lower early-age compressive strengths in mixtures containing 20% and 30% fly ash replacement compared to mixtures with zero fly ash remains. Again, this data shows the potential for reducing the cement content of PCCP mixtures used by ARDOT through an overall reduction in cementitious material content and an increase in fly ash replacement percentage to 30. While early-age strengths would be lower than mixtures containing higher cementitious material contents and lower fly ash replacement percentages, a majority of mixtures with 517 lb/yd^3 cementitious material content achieved the 28-day compressive strength requirement by 7 days of age.

Finally, Figure 4.3 shows compressive strength data for PCCP mixtures with a cementitious material content of 470 lb/yd^3. This was the lowest cementitious material content tested for this project. The figure follows the same format as compressive strength figures corresponding to 564 lb/yd^3 and 517 lb/yd^3 cementitious material content mixtures. As seen in Figure 4.3, all mixtures at a w/cm of 0.38 did not mix. These mixtures did not contain enough paste or water to facilitate a successful mixture. The mixtures were stiffer compared to the previous two groups of mixtures and workability was poor. Once again, as fly ash replacement percentages increased, workability and slump increased.

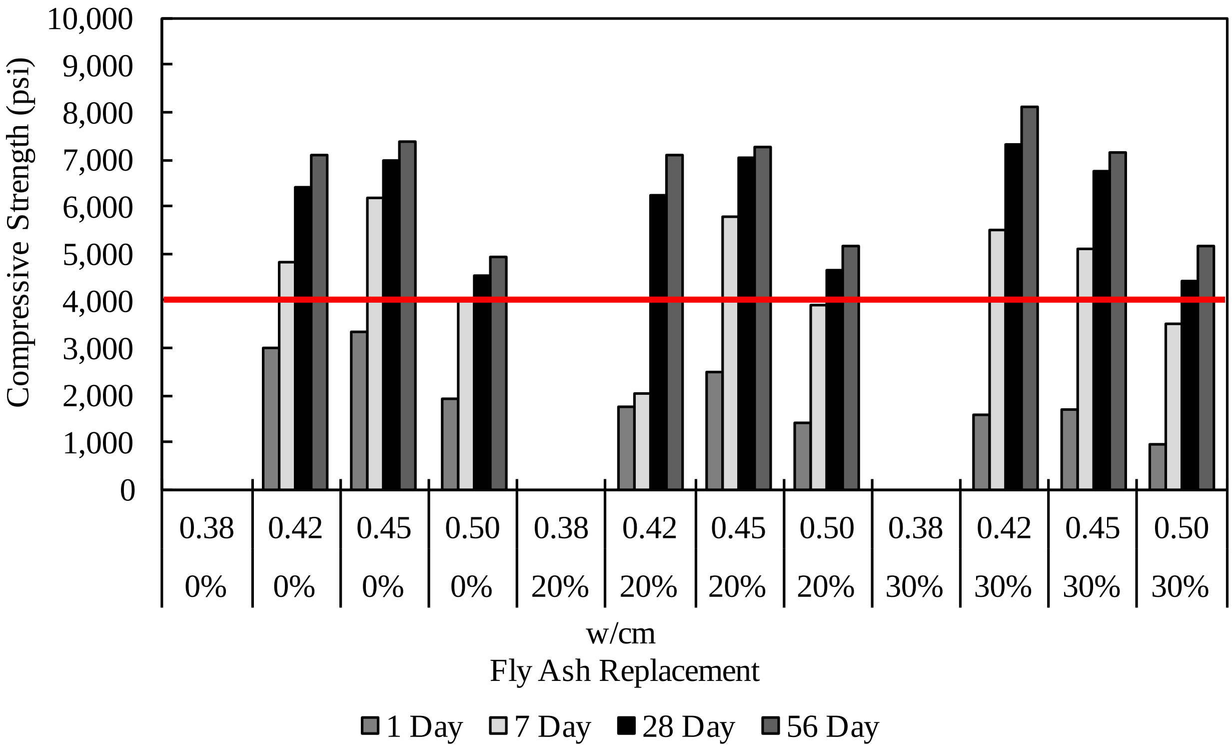


Figure 4.3 – Compressive Strengths of 470 lb/yd^3 Cementitious Material PCCP Mixtures

Despite all mixtures with a w/cm of 0.38 being unmixable, all other mixtures met 28-day compressive strength requirements. Compared to previous cementitious material contents, this group of mixtures has the most consistency in compressive strength across all w/cms and fly ash replacement percentages. Mixtures with zero fly ash and 20% replacement fly ash show nearly identical compressive strength values at a w/cm of 0.42, 0.45, and 0.50 compared to each other, with the 30% fly ash replacement mixtures being nearly identical to the other mixtures at a w/cm of 0.45 and 0.50. Most likely due to the largest percentage of fly ash at a w/cm of 0.42, the 30% fly ash replacement mixture is the strongest of the group, and the 30% fly ash replacement mixtures are the only set of mixtures which exhibit increased compressive strength as w/cm decreases. The other two groups both show decreased compressive strength at a w/cm of 0.50, but, as mentioned previously, compressive strengths are comparable at w/cm of 0.42 and 0.45. The decrease in early-age strength is again present in mixtures containing 470 lb/yd^3 of cementitious material. The mixture with 20% fly ash replacement and a w/cm of 0.42 shows a large increase in compressive strength between 7-day breaks and 28-day breaks. This is most likely due to poor consolidation within the cylinder mold caused by low workability leading to highly porous test cylinders. Despite these conditions, half the mixtures which were able to be mixed achieved 28-day compressive strength requirements in 7 days and all mixtures (excluding the 0.38 mixtures) achieved 4000 psi by 28 days of age. This dataset represents the largest possible decrease in both cementitious material and cement used in PCCP mixtures by ARDOT.

4.2.2. Unrestrained Drying Shrinkage

Drying shrinkage data was separated into figures based upon cementitious material content and data series based upon fly ash replacement percentage and w/cm. Similar to compressive strength figures, for mixtures which data is unavailable, data series are not present within the graph, but is shown for continuity in the legend.

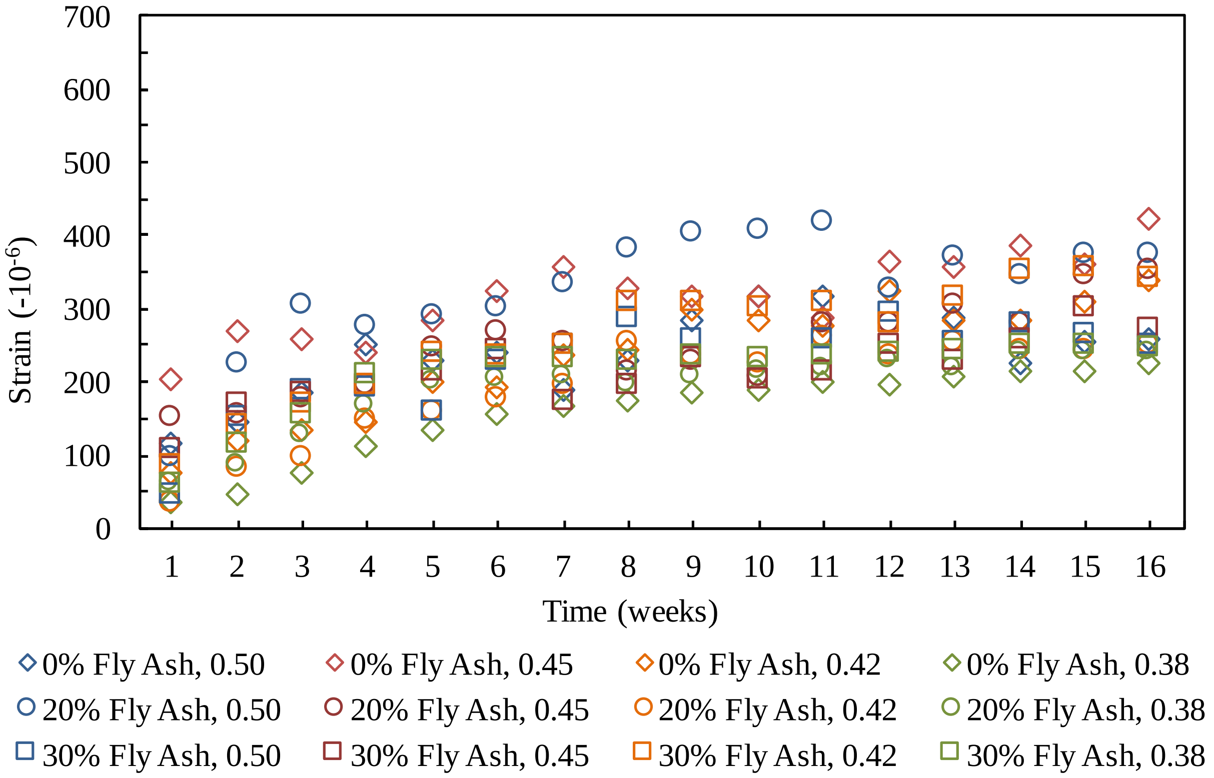


Figure 4.4 presents unrestrained drying shrinkage data for mixtures with 564 lb/yd^3 cementitious material. Additionally, various colors and shapes of data points represent different w/cm and fly as replacement percentages, respectively.

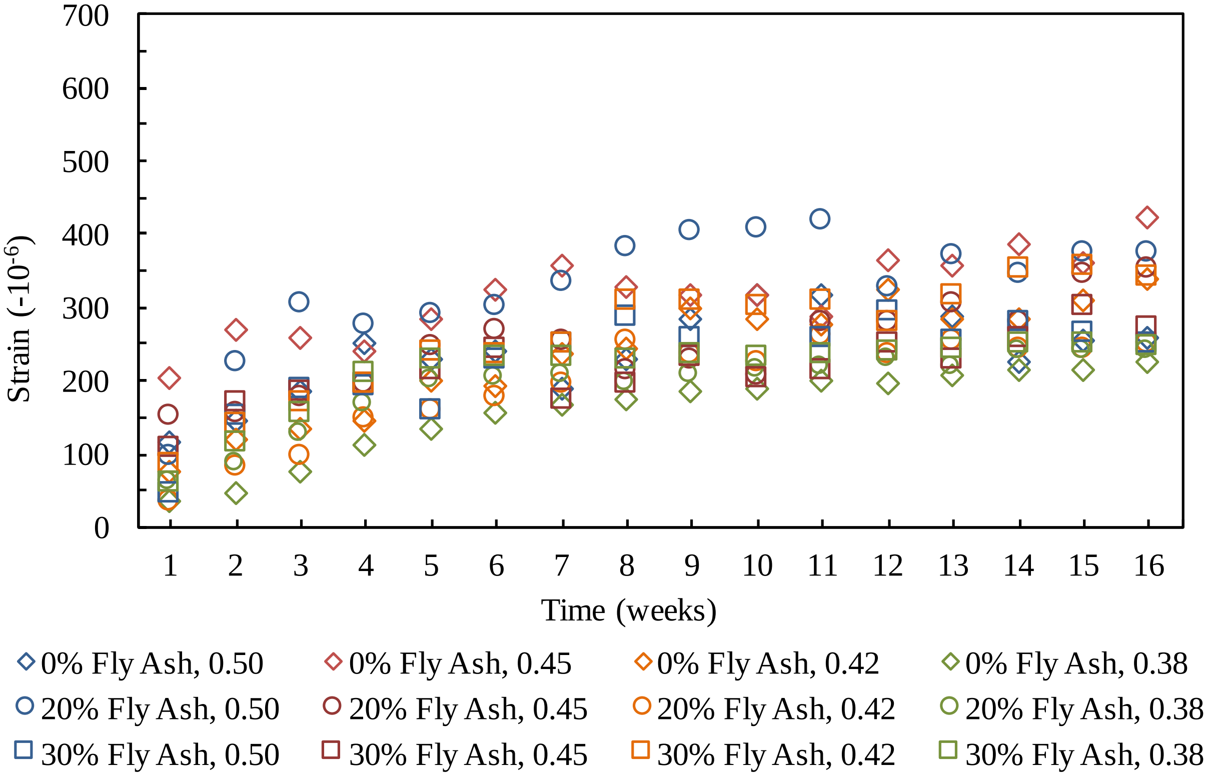


Figure 4.4 – Drying Shrinkage of 564 lb/yd^3 Cementitious Material PCCP Mixtures

As shown in Figure 4.4, while shrinkage data is scattered throughout the range of values, several patterns are evident within data sets of the same w/cm. On average, mixtures with a w/cm of 0.38 display lower values of strain, with the zero fly ash content mixture consistently have the lowest shrinkage values of the data presented in Figure 4. Mixtures with a w/cm of 0.42 are concentrated within the middle of this data group. Additionally, shrinkage values increase almost linearly between week 1 and week 9 before leveling off and stabilizing in week 10 and following. All mixtures remained below 28-day, 90-day, and 16-week unrestrained shrinkage limits recommended by previous research (Mokarem 2002, Babaei and Purvis 1996).

Next, Figure 4. presents unrestrained dry shrinkage data for mixtures containing 517 lb/yd^3 cementitious material. This figure is formatted exactly the same as Figure 4.. Within this data set, the first instance of missing data appears – the mixture containing 0% fly ash replacement and a w/cm of 0.38 was unable to mix properly.

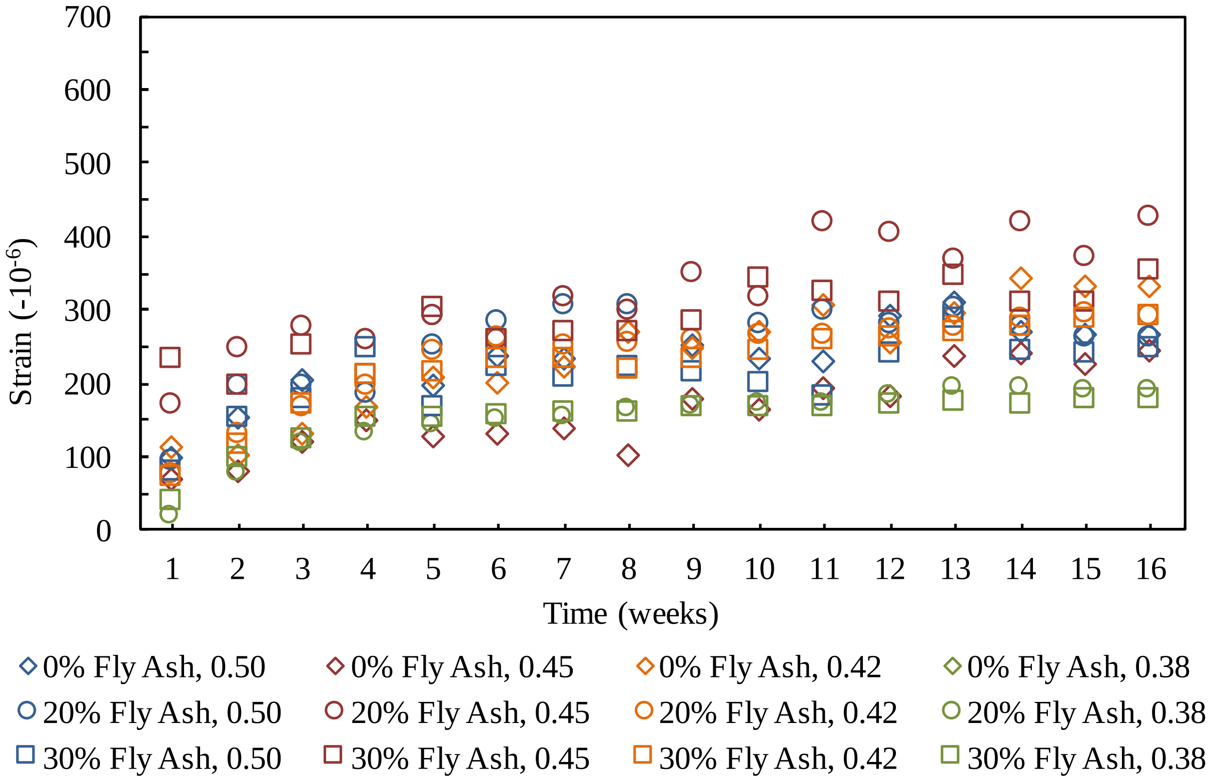


Figure 4.5 – Drying Shrinkage of 517 lb/yd^3 Cementitious Material PCCP Mixtures

Figure 4.5 again shows similar patters to Figure 4.4. While shrinkage data is scattered throughout the range of values, on average, mixtures with a w/cm of 0.38 display lower values of strain, with the mixtures containing 20% and 30% fly ash replacement consistently measuring lower shrinkage values. Mixtures with a w/cm of 0.42 are again concentrated within the middle of this data group and show little variance between different fly ash replacement percentages. For this group of data, most mixtures are shown stabilizing in week 6. All mixtures remained below 28-day, 90-day, and 16-week unrestrained shrinkage limits recommended by previous research (Mokarem 2002, Babaei and Purvis 1996).

Finally, Figure 4.6 displays data from mixtures with a cementitious material content of 470 lb/yd^3. This figure is formatted the same as the two preceding figures, and no data is available for mixtures with a w/cm of 0.38.

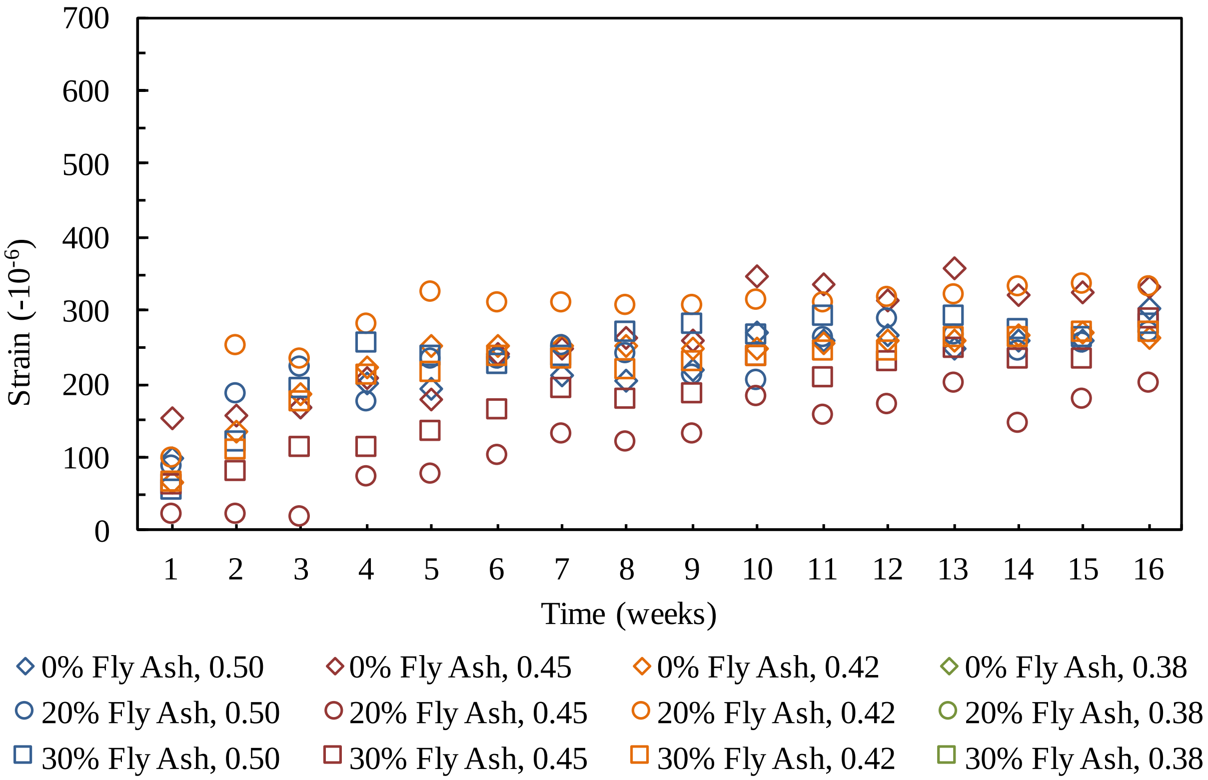
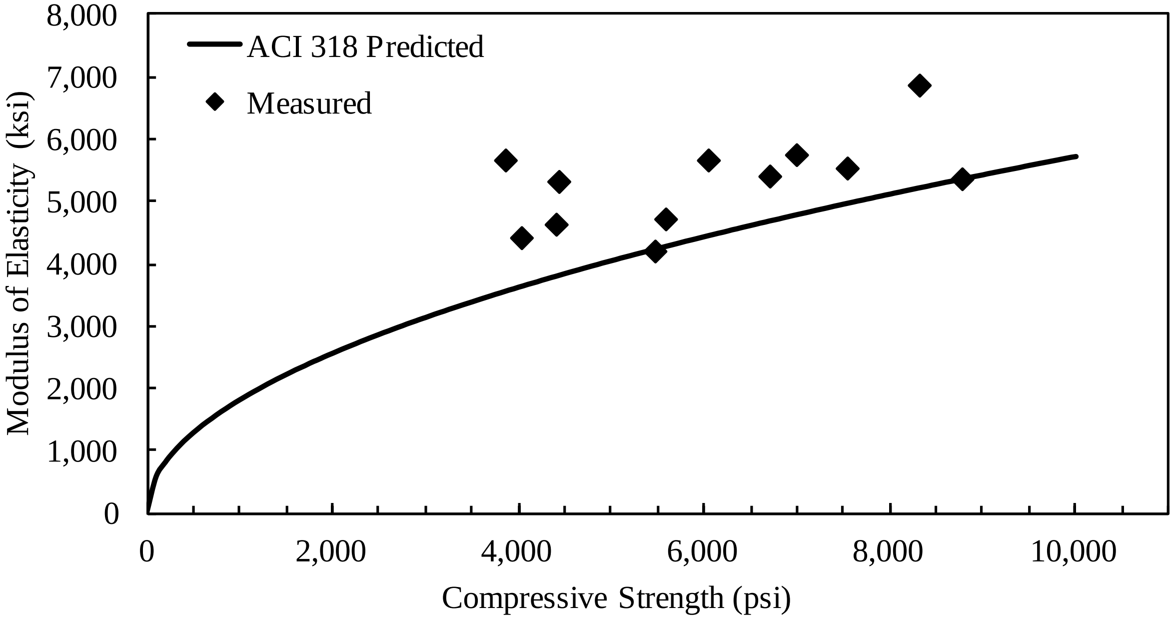


Figure 4.6 – Drying Shrinkage of 470 lb/yd^3 Cementitious Material PCCP Mixtures

The data presented in Figure 4.6 shows fewer patterns than previous data sets. The mixture with 20% fly ash replacement and a w/cm of 0.45 consistently shows the lowest shrinkage values of this group and mixtures of all cementitious material contents. For this group of data, there is little shrinkage after week 7. Consistent with all previous data groups, all mixtures remained below 28-day, 90-day, and 16-week unrestrained shrinkage limits recommended by previous research (Mokarem 2002, Babaei and Purvis 1996).

4.2.3. Static Modulus of Elasticity

Static modulus of elasticity data is presented in Figure 4.7



with the predicted modulus of elasticity from ACI 318-14 (ACI Comittee 318 2014). Static modulus of elasticity was measured at 7 days and 28 days for six mixtures. As previously mentioned, the modulus of elasticity was measured for only the best three performing mixtures and the worst three performing mixtures in relation to compressive strength. As shown in Figure 4., for most mixtures, the equation provided by ACI 318-14 is slightly conservative. One data point falls slightly below predicted modulus of elasticity, while the remaining mixtures are either at or just above the equation's prediction. This data show that mixtures with various cementitious material contents, fly ash replacement percentages, and w/cms will achieve or exceed expected values of modulus of elasticity.

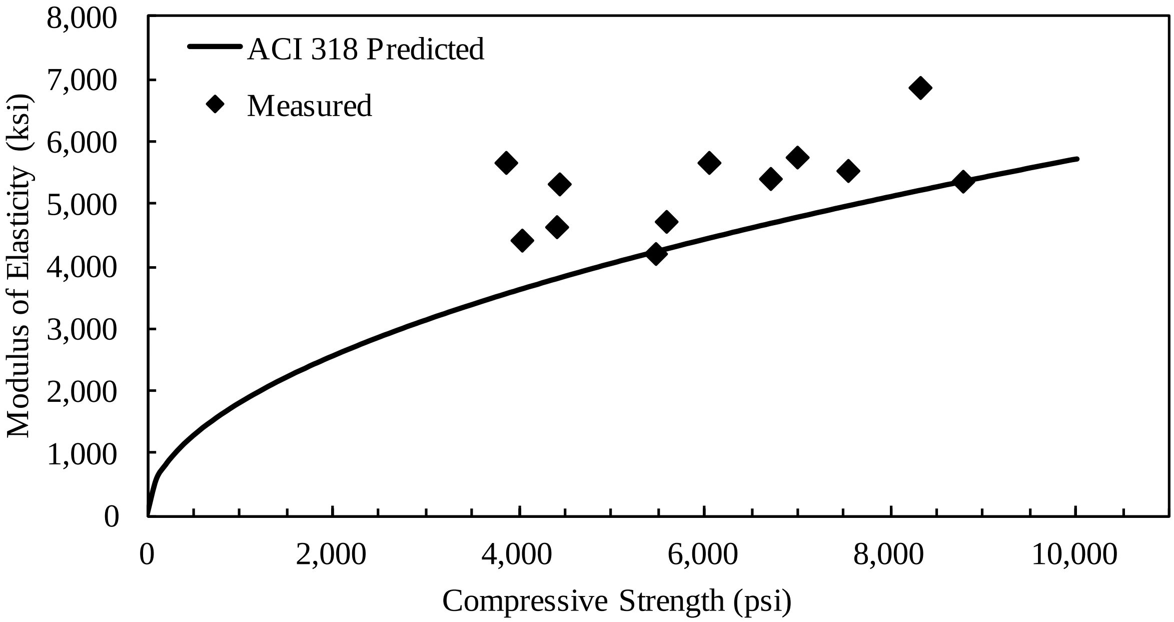


Figure 4.7 – ACI 318 Predicted vs Measured Modulus of Elasticity for PCCP Mixtures

4.3. Results for the Class S Mixtures

The results for the Class S mixtures are presented and discussed in the following sections. The testing matrix and the mixture proportions for the Class S mixtures were discussed in Chapter 3.

4.3.1. Compressive Strength

Figure 4.8 presents the compressive strength of Class S mixtures having cement contents of 611, 564, and 517 lb/yd^3. As a reminder, Class S mixtures only contain entrapped air. At each cement content, the four bars represent the four ages at which the concrete was tested. All concrete mixtures achieved 3500 psi, the specified strength by AHTD at 28 days. As indicated in Figure 4.8, for a given w/cm, increasing the cement content increases the compressive strength. For example, as the cement content was increased from 517 to 611 lb/yd^3 for mixtures at a w/cm of 0.49, the compressive strength at 28 day increased from 6700 to 7510 psi. Figure

4.8 also shows the effect of water content on the workability of the mixtures. Two mixtures, the 564 lb/yd^3 and 517 lb/yd^3 at a w/cm, would not mix. This is a function of the lower w/cm and the lower cement content which then reduces the overall water content.

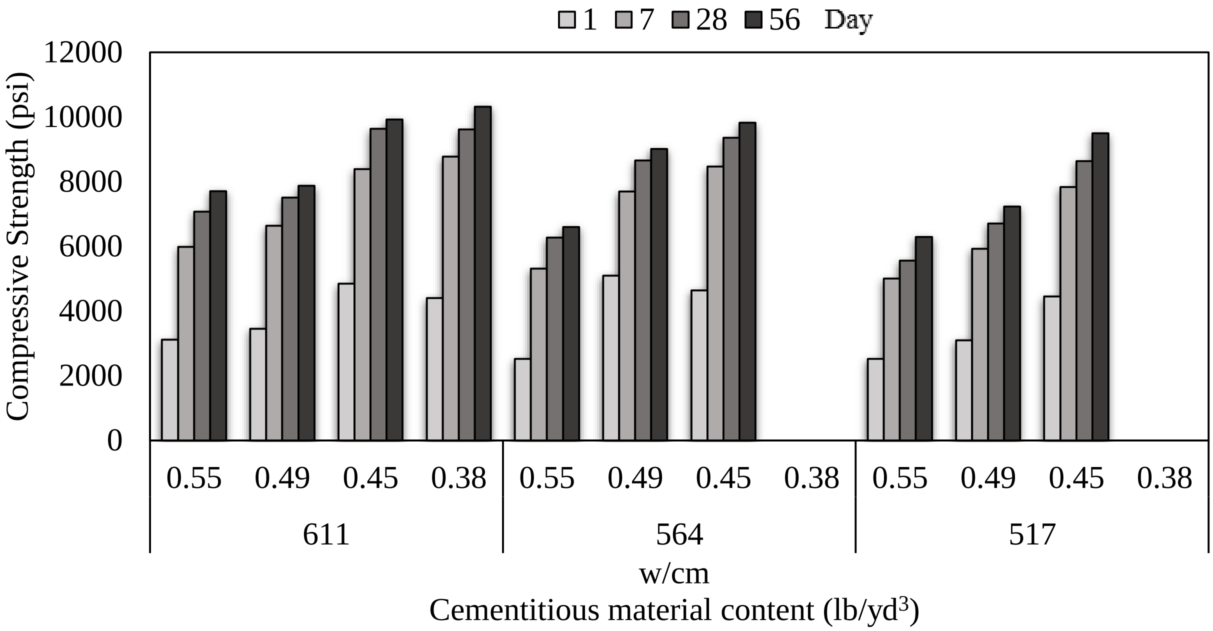


Figure 4.8 – Compressive Strength of Class S Mixtures Containing Only Cement

Figures 4.9, 4.10, and 4.11 show the effect of fly ash on concrete mixtures with cementitious material contents of 611, 564, and 517 lb/yd^3 respectively. It is clear that fly ash replacement affects the compressive strength at early ages of 1 and 7 days. This reduction in strength as fly ash content increases is shown in mixtures having cementitious material content of 611 lb/yd^3 and a w/cm of 0.49. As can been seen in Figure 4.9, the compressive strength at 1 day decreased from 3450 psi to 1810 psi as fly ash content increased from 0 to 30%. This reduction in strength at early ages is expected due to slow reaction of fly ash. The difference in early age strength depends on the fly ash content (Thomas 2007). Also, the difference in strength gain of the mixtures without fly ash compared to the mixtures with fly ash maybe caused by the heat of hydration degree. A rise in concrete temperature may lead to microcracks in the interfacial transition zone (ITZ), which eventually lowers the ultimate strength, but concrete with fly ash tends to have lower temperatures during hydration which prevents the propagation of microcracks (Longarini 2014). As shown in Figures 4.9, 4.10, and 4.11, for a given cementitious material content and w/cm, the compressive strength of concrete mixtures is similar or higher as the fly ash content increased. For example, for mixtures at a w/cm of 0.49 and cementitious content of 517 lb/yd3, the compressive strength of 28 days increased from 6700 to 7990 psi as fly ash content increased from 0 to 30 percent. The addition of fly ash up to 30% affected the compressive strength of concrete mixtures at 7 days; however, the compressive strength at 7 days achieved 3500 psi for all concrete mixtures even with the high w/cm of 0.55. At 1-day compressive strength, there was a significant reduction in strength when fly ash content increased from 0 to 30%. For example, for mixtures with cementitious content of 611 lb/yd^3 at a w/cm of 0.55, the compressive strength decreased from 3110 psi to 1600 psi as fly ash content increased from 0% to 30 %.

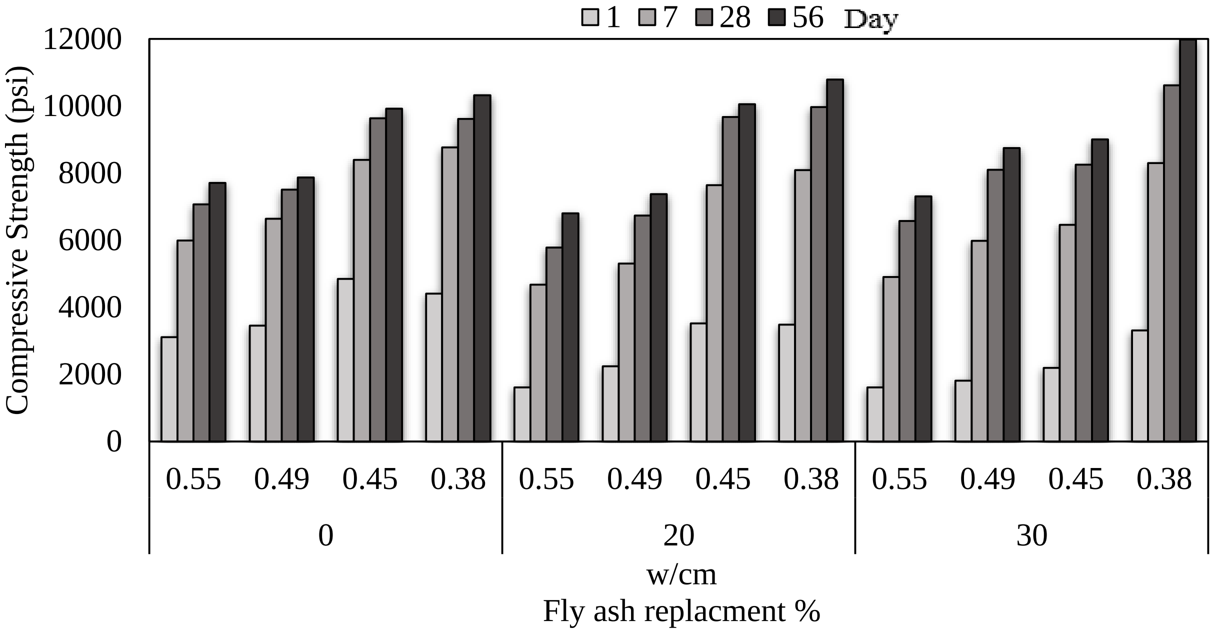


Figure 4.9 – Compressive strength of Class S Mixtures containing 611 lb/yd^3 of Cementitious Material

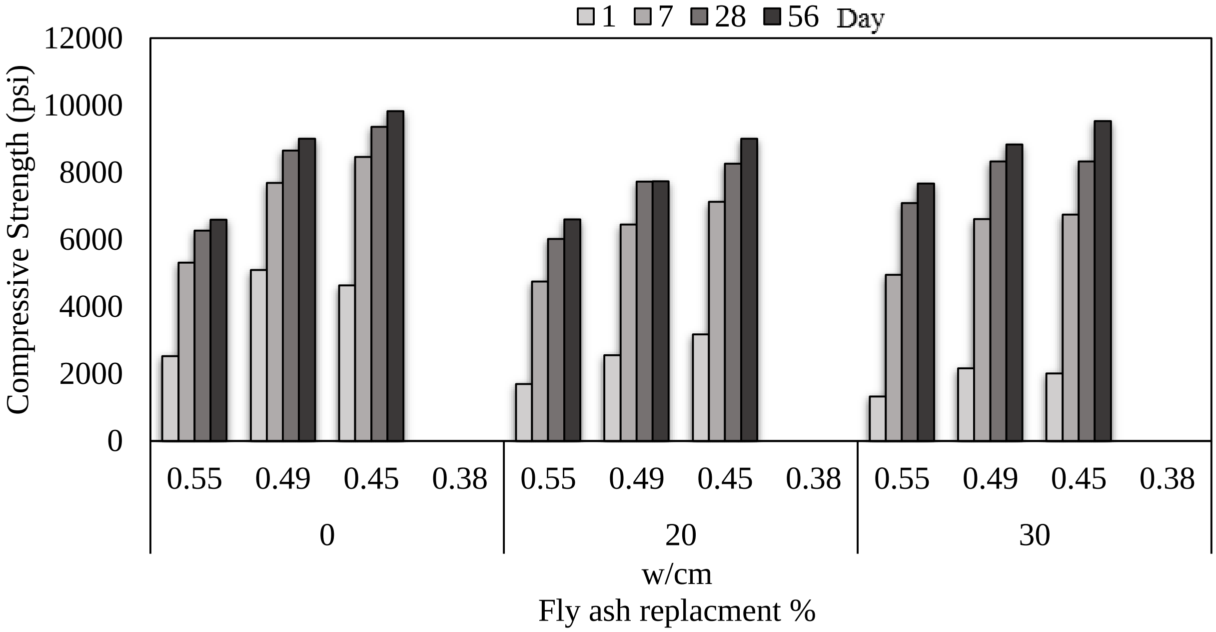


Figure 4.10 – Compressive Strength of Class S Mixtures Containing 564 lb/yd^3 of Cementitious Material

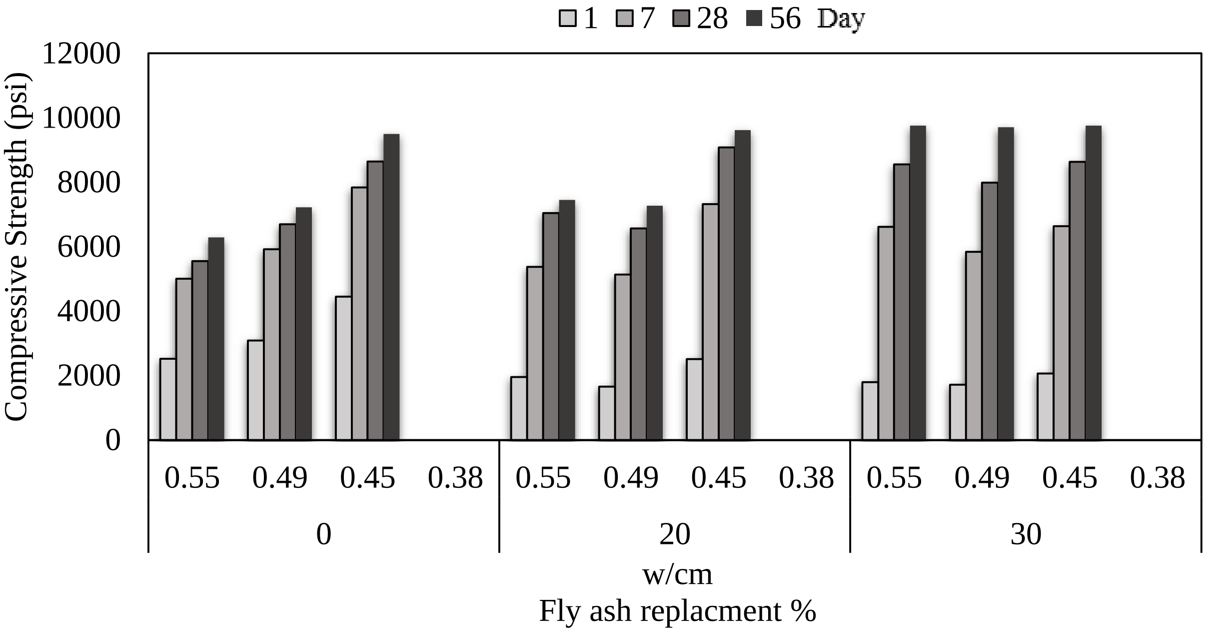


Figure 4.11 – Compressive Strength of Class S Mixtures Containing 517 lb/yd^3 of Cementitious Material

All concrete mixtures tested in this research for compressive strength meet the 28-day required strength by ARDOT of 3500 psi. Based on compressive strength only, there is no risk if the cementitious content is reduced from 611 lb/yd^3, the minimum cementitious content assigned by AHTD, to 517 lb/yd^3. Even though adding fly ash up to 30% reduced the early age strength of all concrete mixtures, the compressive strength at 28 days was similar or higher for mixtures with fly ash compared to the mixtures without fly ash. To observe the behavior of concrete mixtures having higher than expected w/cm, compressive strength was tested for concrete mixtures with 0.55 w/cm. Even at a w/cm of 0.55, all mixtures met the required 28-day compressive strength of 3500. The previous recommendations do not apply for concrete mixtures with cementitious content of 564 lb/yd^3 and 517 lb/yd^3 at a w/cm of 0.38 because they were unable to be batched.

4.3.2. Unrestrained Drying Shrinkage

The drying shrinkage results are discussed in the following sections. The drying shrinkage (ASTM C157) was measured over a period of sixteen weeks. Every week, three prisms were measured and the results discussed in this section represent the average of three prisms. In the following sections, the effect of cement content on drying shrinkage will first be discussed then followed by a discussion on the effect of fly ash on drying shrinkage.

Figure 4.12, 4.13, and 4.14 show concrete strain (drying shrinkage) for mixtures having cement contents of 611, 564, and 517 lb/yd^3 respectively. The 16-week drying shrinkage ranged from approximately 100 to about 350x10^{-6} microstrains for all w/cm ratios and cement contents. When cement content decreases, the strain of mixtures over a period of 16 weeks is quite similar. Wassermann et al. (2009) stated that cement content has a small influence on shrinkage, and the results from this research support that finding. The reason why the strain is similar for all mixtures is because of the high amount of coarse aggregate content of 1800 lb/yd^3. Both increasing aggregate size and content reduces shrinkage due to the less paste needed when increasing the aggregate content (Rao 2001). Additionally, the coarse aggregate helps restrain the paste from shrinking.

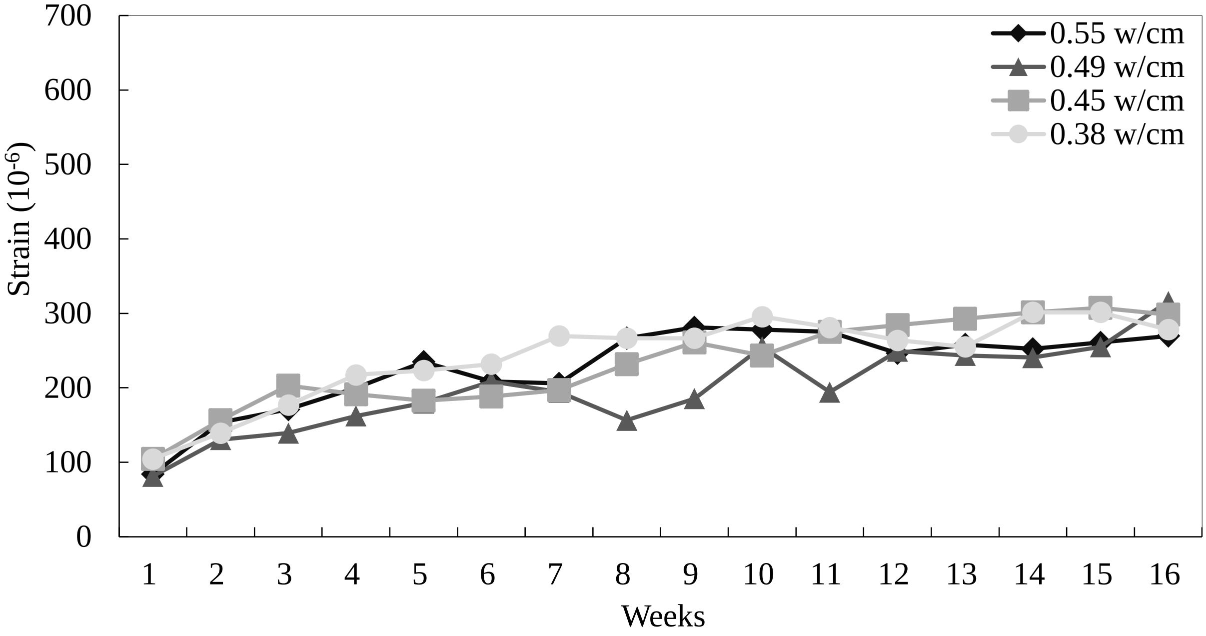


Figure 4.12 – Drying Shrinkage of Class S Mixtures with 611 lb/yd^3 and 0% Fly Ash

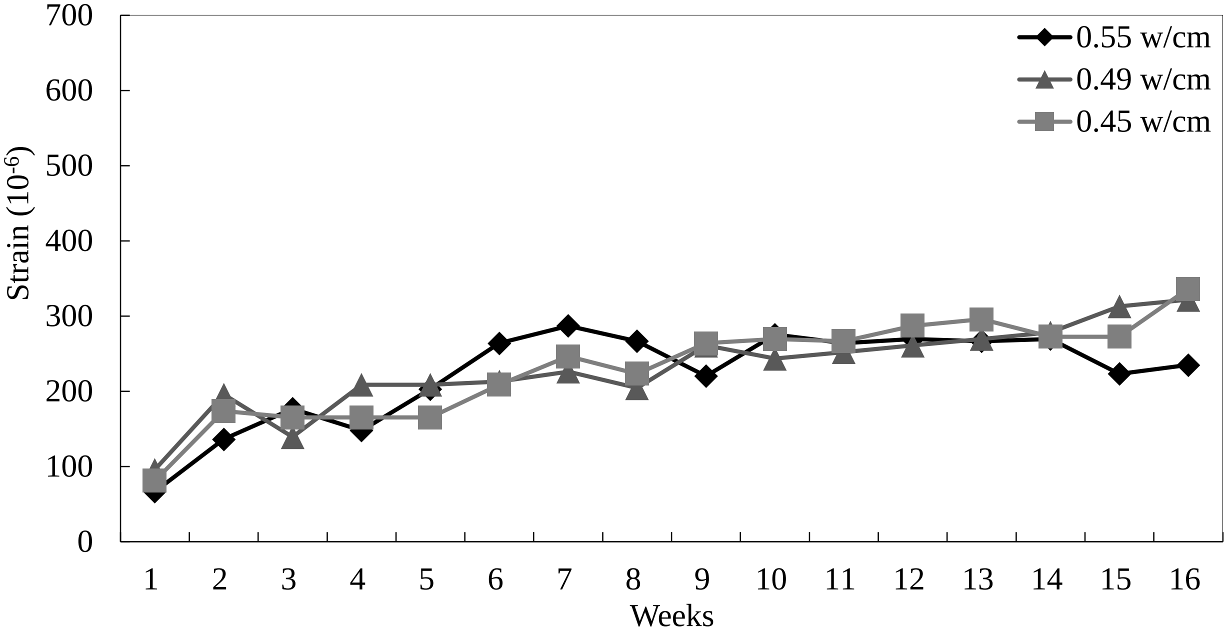


Figure 4.13 – Drying Shrinkage Class S Mixtures with 564 lb/yd^3 and 0% Fly Ash

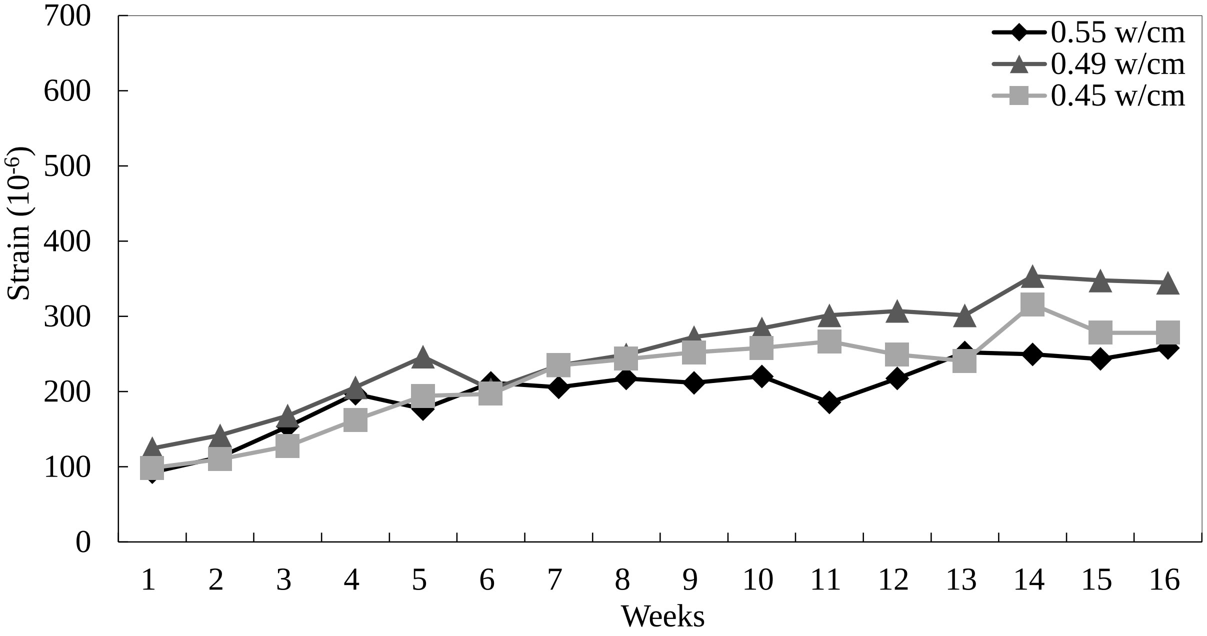


Figure 4.14 – Drying Shrinkage of Class S Mixtures with 517 lb/yd^3 and 0% Fly Ash

Figures 4.15, 4.16, and 4.17 illustrate the shrinkage strain of concrete mixtures having cementitious material content of 611, 564, 517 lb/yd^3 with 20% fly ash respectively. Adding 20% fly ash did not affect the strain of the mixtures. As previously mentioned, having a high amount of coarse aggregate is the reason why there is no considerable change in drying shrinkage for all the concrete mixtures. At a fly ash content of 30%, the range of drying shrinkage over a period of 16 weeks remained within the 100 to about 350x10^{-6} microstrains as can be seen in Figures 4.18, 4.19, and 4.20.

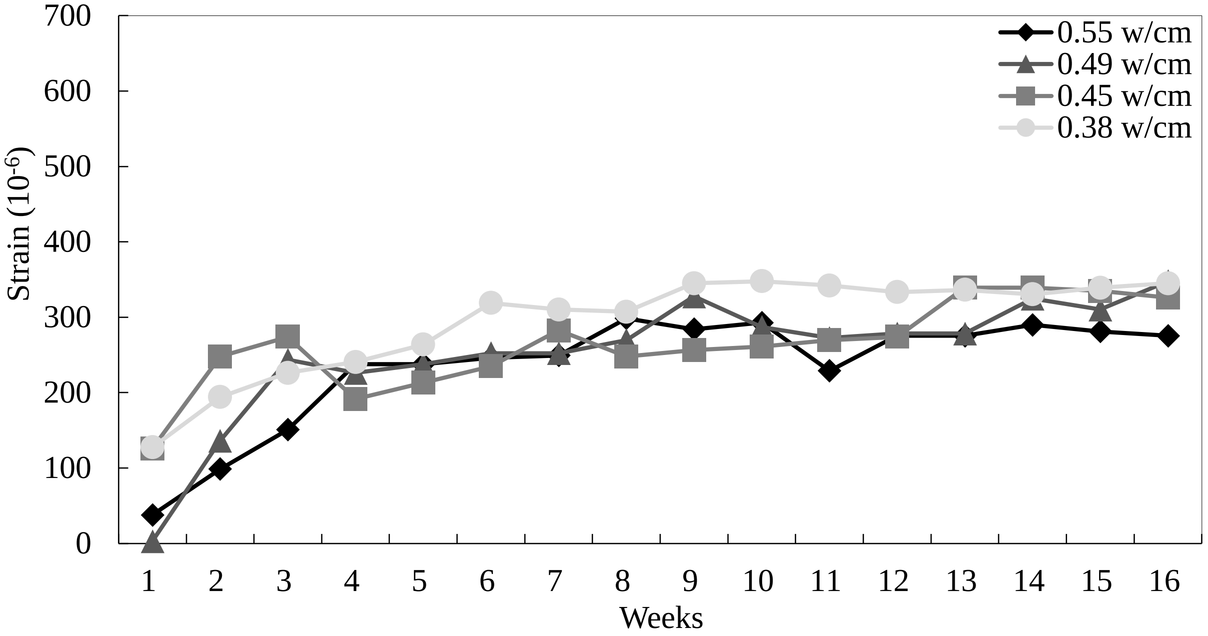


Figure 4.15 – Drying Shrinkage of Class S Mixtures with 611 lb/yd^3 and 20% Fly Ash

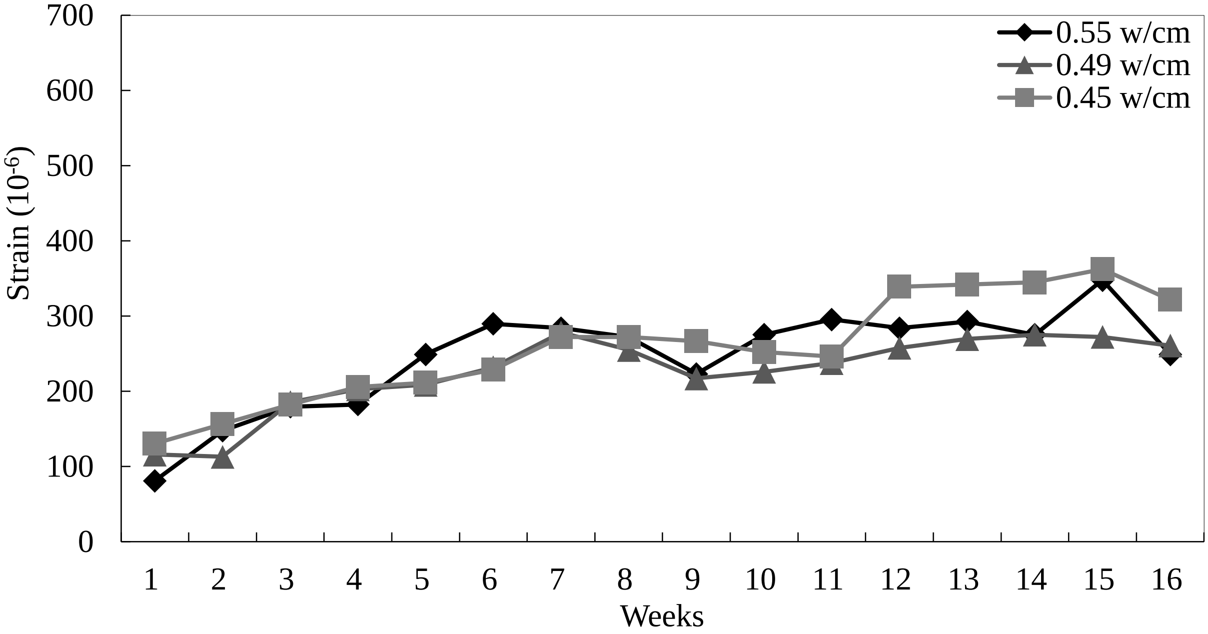


Figure 4.16 – Drying Shrinkage of Class S Mixtures with 564 lb/yd^3 and 20% Fly Ash

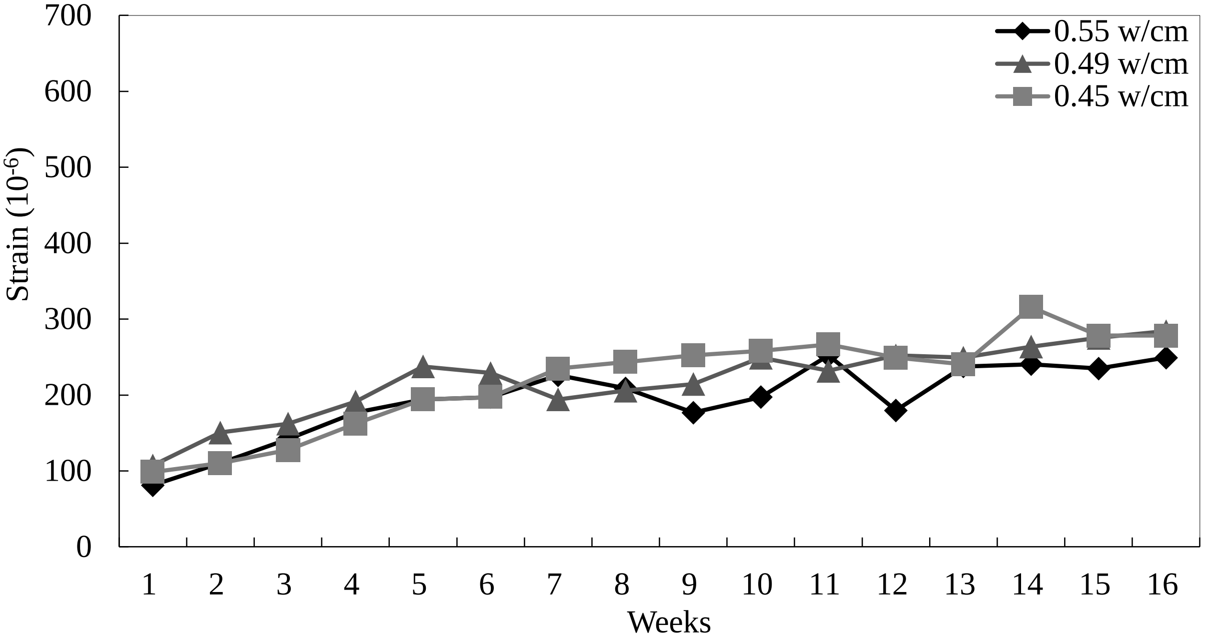


Figure 4.17 – Drying Shrinkage of Class S Mixtures with 517 lb/yd^3 and 20% Fly Ash

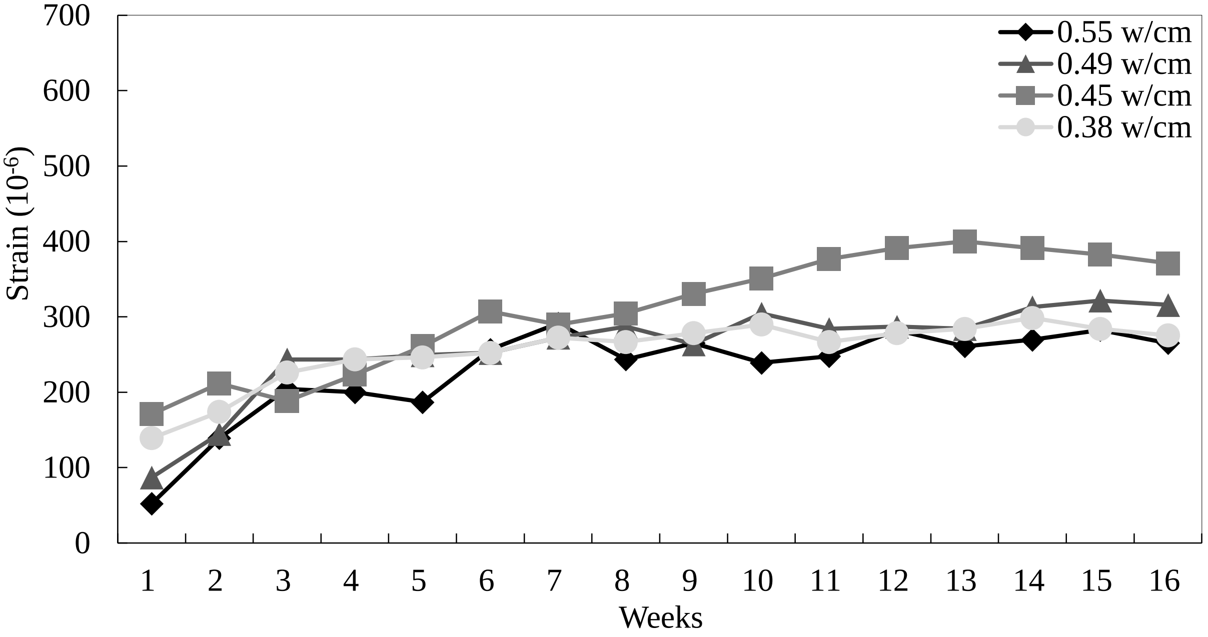


Figure 4.18 – Drying Shrinkage of Class S Mixtures with 611 lb/yd^3 and 30% Fly Ash

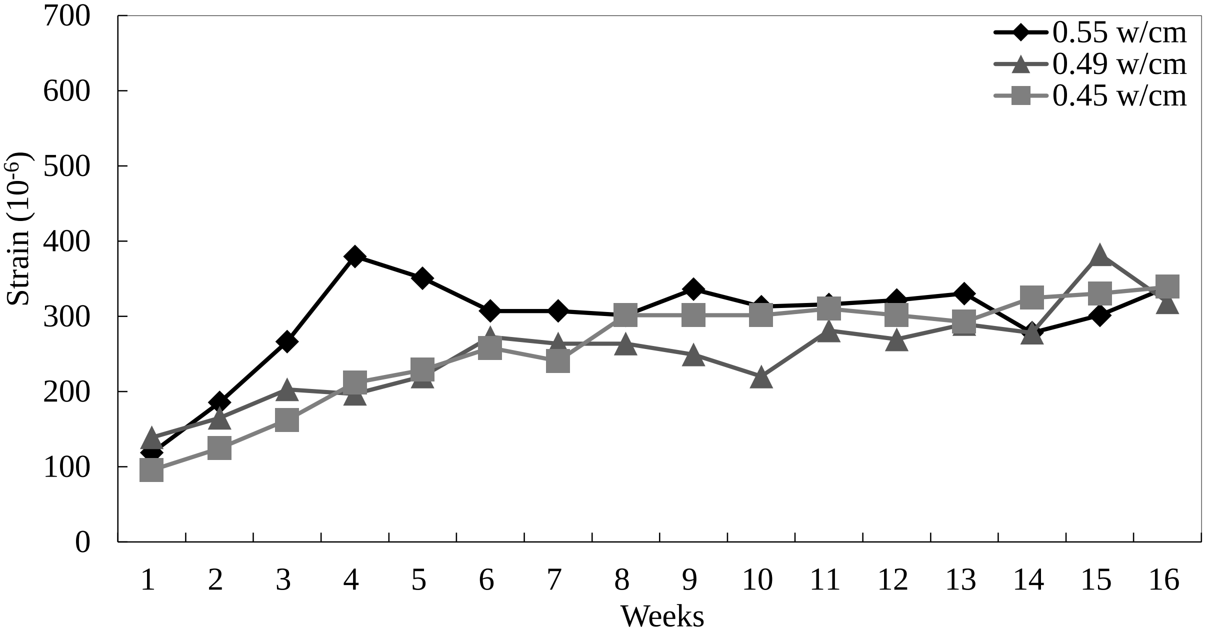


Figure 4.19 – Drying Shrinkage of Class S Mixture with 564 lb/yd^3 and 30% Fly Ash

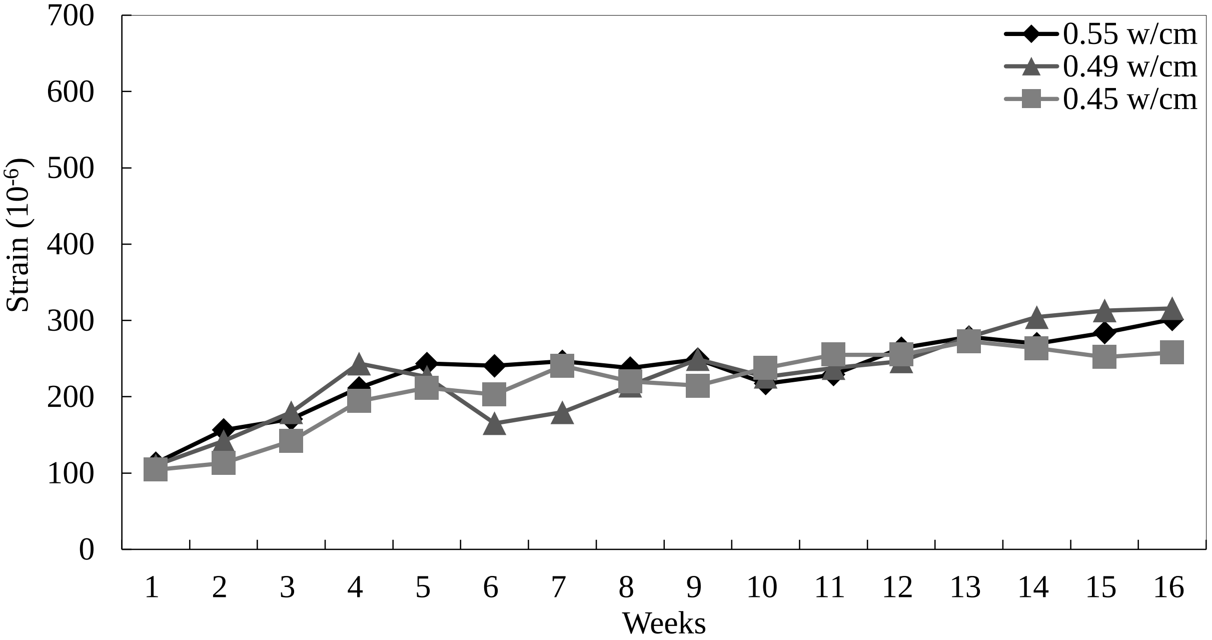


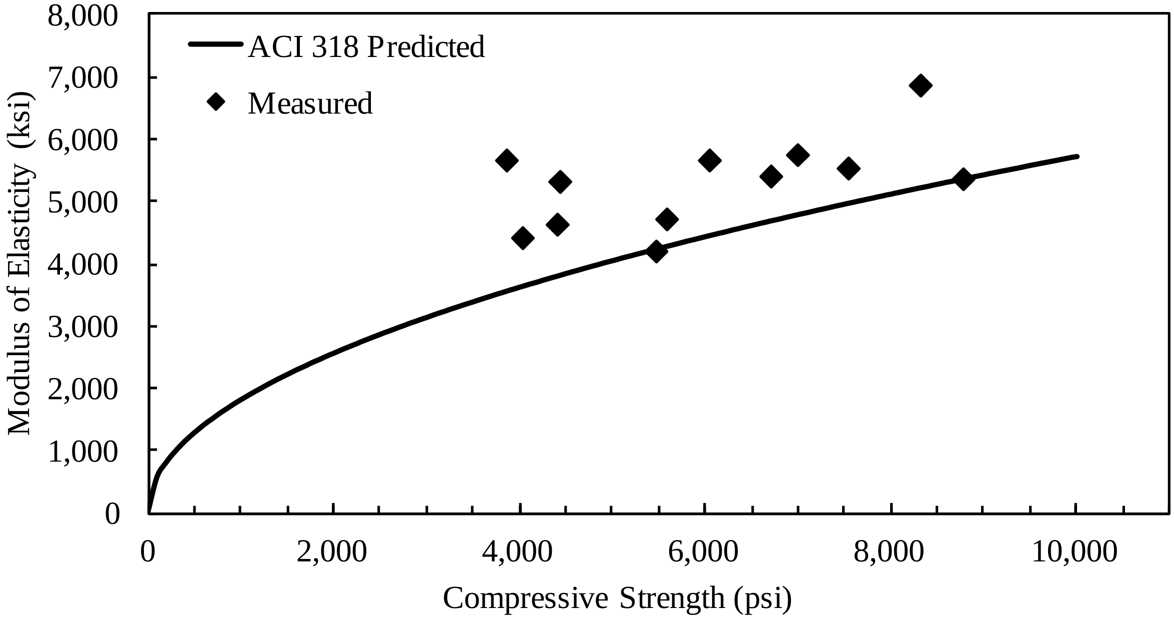
Figure 4.20 – Drying Shrinkage of Class S Mixtures with 517 lb/yd^3 and 30% Fly Ash

Babaei et al (1995) states that shrinkage cracking may be reduced by limiting the 4 months drying shrinkage to 700 x10^{-6} microstrains or less. As shown in figures 4.12 through

4.14, which are the cement only mixtures, the highest strain value of 16 weeks of age is approximately 350x10^{-6} microstrains. Therefore, reducing the cement content from 611 to 517 lb/yd^3 did not significantly change the shrinkage values, and it is expected that the reduction in cement content would not affect cracking due to drying shrinkage. Also, replacing 30% of the cement with fly ash did affect the drying shrinkage of the mixtures. Regarding w/cm, there is no clear effect on the magnitude of drying shrinkage when the w/cm decreased from 0.55 to 0.38. In addition to the high course aggregate content discussed above, research has shown that for a given coarse aggregate content, the w/cm ratio does not clearly influence drying shrinkage (Deshpande et al. 2007).

4.3.3. Static Modulus of Elasticity

Static modulus of elasticity data are presented in Figure 4.21 with the predicted modulus of elasticity from ACI 318-14 (ACI Comittee 318 2014) and AASHTO. Static modulus of elasticity was measured at 7 days and 28 days for six mixtures. As previously mentioned, the modulus of elasticity was measured for only the best three performing



mixtures and the worst three performing mixtures in relation to compressive strength. As shown in Figure 4., both equations provide a reasonable estimate for the modulus of elasticity. Approximately, half of the mixtures plotted above the prediction equations and half plotted below the equations. One reason for why there were more mixture plotting below the line is the higher strength of the Class S mixtures versus that of the PCCP mixtures. There were Class S mixtures which had a compressive strength of 10,000 psi and researchers have found that the ACI and AASHTO equations overestimate modulus of elasticity for high strength concrete.

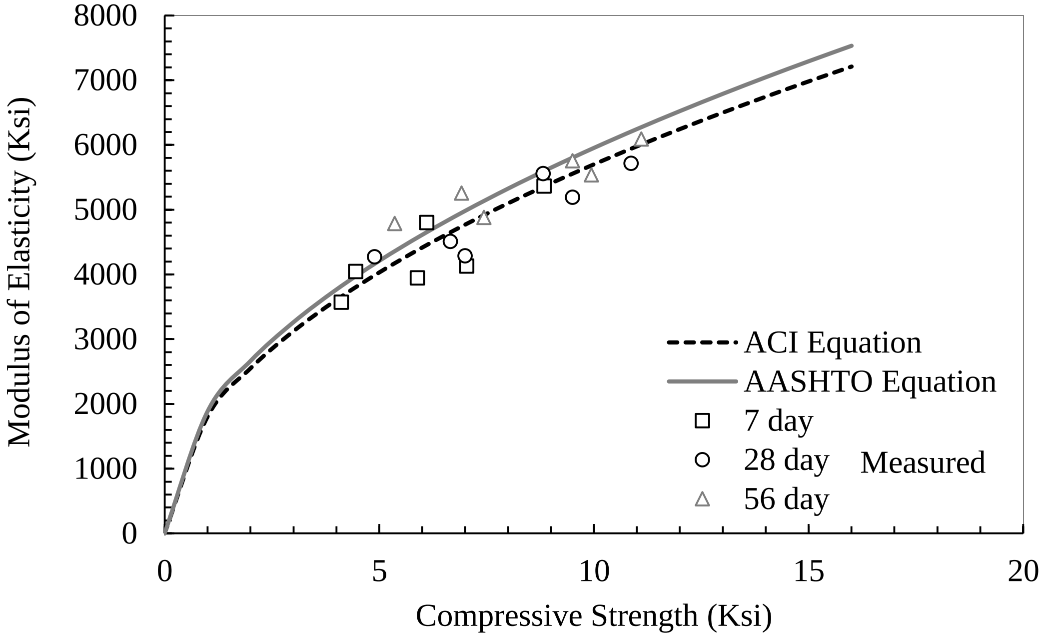


Figure 4.21- Predicted vs. Measured Modulus of Elasticity for Class S Mixtures

4.4. Results for the Class S(AE) Mixtures

The results for the Class S(AE) mixtures are presented and discussed in the following sections. The testing matrix and the mixture proportions for the Class S(AE) mixtures were discussed in Chapter 3.

4.4.1. Compressive Strength

For class S(AE) concrete, ARDOT requires a minimum 28-day compressive strength of 4000 psi, which was achieved by all mixes. Each batch had three cylinders tested at 1, 7, 28, and 56 days. Thus, all of strength values referenced in this report represent the average of 3 specimens. The following is the data collected and how it correlates to some of the focused aspects of this study.

As specified prior, an increase in cement content often relates to an increase in compressive strength. However, within this study the increase of cementitious material from 517 to 564 to 611 lb/yd^3 produced near equivalent compressive strength values, as can be seen in Figure 4.22. All the initial mixes met 4000 psi by 28 days, however about 78% reached this by 7 days. Additionally, it is important to note that even the weakest mix, the 0.50 w/cm 517 lb/yd^3 30% FA mixture, met required strength by 28 days. Based on this data, at a cementitious content of 517 lb/yd^{3,} and a w/cm above ARDOT standards, the 4000-psi compressive strength requirement can be met.

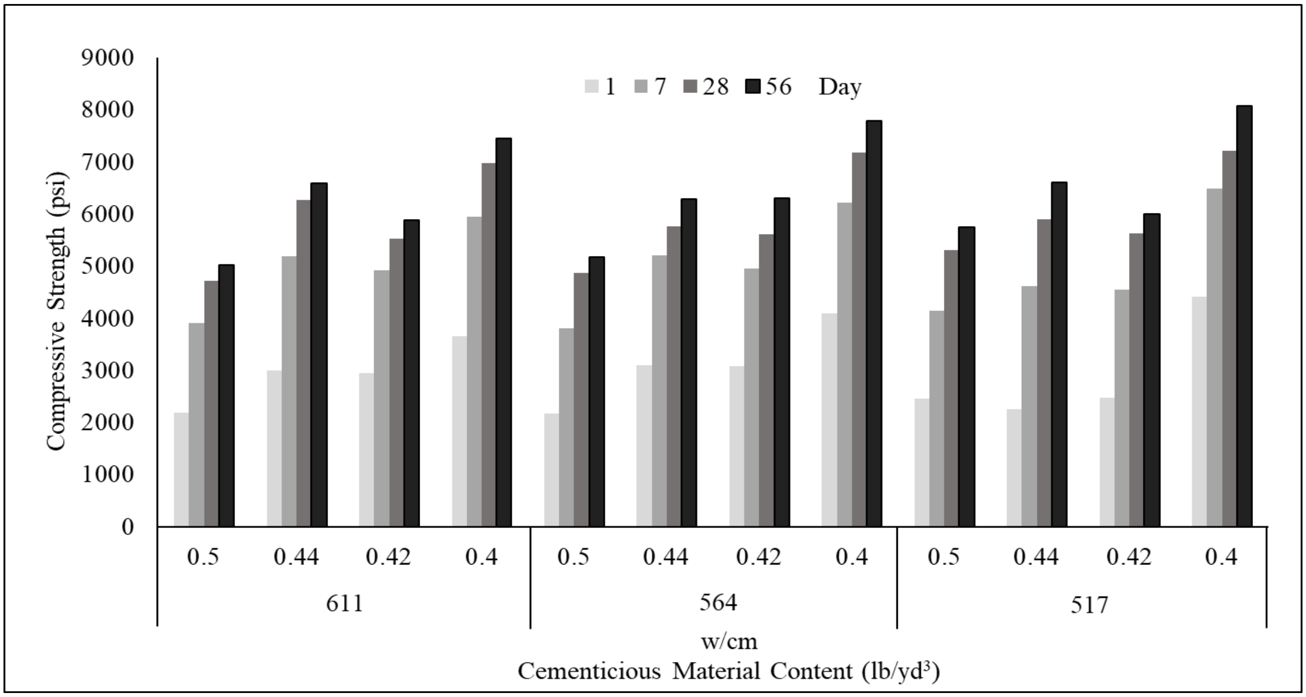


Figure 4.22 – Compressive Strength of Class S(AE) Mixtures Containing Cement Only

Fly ash plays a significant role in ultimate strength values, but for this study focused on is effects on compressive strength and drying shrinkage. Due to the later occurring pozzolanic reaction of fly ash, many fly ash mixes gain strength more slowly than non-fly ash mixes, but gain slightly greater strength overall due to the continued reactions. Thus, when comparing it to a cement only mix, the fly ash mix often has moderate to substantially less strength at 1 and 7 days, as can be viewed graphically in Figures 4.23, 4.24, and 4.25. Additionally, it follows from this that greater amounts of fly ash reduce early age strength development (Thomas, 2007). This is especially true for lower cementitious contents, such as the 517 lb/yd^3 mix, as these mixes already have reduced cement and portions of the mixtures are replaced with a less reactive material. In an almost opposite role, looking later into the life of concrete, this same slower reacting fly ash often resulted in equal to slightly greater strength than mixes with little to no fly ash at similar water cement ratios.

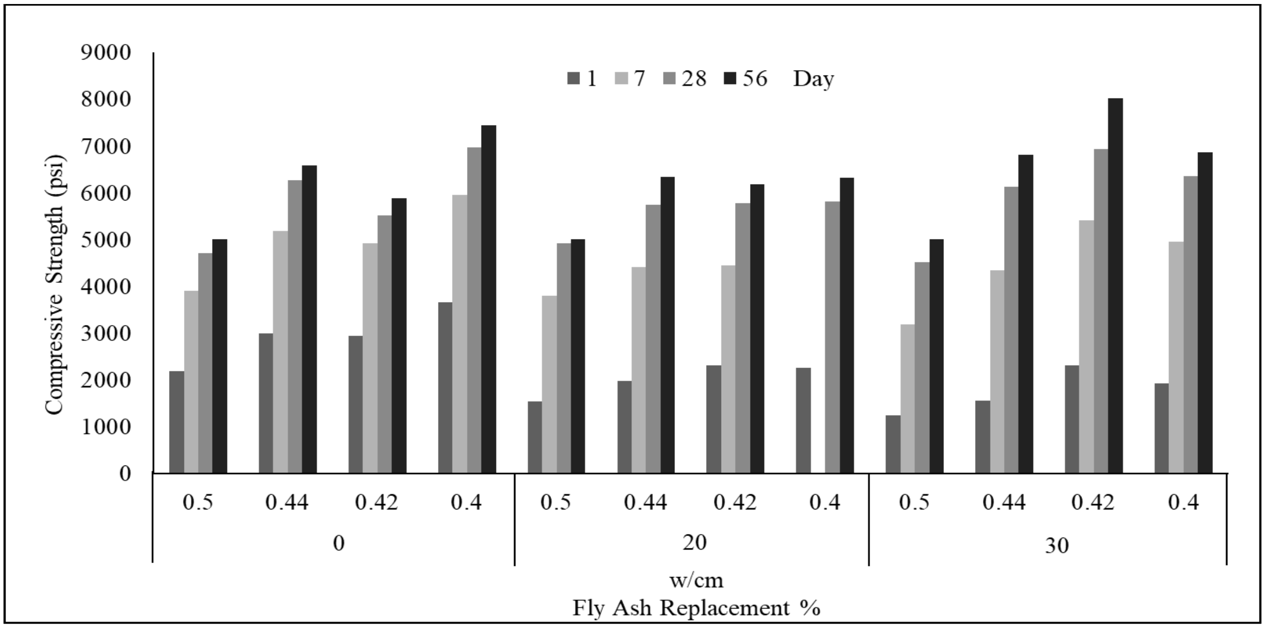


Figure 4.23 – Compressive Strength of Class S(AE) Mixtures with 611 lb/yd^3 of Cementitious Material

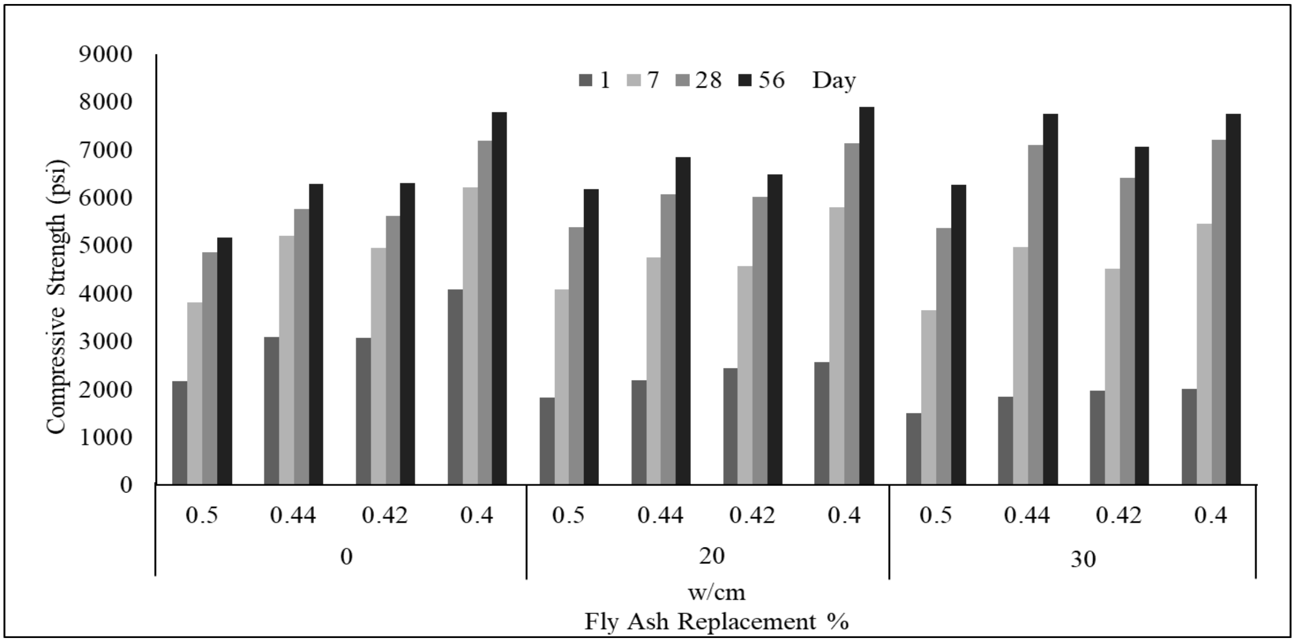


Figure 4.24 – Compressive Strength of Class S(AE) Mixtures with 564 lb/yd^3 of Cementitious Material

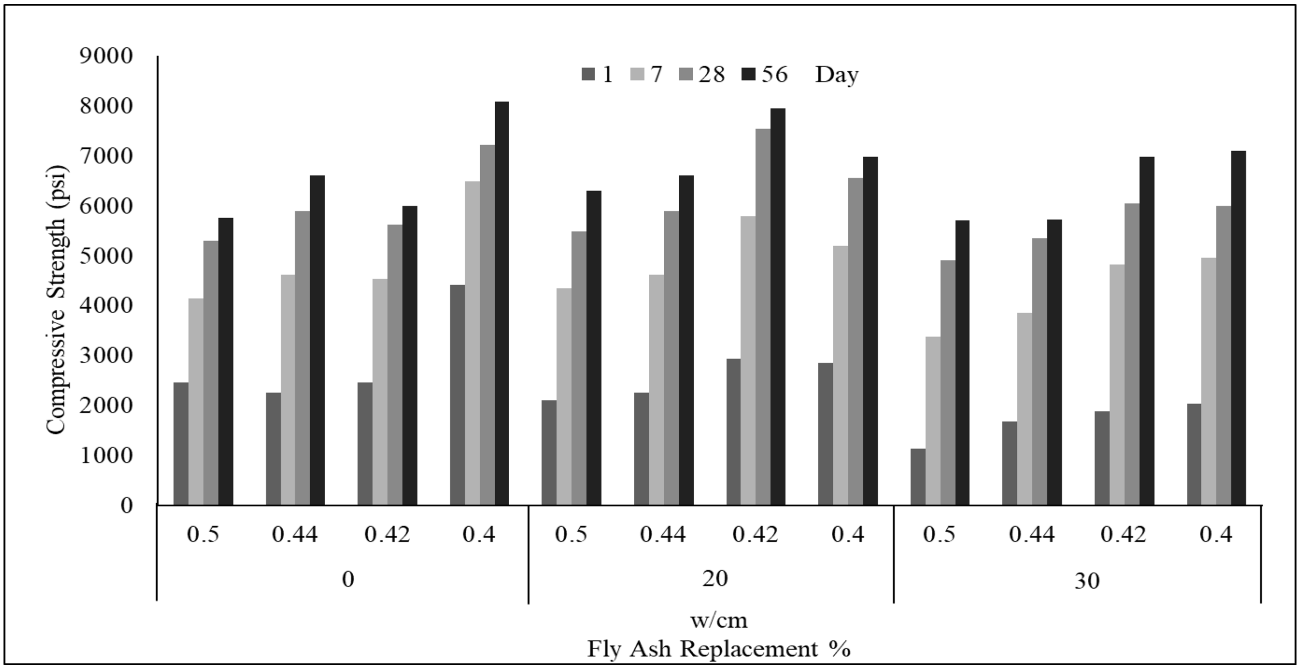


Figure 4.25 – Compressive Strength of Class S(AE) Mixtures with 517 lb/yd^3 of Cementitious Material

The results showed that the ARDOT standards of 611 lb/yd^3 of cementitious material could be reduced to 564 or 517 lb/yd^3 for Class S(AE) concrete since all the mixtures exceeded the minimum compressive strength of 4000 psi by 28 days. This includes the cases of fly ash replacement mixes with 0, 20, and even 30%. Though the mixes with higher fly ash contents did show lower early strength, by 28 days they developed sufficient strength. Considering this, it seems that the ARDOT standard of a maximum 20% fly ash could be increased to 30% based on compressive strength tests. Additionally, to further cement these findings it is important to note that even in the case of a w/cm ratio of 0.50, well above the ARDOT max of 0.44, all mixes still met the requirements. In the end, the strength data show that in many cases current standards overdesign, and reduction of cement is both plausible and helpful monetarily and environmentally.

4.4.2. Unrestrained Drying Shrinkage

Figures 4.26, 4.27, and 4.28 represent findings for the cement only, Class S(AE) mixtures for all w/cms 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/yd^3 caused an approximate decrease in microstrain of 100 x 10^{-6}. As the w/cm decreased from the max of 0.50 to the minimum of 0.40, there was an approximate decrease of 50 x 10^{-6} microstrain. The similarity in strain is likely attributed to the high amount of coarse aggregate content, 1800 lb/yd^3, in each mix. By the end of 16 weeks, many of the measurements for these mixes read near 500 x 10^{-6} microstrain.

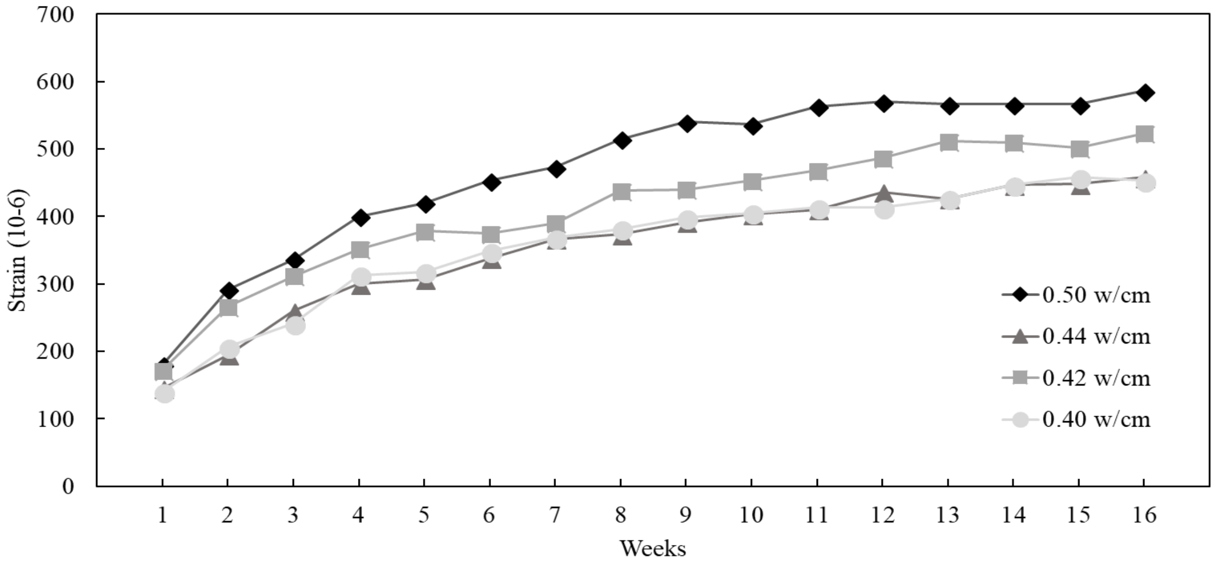


Figure 4.26 – Class S(AE) Drying Shrinkage for Mixtures with 611 lb/yd^3 and 0% Fly Ash

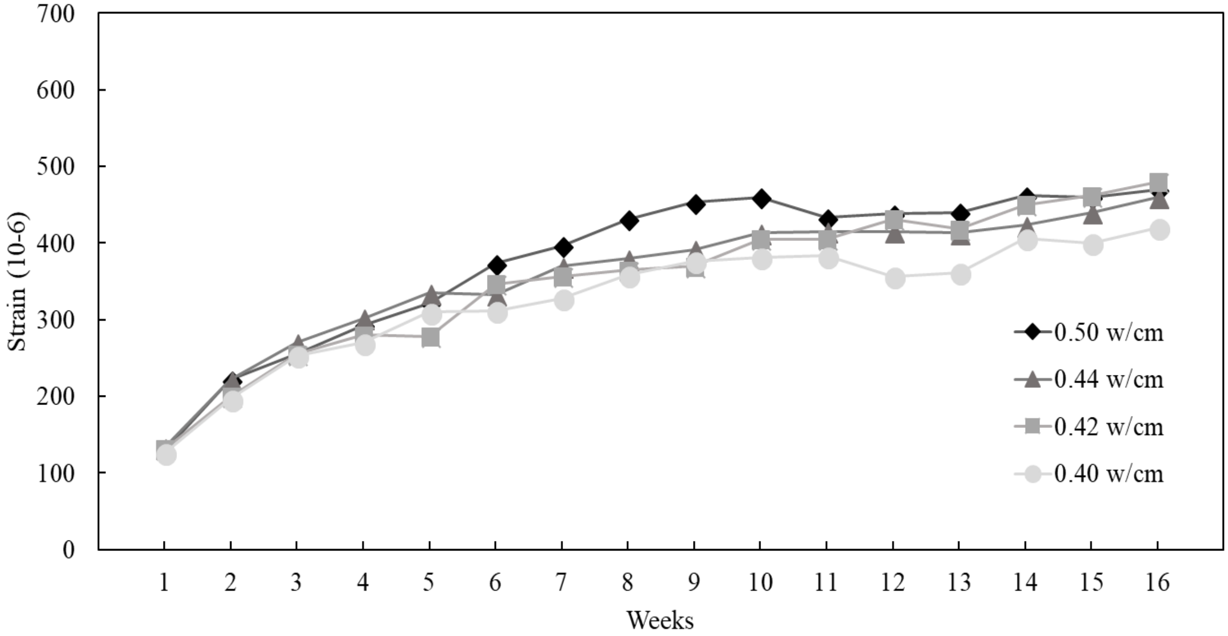


Figure 4.27 – Class S(AE) Drying Shrinkage for Mixtures with 564 lb/yd^3 and 0% Fly Ash

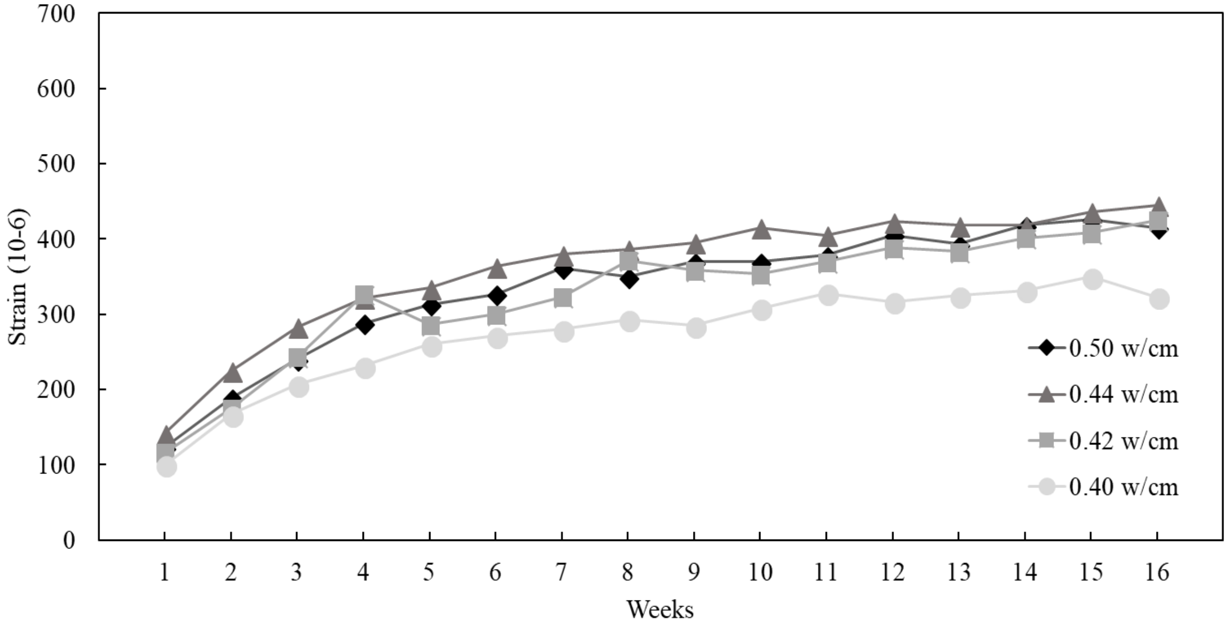


Figure 4.28 – Class S(AE) Drying Shrinkage for Mixtures with 517 lb/yd^3 and 0% Fly Ash

The contribution of fly ash to strain and drying shrinkage was minimal. Overall, fly ash affected the strain and thus the shrinkage in a very similar manner as it effected strength.

Mixes with 20 or 30% fly ash showed approximately equivalent or slightly greater 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 ratio decreased were noted and, still applied to fly ash mixes. All of this can be seen in Figures 4.29 through 4.34.

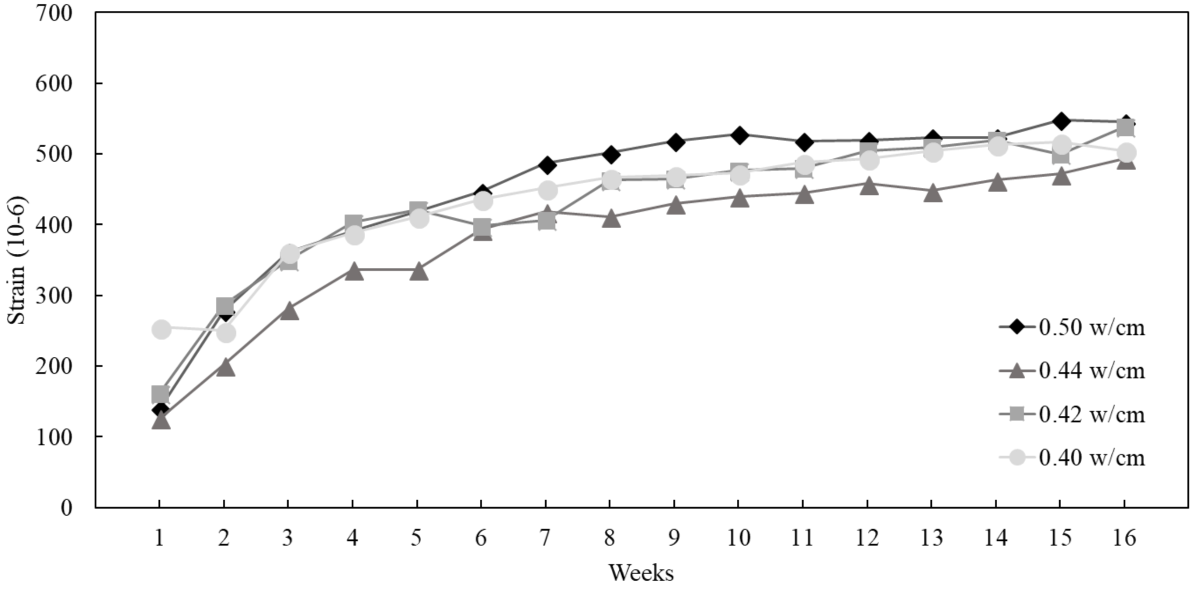


Figure 4.29 – Class S(AE) Drying Shrinkage for Mixtures with 611 lb/yd^3 and 20% Fly Ash

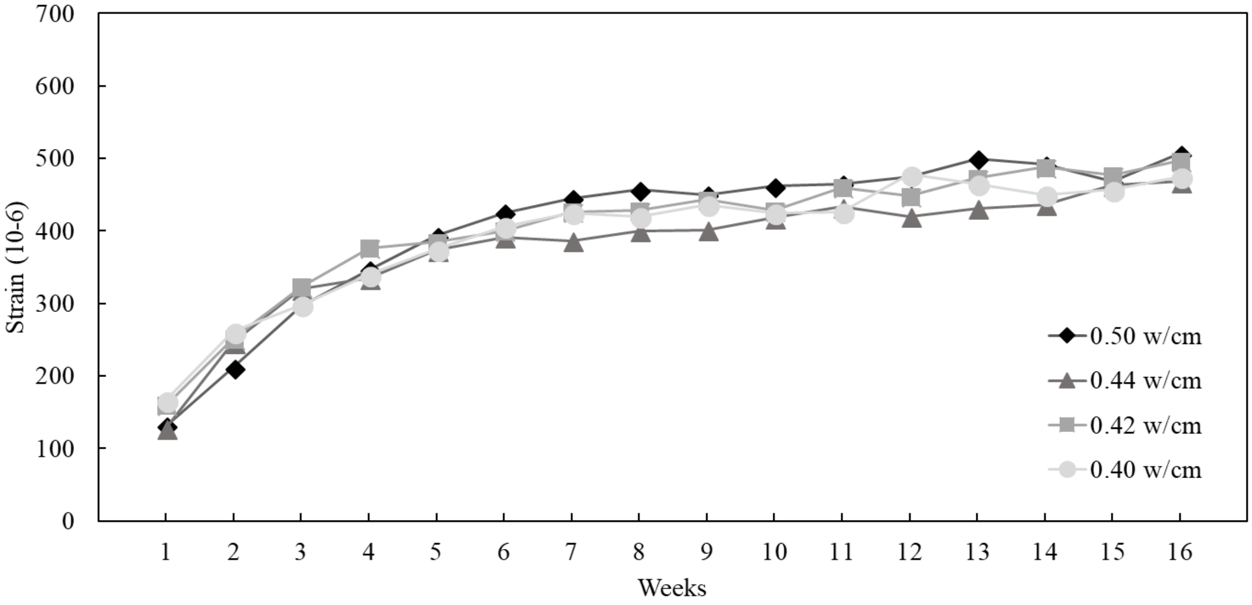


Figure 4.30 – Class S(AE) Drying Shrinkage for Mixtures with 564 lb/yd^3 and 20% Fly Ash

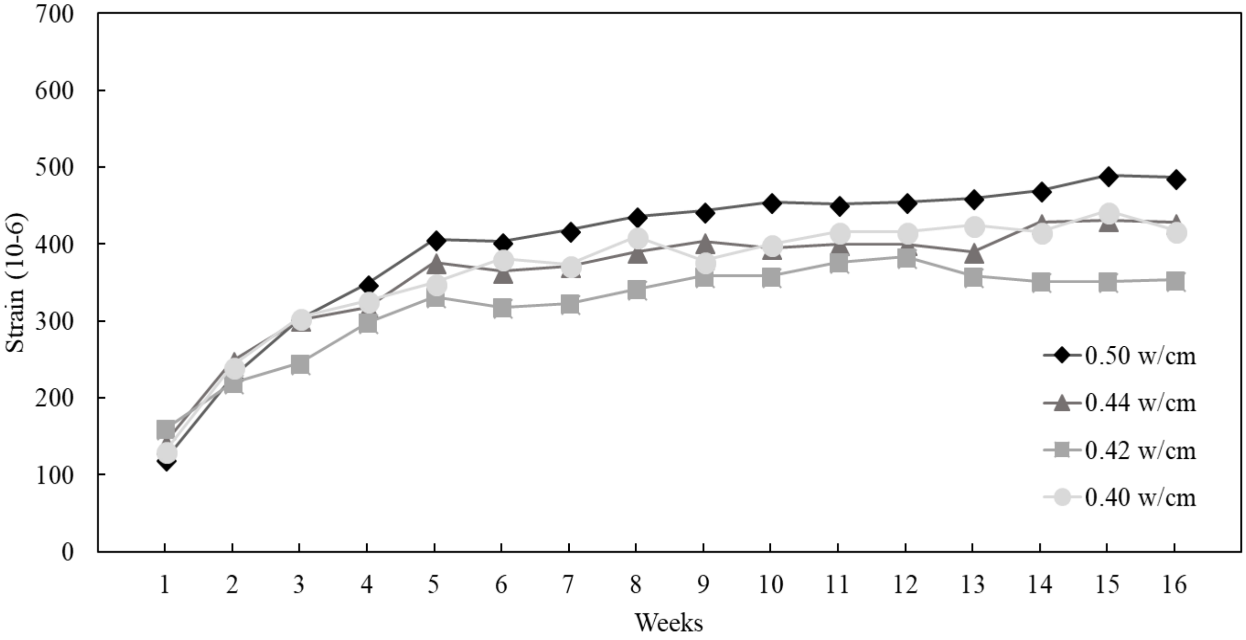


Figure 4.31 – Class S(AE) Drying Shrinkage for Mixtures with 517 lb/yd^3 and 20% Fly Ash

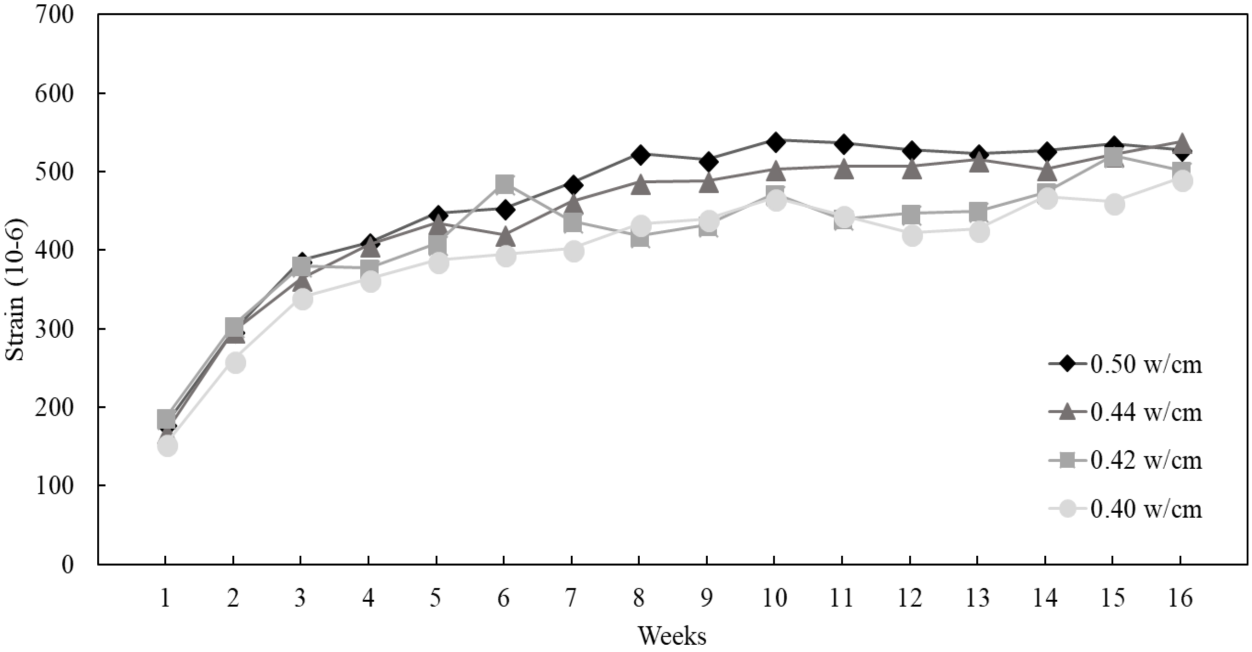


Figure 4.32- Class S(AE) Drying Shrinkage for Mixtures with 611 lb/yd^3 and 30% Fly Ash

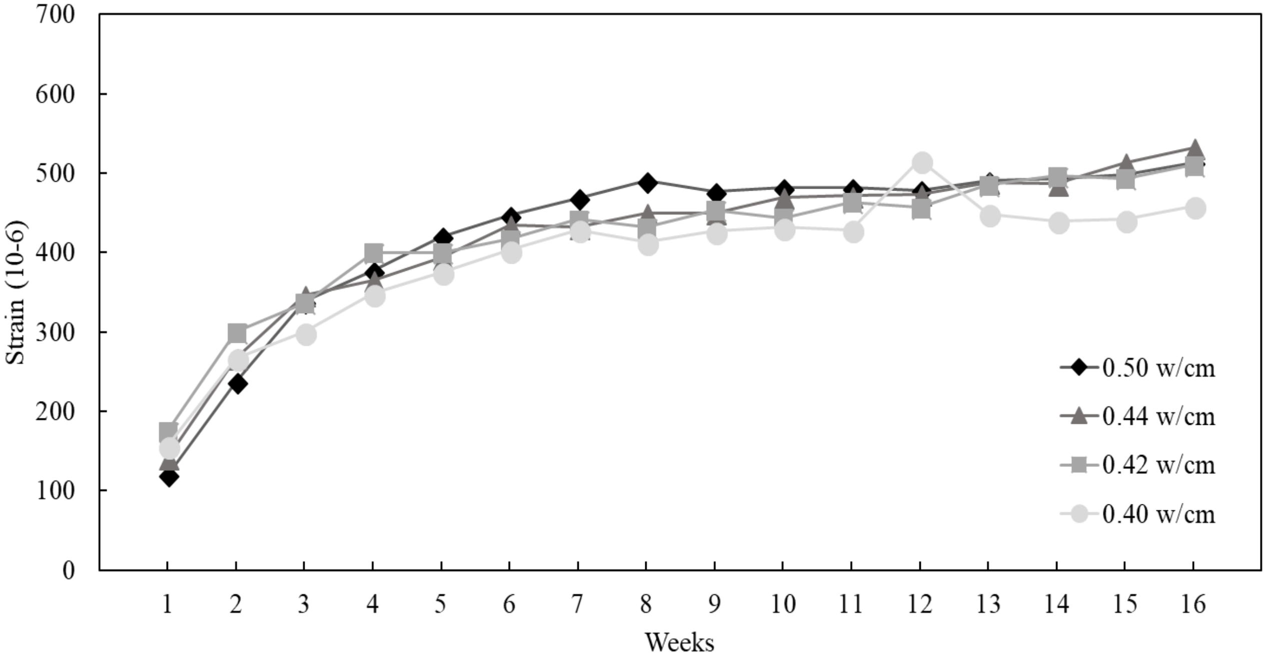


Figure 4.33 – Class S(AE) Drying Shrinkage for Mixtures with 564 lb/yd^3 and 30% Fly Ash

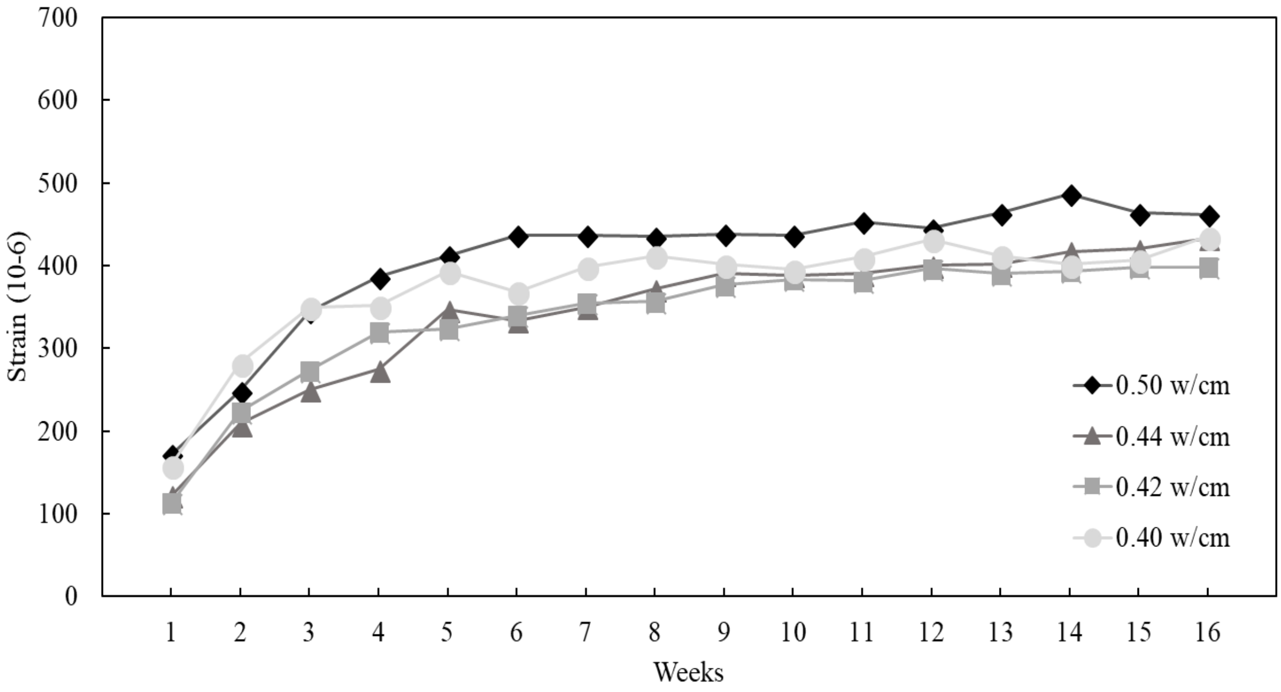


Figure 4.34 – Class S(AE) Drying Shrinkage for Mixtures with 517 lb/yd^3 and 30% Fly Ash

From the shrinkage data we can determine the reduction in cement has no negative effects on drying shrinkage. In addition, it appears the addition of fly ash is of little to no consequences in regard to drying shrinkage, as it causes equal to slightly greater strain than those mixes with no fly ash. In all initial 36 cases, no mix exceeded 600 x 10^{-6} microstrain, meaning the maximum shrinkage values were less than value (700 x 10^{-6}) that is suggested to cause cracking in restrained conditions. Additionally, it was noted that as the 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 performed more than adequately to meet ARDOT standards, while not increasing strain leading to cracking.

4.5. Additional Testing

Both Modulus of Elasticity (MOE) and Rapid Chloride Ion Penetrability (RCIP), per ASTM C1202, testing were performed for 9 additional 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, strength, and shrinkage between the weakest mixtures tested for these three classes. The 3 mixes tested used no fly ash and were: Class S(AE) with 517 lb/yd^3 at a w/cm of 0.50, Class S with 517 lb/yd^3 at a w/cm of 0.55, and class PCCP with 470 lb/yd^3 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.

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 4.35.

$$E_c = 57{,}000\sqrt{f'_c} \qquad \text{Eq.1}$$

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

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. All the while, the sandstone failed to meet expectations at either 28 or 56 days.

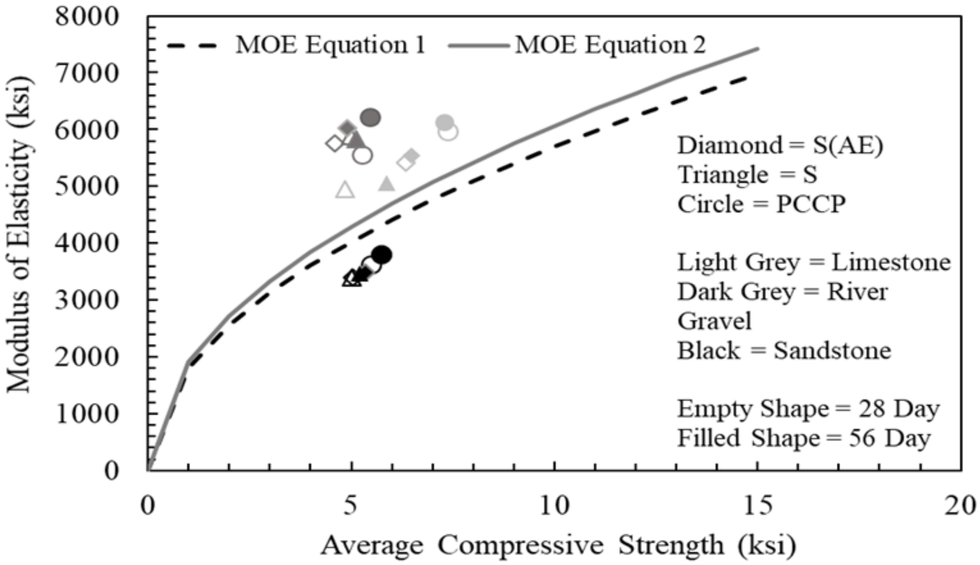


Figure 4.35 – Measured Modulus of Elasticity versus Predicted Values

Figure 4.36 presents the findings for RCIP and shows the standards for chloride ion permeability based on ASTM C1202. It should be noted in Figure 4.36 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 values substantially higher 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

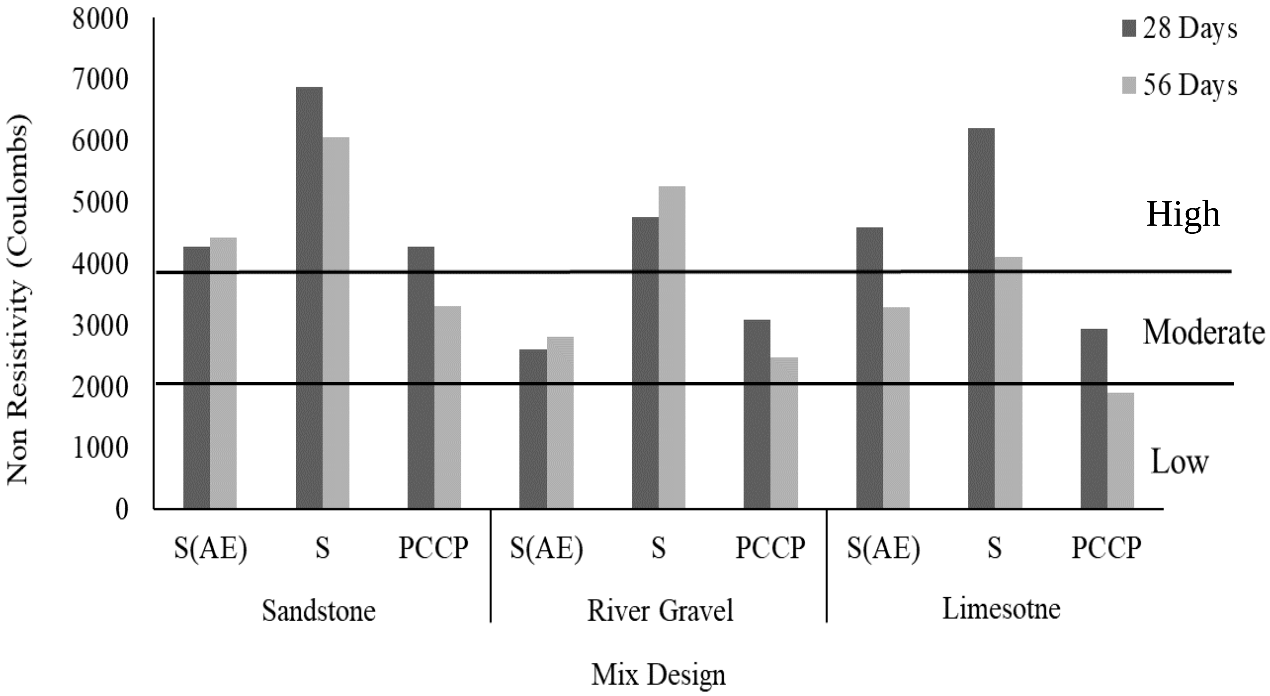


Figure 4.36 - Measured RCIP Values

5. Conclusions and Recommendations

This research project examined the effects of reducing cementitious material content and increasing fly ash replacement percentage for PCCP, Class S, and Class S(AE) mixtures on compressive strength, unrestrained drying shrinkage, static modulus of elasticity, and costs. The results of this investigation are discussed below.

5.1. PCCP Mixtures

- The current minimum cementitious material content of 564 lb/yd^3 is not necessary to achieve specified 28-day compressive strength of 4,000 psi. All mixtures containing the current requirement exceeded specified compressive strength by 28 days of age. A majority of mixtures reached target strength by 7 days of age.
- Mixtures containing 517 lb/yd^3 and 470 lb/yd^3 cementitious material also all met 28-day compressive strength specifications, with a majority of mixtures also achieving this requirement by 7 days of age.
- The required cement content could be reduced to 470 lb/yd^3 without adversely affecting compressive strength or shrinkage performance.
- Fly ash content could be increased to 30% and still achieve the specified compressive strength.
- Early age compressive strengths were lower in mixtures containing fly ash, compared to mixtures without.
- Unrestrained drying shrinkage for mixtures of all cementitious material contents were within acceptable ranges for shrinkage cracking to not be a concern.

5.2. Class S Mixtures

- The current minimum cementitious material content of 611 lb/yd^3 is not necessary to achieve specified 28-day compressive strength of 3,500 psi. All mixtures containing the current requirement exceeded specified compressive strength by 28 days of age. A majority of mixtures reached target strength by 7 days of age.
- The minimum cement content for Class S concrete could be reduced to 517 lb/yd^3 without adversely affecting compressive strength or shrinkage performance.
- When the w/cm was 0.55 (above the specified value), the concrete mixture having 517 lb/yd^3 and 30% fly ash met the required compressive strength.
- Class C fly ash content is recommended to allow maximum replacement percentage to increase to 30%.
- Concrete mixtures with 20 and 30 % Class C fly ash have similar or higher compressive strength at 28 day and 56 day compared to mixtures with 0 % Class C fly ash.
- Unrestrained drying shrinkage for mixtures of all cementitious material contents were within acceptable ranges for shrinkage cracking to not be a concern.

5.3. Class S(AE) Mixtures

- ARDOT could allow their minimum required cementitious material content for class S(AE) concrete to be reduced from 611 to 517 lb/yd^3 while still meeting requirements for fresh and hardened properties.
- Class C fly ash content could be increased to a max of 30% while still meeting

ARDOT requirements.At the highest w/cm ratio of 0.50 with the lowest cementitious material value of 517 lb/yd^3 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 day, with most exceeding this value by 7 days.
- Mixes batched with 20 or 30 % class C fly ash had equivalent to 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 changes overall with approximate drops of 100 microstrain from 611 to 517 lb/yd^3 and of 50 microstrain from 0.50 to 0.40 w/cm ratios.

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