8-2017

Optimization of Concrete Mixtures for Use in Structural Elements

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Recommended Citation

Almutairi, Waleed, "Optimization of Concrete Mixtures for Use in Structural Elements" (2017). *Theses and Dissertations*. 2482.
http://scholarworks.uark.edu/etd/2482

Optimization of Concrete Mixtures for Use in Structural Elements

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

by

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Qassim University
Bachelor of Science in Civil Engineering, 2013

August 2017
University of Arkansas

This thesis is approved for recommendation to the Graduate Council.

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Abstract

Portland cement is an essential ingredient in concrete. The use of cement is to enhance the strength as well as other hardened properties of concrete mixtures. Determining the accurate amount of cement is important because the required strength may not be achieved if not enough cement is used. By contrast, when using too much cement, concrete cracking may occur that leads to reducing durability. Researchers at the University of Arkansas (UA) have shown that many bridge decks achieve their 28 day design strength of 4000 psi by 7 days of age. Bridge decks having high strength may experience cracking, which affects the durability. The Arkansas State Highway and Transportation Department (AHTD) classifies two types of concrete mixtures that can be used in bridges. The first is Class S concrete, and the second is Class S(AE). Class S is used for the structural components and does not contain air entrainment while Class S (AE) is mainly used for bridge decks and contains air entrainment. AHTD requires the same minimum cementitious material content for both classes of concrete. The purpose of this research is to determine if the cementitious material content of Class S mixtures can be reduced while still meeting AHTD specifications. The research program examined cementitious material content, Class C fly ash content, and water to cementitious material ratio (w/cm). For all mixtures, selected fresh and hardened concrete properties were measured to ensure that they complied with AHTD requirements.

Acknowledgments

I am very grateful to GOD for having given me the opportunity to come to the United States where I have gained so much experience. I am also thankful for His grace and blessing helping me to finish this research.

My deepest thanks to Saudi Arabian cultural mission for providing me a full scholarship to do my grad school here at the University of Arkansas.

I would like to express my gratitude to my adviser professor Micah Hale for his helpful guidance, support and contribution. I also want to thank Dr. Gary Prinz and Dr. Michelle Bernhardt for serving on my committee.

My thanks also go to Dr. Hale’s students for helping me whenever I needed help at the laboratory. Special thanks to my partner and friend Bryan Casillas for his endless help.

My parents and my siblings, I am so thankful to God for having you. Faleh and Roqya, my parents, I thank you for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without them. Thank you.

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1. Introduction

1.1. Research Motivation

Concrete has been used for many engineering applications, such as building and bridges. It is simply made of coarse and fine aggregates that are glued together by portland cement after chemical reactions with water. The ingredients in a concrete mixture can affect its properties. Engineers usually specify minimum compressive strength requirements for their structural elements. The compressive strength of concrete is typically measured and can be the only hardened concrete property specified. From compressive strength, many other hardened concrete properties can be determined (Mehta and Monteiro, 2006); however, it is not always the right decision to specify only compressive strength and ignore the other properties. Generally, compressive strength increases as cement content increases, but a mixture that has more than the necessary cement may not meet the requirements in terms of workability, dimensional stability, durability, and cost (Fowler and Rached, 2011; Wassermann, Katz and Bentur, 2009). Mehta and Monteiro (2006) state that designing concrete mixtures is an art, not science, since its properties can vary. Furthermore, concrete mixture proportioning is a trial and error process which will hopefully result in a mixture that meets the specified requirements.

The Arkansas State Highway and Transportation Department (AHTD) specifies a minimum 28 day compressive strength of 3500 psi for Class S mixtures which are the focus of this research program. Class S mixtures are used for the structural elements of bridges, such as retaining walls, box culverts, footings, piers, and abutments cast in Arkansas. Table 1.1 shows the additional requirements for Class S concrete.

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

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

Note. Adapted from AHTD division. (2013).

Researchers at the UA have shown that Class S (AE) concrete (AE for air entrained), used typically for bridge decks, have exceeded the required strength at 28 days (Reed and Hale, 2013). The specifications for Class S(AE) concrete are also shown in Table 1.1. The major difference between the two types of mixtures is the lower compressive strength, higher water to cementitious material ration (w/cm), and lower air content for Class S mixtures. In their study, the researchers took samples from the concrete of five bridge decks. All five mixtures were designed according to AHTD standards for Class S(AE) concrete. By seven days of age, four mixtures had achieved 4000 psi, their 28 days design strength, and the other one achieved slightly over 3500 psi (Reed and Hale, 2013).

Researchers have shown that bridge deck cracking increases as concrete compressive strength increases (Schmitt and Darwin, 1999). Class S (AE) concrete mixtures, like Class S mixtures, have a minimum cementitious content of 611 lb/yd^3. Researcher in Arkansas measured the cracking density, crack length per unit area, in five bridge decks (Peyton et al., 2012). The five bridge decks were cast with Class S(AE) concrete and contained 611 lb/yd^3 of cementitious material, and three of them had 9 to 12 % fly ash replacement. The w/cm was 0.44 for 4 mixtures and 0.41 for the one that had 12 % of cement replaced with fly ash, and a high range water reducer (HRWR) was added to the mix with lowest w/cm. The cracking density varied from 0.05 to 0.315ft/ft^2. for the five bridges. The author concludes that the bridge deck that had the highest compressive strength at 7 and 28 days of age had the highest crack density. The researcher hypothesized that the cracking might have occurred due to the significant compressive strength gain between 1 and 7 days of age.

Bridge deck cracking is not only a problem for Arkansas bridges. A survey by the Michigan Department of Transportation (MDOT) indicated that 30 out of 31 states shown in Figure 1.1 have experienced cracking in bridge decks. Of those 30 states, almost 70% of the observed cracking in the first few months (Aktan et al., 2003).

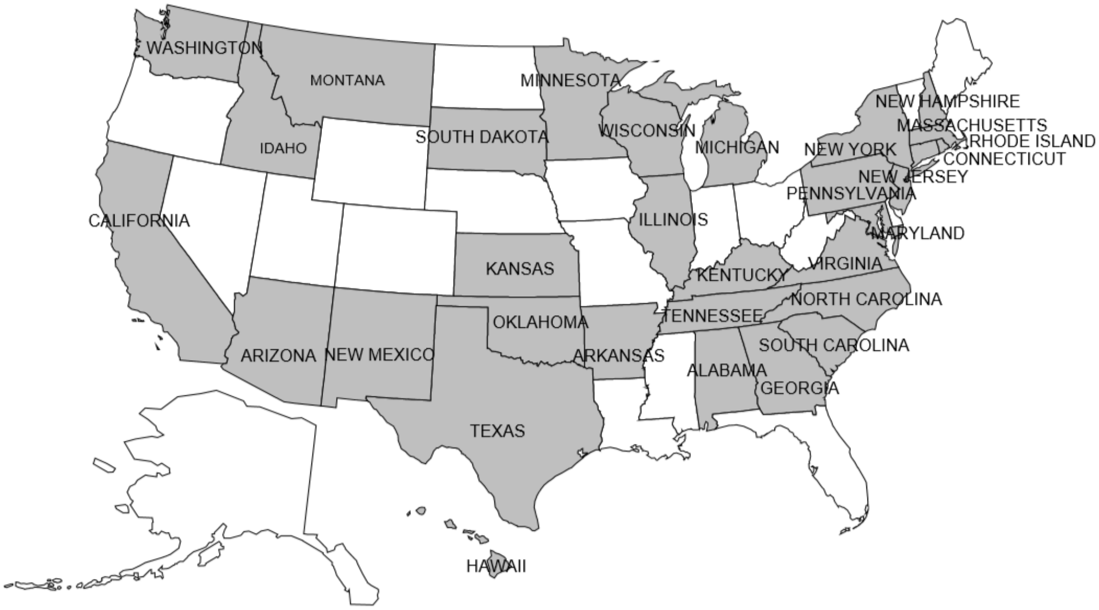

Figure 1.1. Indicating states that responded to MDOT's survey (Aktan et al., 2003)

As previously shown, higher compressive strengths can lead to bridge deck cracking. The cement content in a concrete mixture directly influences concrete strength. As cement content increases, compressive strength also increases (Mehta and Monteiro, 2006; Schmitt and Darwin, 1999). Additionally, cement is the most expensive ingredient in concrete, and cement production is a major contributor to carbon dioxide. Mehta (2001) states that about 1 ton of carbon dioxide is released into the atmosphere when producing 1 ton of portland cement is produced. The Environmental Protection Agency (EPA, 2016) claims that the cement industry is considered the third largest source causing pollution. According to Mehta (2001) cement production accounts for 7% of the global loading of carbon dioxide into the atmosphere. More than 500,000 tons of sulfur dioxide, nitrogen oxide, and carbon monoxide are added to the environment on a yearly basis, thus, harming the environment and human health. By reducing the quantity of cement in the concrete mixture, cracking decreases and the environmental impact of the concrete is reduced.

1.2. Research Goal

Research has shown that concrete strength and cement content affects bridge deck cracking in Class S(AE) concrete. By reducing the cement content, bridge deck cracking can also be reduced. The purpose of this project was to determine if these findings remain true for other structural concrete, specifically AHTD Class S concrete mixtures. A number of concrete mixtures with different cement contents, fly ash contents, and w/cm were cast and tested in the lab to ensure that they met AHTD specifications. These tests evaluated the fresh and hardened concrete properties, and with the results a better understanding of how the mixture proportioning affects compressive strength, workability, shrinkage. The final goal of the project is recommend a lower cement content for Class S concrete which can potential reduce cracking and provide a more economically and environmentally friendly concrete.

2. Literature Review

The literature review will summarize the findings of research projects that examined the effects that lowering the cement content has on the fresh and hardened concrete properties. This section will specifically focus on the effects cement content has on workability, compressive strength, and drying shrinkage.

2.1. Concrete Mixture Proportioning

Concrete is one of the most widely consumed construction materials (Bjork, 1999). ASTM C 125 defines concrete as “Concrete is a composite material that consists essentially of a binding medium within which are embedded particles or fragments of aggregate. In hydraulic cement concrete, the binder is formed from a mixture of hydraulic cement and water”.

When designing normal strength concrete with a 28 day compressive strength of 2000 to 7000 Psi, engineers usually follow the ACI 211.1, *Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete* (Qasrawi, 2016). Following the ACI 211.1, a designer can start with the recommended slump according to the type of construction. Regarding the nominal maximum size of the aggregate used and the slump chosen, the designer can determine the approximate mixing water. The w/cm is selected according to the required compressive strength, but there is a recommended maximum limit depending on the exposure of the structural elements. Also, different types of portland cement are suggested for each exposure. After determine the weight of water, coarse aggregate, and cement, the absolute volume method is used to calculate the amount of fine aggregate. The absolute volume method is based on the fact that the volume of concrete equals the summation of the absolute volumes of all ingredients, considering air voids (Qasrawi, 2016).

Portland cement is the most expensive among most of ingredients of concrete (Fowler and Rached 2011). Zachar (2010) indicates that cement in the United States costs approximately $115 per ton. He also states that by replacing 30% of the cement with fly ash in a building consuming 918t of portland cement leads to lessening the cement consumption to nearly 272t, which saves about $23,000.

2.2. Cement Content

Portland cement is the ingredient that bonds the coarse and fine aggregate together through a chemical reaction called hydration (Skalny and Roberts, 1987). As the cement content in a concrete mixture increases, the compressive strength also increases (Mehta and Monteiro, 2006; Schmitt and Darwin, 1999). Many specifications intentionally promote overdesigned concrete mixtures by requiring more cement than necessary which leads to another factor of safety (Taylor et al., 2015). However, this can lead to higher production costs and maintenance costs because of the cracking that may occur due to the higher hydration of heat and increased drying shrinkage (Hendriks et al., 1998; Chamberlin, 1995). Additionally, a negative impact on the environment is caused by the increase of cement production (Rached et al., 2010). The effects of the cement content on concrete properties are further discussed below.

2.2.1. Effect of Cement Content on Workability

For a given water content, increasing the cement content improves the cohesiveness, but too much cement results in a concrete mixture that requires more effort to place. On the other hand, concrete mixtures are also difficult to place when they contain a low cement content, so it is essential to determine the right cement content to have the desired workability (Mehta and Monteiro, 2006). Cement gradation also can affect the workability of concrete. Bleeding and segregation decreases with finer cement, but the water demand also increases because of the high surface area (Neville and Brooks, 2010; Mindess et al., 2003). For a given w/cm, finer cement reduces workability due to the increased surface area which absorbs water from the mixture (Mindess et al., 2003).

2.2.2. Effect of Cement Content on Compressive Strength

As previously discussed, one method to increase compressive strength is to increase the cement content in a mixture (American Society of Concrete Contractors, 2005). As shown in Figure 2.1, for a given w/cm, compressive strength increases with the increase of cement content. Rixom and Mailvaganam (1999) claim that it is difficult to have a high strength mixture when the amount of cement is below 590 lb/yd^3. However, according to Abrams rule, the quality of cement paste is the main influence strength regardless of its quantity (Popovics, 1990). Wassermann et al. (2009) also states that compressive strength is independent of cement content because it is a function of w/cm. Another investigation done by Taylor (2015) shows that for a specified compressive strength, when the minimum cement concrete required is reached, adding more cement does not significantly improve the strength.

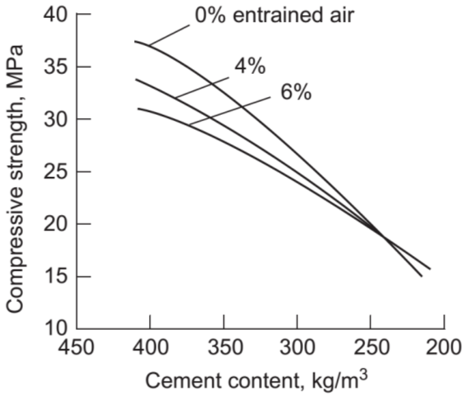

Figure 2.1. Relationship of concrete compressive strength and cementitious content (Mehta and Monteiro, 2006).

2.2.3. Effect of Cement Content on Drying Shrinkage

Drying Shrinkage is defined as the loss of moisture from the hardened concrete causing change in volume (Zhang et al., 2014). Wassermann et al. (2009) state that when increasing the cement content in order to reduce the w/cm, shrinkage should decrease due to the reduction in water content. However, for a given w/cm, when cement content increases, drying shrinkage also increases since there is more cement paste in the hardened concrete which can shrink (IMCP, 2006; Dhir et al., 2004). Schmitt and Darwin (1999) determined a direct correlation between cement content and cracking, and they stated that too much cement can lead to drying shrinkage and therefore cracking in bridge decks. They observed that the mean cracking density increased from 0.05 ft/ft^2 to 0.23 ft/ft^2 for bridge decks having 602 and 605 lb/yd^3 and 639 lb/yd^3 respectively.

In addition to cracking from drying shrinkage, high cement content produces high early strength concrete mixture, but the high heat of hydration increases the risk of early cracks (Xi et al., 2003). It is recommended to use as low cement as possible to control thermal and drying shrinkage (Aktan et al., 2003). Different amounts were recommended for maximum and minimum cement content. For example, 545 lb/yd^3 is the minimum cement content assigned by ACI committee 345, but Xi et al. (2003) suggested 470 lb/yd^3 as a maximum cement content to reduce the risk of cracking.

Cement properties, such as particles size or cement gradation may affect concrete shrinkage. Type II cement is preferred because of the lower heat of hydration, which can cause a reduction in thermal shrinkage affecting cracking (Babaei and Fouladgar, 1997). ACI 224.R-01 (2001), there is a direct relation between cement properties and concrete shrinkage. ACI Committee 224, *Cracking*, states that shrinkage increases with finer cement. On the other hand, Mehta (2006), states that the cement graduation slightly affects the mortar shrinkage; however, the effects of cement fineness on concrete shrinkage is small.

2.2.4. Effect of Cement Content on Durability

ACI Committee 201, *Durability of Concrete*, defines durability as “the ability to resist weathering action, chemical attack, abrasion, or any other process of deterioration and retain its original form, quality, and serviceability when exposed to its environment”. The durability of concrete is influenced by permeability, cracking resistance.

For a constant w/cm, durability decreases when the cementitious content increases. The reduction in durability is because of the higher permeability due to cracking which allows chloride penetration. (Wassermann et al., 2009; Dhir et al., 2004). In certain concrete mixtures, the use of larger size rock will decrease the amount of cementitious content required because the area of the interfacial transition zone between the aggregate and cementitious paste is proportional. While cementitious matrix hydrates, the interfacial transition zone is not strong enough and vulnerable to cracking. This leads to cracking propagation inside the concrete, which causes an increase in concrete permeability. This factor results in the high permeability of concrete in the field. However, the use of slag cement or fly ash can reduce the concrete permeability to an acceptable range (Russel, 2004; Naik et al., 1996).

Schmitt and Darwin (1999) found that cracking density increases when the cement content increases. They also found that at the crack locations, the chloride ion concentration exceeded the threshold level for corrosion in less than three years, which indicates that the service life of the structure lessens (Miller and Darwin, 2000).

2.3. Previous Research on Cement Content

Yurdakul (2010) examined concrete mixtures properties where the cement content was minimized. The cement contents in the research were 400, 500, 600, 700 lb/yd^3 , and the w/cm ranged from 0.35 to 0.55. Materials used in this study were ASTM Type I portland cement, No. 4 nominal maximum size fine aggregate, crushed limestone with a 1-in nominal maximum size, and the HRWR was the only admixture used in this research. Compressive strength, slump, and permeability penetration were examined to ensure that concrete mixtures meet the strength, workability, and durability requirements for concrete pavement.

In terms of workability, the Yurdakul (2010) states that for a given w/cm, when cement content decreases, the workability decreases. That happened because of the low paste content to lubricate the aggregate. Yurdakul (2010) recommended the use of supplementary cementitious materials (SCM), HRWR, or a different aggregate gradation to improve workability for mixtures with a cement content of 500 lb/yd^3.

Compressive strength was also affected by cement content. Yurdakul (2010) found that for a given w/cm, the concrete mixture with 400 lb/yd^3 cement content had the lowest compressive strength due to the high porosity caused by low paste content. They also mentioned that for a w/cm greater than 0.35, increasing cement content more than 500 lb/yd^3 reduced compressive strength. Yurdakul (2010) states that when cement content increased from 500 lb/yd^3 to 700 lb/yd^3, 28 day compressive strength decreased by approximately 15%. Yurdakul (2010) states that the paste volume should be ranged between 140% to 170% of the voids volume in a concrete mixture to achieve the required strength, and increasing the paste volume more than this range will not develop the mixture's strength. The author states that for a given w/cm, the most appropriate cement content ranges from 500 lb/yd^3 to 600 lb/yd^3, which provides the desired workability, strength, and resistance to chloride penetration.

Yurdakul et al. (2013) investigated the fresh and hardened properties when minimizing cement content by incorporating Class C and F fly ash. The cementitious content was fixed at 600 lb/yd^3 and the w/cm was 0.40 and 0.45. Fly ash replacement for both Class C and F was 15% and 30%. For a constant w/cm and fly ash replacement, the compressive strength at 28 days was similar for the control mixture, with 100% cement content, and the one containing Class C fly ash; however, the mixture with Class F fly ash showed lower compressive strength due to the slow pozzolanic reactivity of Class F fly ash (Fajun et al., 1985). The reason why Class F fly ash gains lower strength than Class C fly ash is that Class C fly ash has some cementitious properties in addition to its pozzolanic properties, but Class F fly ash has only pozzolanic properties (Thomas, 2007). The authors found that increasing the fly ash replacement from 15 to 30% did not considerably influence the compressive strength. Shrinkage also was examined in this research. They found that increasing the replacement level of Class F fly ash reduced shrinkage. In mixtures with high-volume fly ash, shrinkage might be restrained by the unhydrated cementitious material acting as aggregate (Bisaillon et al., 1994). For a given w/cm, compared to concrete mixtures with no fly ash, All concrete mixtures with Class F had lower shrinkage, but some mixtures with Class C fly ash had slightly higher shrinkage. Generally, they concluded that concrete mixtures containing Class F and C fly ash performed better than the mixtures without fly ash.

Salem et al. (2004) developed a high performance concrete mixture for Tennessee bridge decks. In their study, compressive strength, drying shrinkage, and chloride penetration were investigated. The cementitious materials used in this research are Type I portland cement, Class

C fly ash, slag cement, and silica fume. The aggregates were limestone #57, limestone #7, and natural sand. The w/cm was 0.4 for all concrete mixtures. Class D concrete mixture had 611 lb/yd^3 cementitious material content, but the other four modified concrete mixtures FA, FASF, S, and SSF had 20% less cementitious material content than Class D, and they had different SCMs along with different replacement rates. Class D was the control mixture that did not contain any SCMs. Mix FA contained 25% Class C fly ash, FASF refers to a combination of 20% Class C fly ash and 5% silica fume, S mixture contains 35% slag cement, and SSF refers to the mixture with 35% slag cement and 5% silica fume. Class D mixture had only #57 limestone, and the other four mixtures had both #57 and #7 limestone.

They determined that all the concrete mixtures containing SCMs had higher 28 day compressive strength than the control mixture (Class D). The authors say that because the w/cm was the same for all mixtures, the mixing water and cement content were less for the four modified mixtures with SCMs. The four modified mixtures had less cement paste; therefore, the amount of aggregates is higher per unit volume. Additional strength was developed by improving the aggregate interlocking in the cement paste because the aggregate particles became close to each other.

Salem et. al (2004) measured drying shrinkage for 16 weeks. The control mixture had the highest drying shrinkage, but it also had the greatest paste content. Reducing the cement content for the other four mixtures reduced drying shrinkage. They also noticed that drying shrinkage increased rapidly for the first 4 weeks and then it slightly increased with an almost flat slope. One of their goals in this study was to develop a durable mixture allowing minimal chloride penetration to avoid steel corrosion. They found that the modified mixtures had considerably lower permeability values compared to Class D mixture. They also stated that less porous material is produced in a given volume when lowering cement paste, which gives higher resistance to chloride penetration. Total porosity is measured by measuring the total absorption, and the absorption reduced with the reduction of cement content for a given w/cm (Wassermann et al., 2009).

Fowler and Rached (2011) optimized aggregates gradation to reduce the cement content in concrete without reducing quality. The microfines used in their study were a limestone obtained as pond fines, a limestone obtained by sieving from screenings, and a granite obtained by sieving from screening. Normal portland cement, Type I/II, was used for all concrete mixtures. The researchers reduced the cement and mixing water contents by 10%,20%, and 30% while holding the paste volume constant at 28% by substituting the removed cement and water volume with microfines. As a result, the w/cm was the same, but the water to powder ratio (w/p) decreased. Microfines replacement provides higher compressive strength. The only decrease in strength was at the highest replacement of 30% by granite. When increasing the microfines replacement, drying shrinkage and permeability decreased.

Seo et al. (2007) studied the cracking behavior when minimizing cement content by adding fly ash. The materials used in this research were ordinary portland cement, Class C fly ash, natural sand, and crushed stone. The first mixture contained 564 lb/yd^3 with 0.55 w/cm, and the other one had 20% fly ash replacement with 0.69 w/cm. The authors examined the strain of drying shrinkage and restrained shrinkage cracking. They found that the concrete mixture containing fly ash had smaller shrinkage than the portland cement concrete due to the pozzolan effect by fly ash. For cracking test, they say that the crack occurred in the specimen containing fly ash slightly later than the portland cement concrete specimen.

2.4. Summary

Cement content affects the fresh and hardened concrete properties, mixture cost, and has implications on the environment. Researchers have shown that minimizing cement content results in a high performance concrete mixture for several reasons. With less cement, concrete mixtures have a higher resistance to chloride penetration, which improves durability. Drying shrinkage can decrease when cement content is reduced which is due to the lower amount of paste. Cracking caused by drying shrinkage is also minimized due to the lower cement content. Studies have shown that minimizing cement content by replacing a portion of the cement with fly ash improves concrete compressive strength at later ages. Workability may be affected when minimizing cement; however, researchers suggested that the use of SCMs or chemical admixtures, such as fly ash and HRWR can offset the reduction in workability.

3. Experimental Investigation

3.1. Scope

As previously mention, the goal of the research program is to determine if the minimum cement content for Class S concrete can be reduced. In the project, several concrete mixtures were examined. These concrete mixtures vary in cement content from 517 to 611 lb/yd^3, and Class C fly ash content ranged from 0 to 30% of the total cementitious material content. Finally, the w/cm ranged from 0.38 to 0.55. The compressive strength and drying shrinkage were evaluated for each mixture to determine the effect of cement content on the hardened concrete properties.

3.2. Materials

The material properties for the aggregates used in the research program are described below in Table 3.1. The coarse aggregate was crushed limestone from McClinton-Anchor in Springdale, AR. The fine aggregate was a river sand from Van Buren, AR. Both coarse and fine aggregate properties, such as absorption (ASTM C127 and ASTM C128), specific gravity (ASTM C127 and ASTM C128), and dry rodded unit weight (ASTM C29) are listed in Table 3.1.

Table 3.1. 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	2.63
Absorption Capacity (%)	0.86	0.86
Fineness Modulus	2.99	-

Crushed limestone used was #57, which complies with AHTD specified gradation. Sieve analysis (ASTM C33) was performed to ensure that the gradation of fine and coarse aggregate meets the specified gradation by AHTD. Table 3.2 shows the sieve result of the fine aggregate and the specified gradation by AHTD, and the coarse aggregate gradation is listed in Table 3.3.

Table 3.2. Fine aggregate sieve analysis

Sieve	Fine Aggregate % Passing	AHTD 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 3.3. Coarse aggregate sieve analysis

Sieve	Coarse Aggregate % Passing	AHTD Specification % Passing	AASHTO M43 #57
1½"	100	100	100
1"	100	60-100	95-100
3/4"	75	35-75	-
1/2"	25	-	25-60
3/8"	12	10-30	-
#4	2	0.5	0-10
#8	1	-	0-5

Type I/II cement, from a single source, was used in this research, and Class C fly ash, also from a single source, was the only SCM used. The fly ash and cement properties are listed in Table 3.4 and 3.5 respectively. A carboxylate based HRWR admixture, ADVA Cast 575, was used to increase concrete workability when needed.

Table 3.4. Fly ash properties

Item	Description
SiO_2	36.73%
Al_2O_3	21.49
Fe_2O_3	5.68%
CaO	22.70%
Na_2O	1.48%
K_2O	0.57%
MgO	4.30%
∑ Oxides	63.90%
∑ Alkalis	29.05%

Table 3.5. Cement properties

Item	Description
Chemical	
SiO_2	20.11%
Al_2O_3	5.07%
Fe_2O_3	3.80%
CaO	64.15%
MgO	0.98%
SO_3	3.23%
Loss on ignition	2.39%
Na_2O	0.18%
K_2O	0.56%
Insoluble Residue	0.40%
CO_2	1.09%
Limestone	2.80%
$CaCO_3$	88.23%
Potential compounds	
C_3S	55%
C_2S	14%
C_3A	7%
C_4AF	11%
$C_3S + 4.75\ C_3A$	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. Experimental Procedure

3.3.1. Mixture Proportions and Testing Matrix

AHTD provided the data shown below in Tables 3.6. This table shows the typical mixtures proportions for the Class S used in Arkansas through the 9 AHTD districts. 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 (611 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 3.6. Representative Class S Mixtures

Material or Property	Concrete Producers							
	ACC	PBSG	ABC	SRM	MCCC	RCC	WRM	Tune
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
Rock (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

The testing matrix followed in this research program is shown below in Table 3.7. The cementitious material content ranged from 517 to 611 lb/yd^3. This included the current AHTD minimum of 611 lb/yd^3 but then included 517 and 564 lb/yd^3. This represents a “1/2 bag” and full bag of cement less than the AHTD 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 AHTD

Table 3.7. Class S Batching Matrix

Cementitious Material content (lb/yd^3)	w/cm			
	0.38	0.45	0.49	0.55
	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. Mixing

One day prior to mixing, three and two 5 gallon buckets of coarse and fine aggregate were filled from the aggregate stockpiles located at the Engineering research center (ENRC). Lids were placed on each bucket to prevent moisture loss from the time of sampling to batching. Representative samples of fine and coarse aggregate were taken to measure the moisture content for each mixture. ASTM C566 method was followed to determine the moisture content.

The mixing procedure conformed to ASTM C192. While the concrete mixer was at rest, all coarse aggregate was added along with some of the mixing water containing HRWR if needed. Then, fine aggregate was added, followed by the cementitious materials and the remaining mixing water were added to that mixer while it was rotating. The size of each mixture was 1.6 ft^3, which was adequate to perform slump and unit weight tests, and cast 12 cylinders for compressive strength testing and 3 prisms from shrinkage testing. The cylinders and prisms were cast according to ASTM C192.

3.3.3. Curing

The environmental chamber where the specimens was stored had a constant temperature of approximately 73°F with a relative humidity of 50% as per ASTM C192. Drying shrinkage prisms were de-molded after 24 hours of casting and were stored in the environmental chamber on small wooden rollers to allow free movement as shown in Figure 3.1. Cylinders were placed inside the environmental chamber after casting, de-molded at 24 hours, and placed in a water bath as shown in Figure 3.2.

Figure 3.1. Drying Shrinkage specimens

Figure 3.2. Compressive Strength specimens

3.3.4. Fresh and Hardened Concrete Property Tests

For each mixture, the slump (ASTM C143) and unit weight (ASTM C136) were performed to determine the fresh properties of each mixture. The hardened property tests included drying shrinkage (ASTM C157), compressive strength (ASTM C39), and modulus of elasticity (ASTM C496) were measured to examine the hardened properties.

The purpose of drying shrinkage test is to evaluate the cracking resistance of the mixtures, and to determine if reducing the cement content also decreases drying shrinkage. Three prisms of 4 in. by 4 in. by 11¼ in. were cast from each mixture to measure concrete shrinkage. Testing procedure was done according to ASTM C157 as shown in Figure 3.3. An initial reading was taking for all the three prisms, and then a weekly reading was taken over a period of sixteen weeks.

Figure 3.3. Prism resting in shrinkage apparatus

Compressive strength was measured for each concrete mixture. The dimensions of the cylinders used were 4 in. by 8 in. Three cylinders were tested according to ASTM C39 at 1, 7, 28, and 56 days, for a total of twelve cylinders. Aluminum rings containing neoprene pads were used when the compressive strength was tested as shown in Figure 3.4.

Figure 3.4. Compressive test

The modulus of elasticity was determined based on ASTM C496 as shown in Figure 3.5. In this research, the modulus of elasticity of several concrete mixtures was examined. Three mixtures with highest and lowest 28 day compressive strengths were selected. In total, 9 cylinders of 4 in. by 8 in. were used to measure the modulus of elasticity at 7, 28, and 56 days. The results of modulus of elasticity for each concrete mixture were analyzed and compared with the current specification to study the possible outcomes of minimizing the cementitious content (AASHTO 2012; ACI Committee 318 2011). After analyzing the results of the modulus of elasticity, the values for each mixture were compared with the predicted values by the standard ACI/AASHTO prediction equations which is further discussed in Chapter 4.

Figure 3.5. Modulus of elasticity setup using Forney

4. Results and Discussion

4.1. Research Goal

The goal of this project is to determine the minimum required cement content for Class S concrete mixtures. A number of concrete mixtures with different cement contents, fly ash contents, and w/cm were cast and tested in the lab to ensure that they met AHTD specifications. The fresh concrete properties will be discussed first then followed by the results from the hardened concrete tests.

4.2. Fresh Properties

The slump and unit weight were measured for each concrete mixture. The results of the slump and unit weight tests are shown below in Table 4.1 and 4.2. The values shown in the table represent one test conducted per ASTM C143 and ASTM C136.

It was observed that when reducing the amount of cement content, the mixture's workability decreases as shown in Table 4.1. For example, as the cement content was reduced from 611 lb/yd^3 to 564 lb/yd^3 for mixtures at a w/cm of 0.49, the slump decreased from 3 to 2 in. This also apparent in Figure 4.1 which is a picture of the mixture with the lowest w/cm of 0.38 and a cement content of 564 lb/yd^3. For those mixtures that had a low cement content and low water content, a HRWR (ASTM C494 Type A and F, and ASTM C1017 Type I) was used to increase workability. As the cement content and w/cm decreased, the total water content in the mixtures also decreased which reduced workability and at times prevented mixing which is shown in Figure 4.1. Because the mixtures with the lowest w/cm of 0.38 and the cement contents of 564 lb/yd^3 and 517 lb/yd^3 did not have enough paste and therefore had poor workability, there are no slump and unit weight results for those mixtures listed in Tables 4.1 and 4.2.

Another thing was noticed is that for a constant cementitious content and w/cm, workability or slump increased as fly ash content. As shown in Table 4.2, for a given cementitious material content and w/cm, slump increased as the fly ash content also increased. For example, for mixtures at a w/cm of 0.49 and cementitious content of 611, the slump increased from 3 to 4 in. as the fly ash content increased from 0 to 30 percent. This increase in slump is due to the spherical shape of the fly ash which increases concrete workability (Best 1980). The different amount of HRWR used for some concrete mixtures significantly affects slump. For example, for concrete mixture at a w/cm of 0.49 and cementitious content of 517 lb/yd^3, the slump was 3.50 in., which is higher slump than the mixture at a w/cm of 0.55 and cementitious content of 517 lb/yd^3 as shown in Table 4.1. Overall, most of the mixtures met the AHTD slump specifications of 1 to 4 in., but some mixtures had higher slumps. This was due to the higher w/cm of 0.55 or the use of the HRWR.

Figure 4.1. Mixtures with the lowest w/cm of 0.38 and cement content of 564 lb/yd^3

The average unit weight measured for all concrete mixtures was 148.0 lb/ft^3. The highest and lowest unit weight were 153.1 lb/ft^3 and 143.7 lb/ft^3, respectively. The differences in w/cm were the major factor resulting in the range of unit weight. For examples, mixtures with the lowest w/cm had the greatest unit weight, whereas the mixtures with the highest w/cm had the lowest unit weight. This is expected since the water is the lightest ingredient in the concrete (except for air).

Table 4.1. Slump and Unit weight for mixtures containing cement only

Cementitious Content (lb/yd^3)	% Class C Fly Ash	w/cm	Slump (in.)	Unit weight (lb/yd^3)
611	0	0.38	2.50	153.1
		0.45	2.50	150.5
		0.49	3.00	148.1
		0.55	6.00	145.9
564	0	0.38		
		0.45	2.00	151.0
		0.49	2.00	149.0
		0.55	5.50	147.4
517	0	0.38		
		0.45	2.00	151.5
		0.49	3.50	150.0
		0.55	2.00	148.9

Table 4.2. Slump and Unit weight for mixtures containing fly ash

Cementitious Content (lb/yd^3)	% Class C Fly Ash	w/cm	Slump (in.)	Unit weight (lb/yd^3)
611	20	0.38	4.50	151.0
		0.45	4.00	147.9
		0.49	4.00	146.2
		0.55	6.50	145.0
	30	0.38	4.00	150.2
		0.45	4.50	147.1
		0.49	4.00	146.0
		0.55	6.50	143.7
564	20	0.38		
		0.45	4.00	149.1
		0.49	4.00	148.9
		0.55	6.00	145.9
	30	0.38		
		0.45	2.50	148.2
		0.49	3.50	147.0
		0.55	6.50	145.6
517	20	0.38		
		0.45	2.50	149.9
		0.49	4.00	148.4
		0.55	2.50	147.0
	30	0.38		
		0.45	3.50	149.4
		0.49	2.00	148.0
		0.55	3.00	147.0

4.3. Hardened Properties

4.3.1. Compressive Strength

The compressive strength results are discussed in the following sections. The compressive strength (ASTM C39) was measured at 1, 7, 28, and 56 days of age. At each age, three cylinders were tested and the results discussed in this section represent the average of three cylinder tests. As mentioned in Chapter 3, AHTD requires a 28 day compressive strength of 3500 psi for Class S mixtures. In the following sections, the effect of cement content on compressive strength will first be discussed then followed by a discussion on the effect of fly ash on compressive strength.

4.3.1.1. Effect of Cement Content on Strength

Figure 4.2 represents the compressive strength of concrete mixtures having cement content of 611, 564, and 517 lb/yd^3. 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 4.2, 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 6710 to 7520 psi. Based on a 28 day strength of 3500 psi, a cement content of 517 lb/yd^3 and a w/cm of 0.55 would be acceptable. This is significant, because that mixture represents one in which the w/cm was out of specification (too high) and it contained the least amount of cement. At 1 day, the compressive strength of all concrete mixtures shown in Figure 4.2 was not low. The lowest compressive strength was 2530 psi, which is higher than the half of compressive strength specified at 28 day. At 7 days, all concrete mixtures achieved the compressive strength of 3500 psi as shown in Figure 4.2. This is a good indication to use fly ash and increase its percentage in these concrete mixtures.

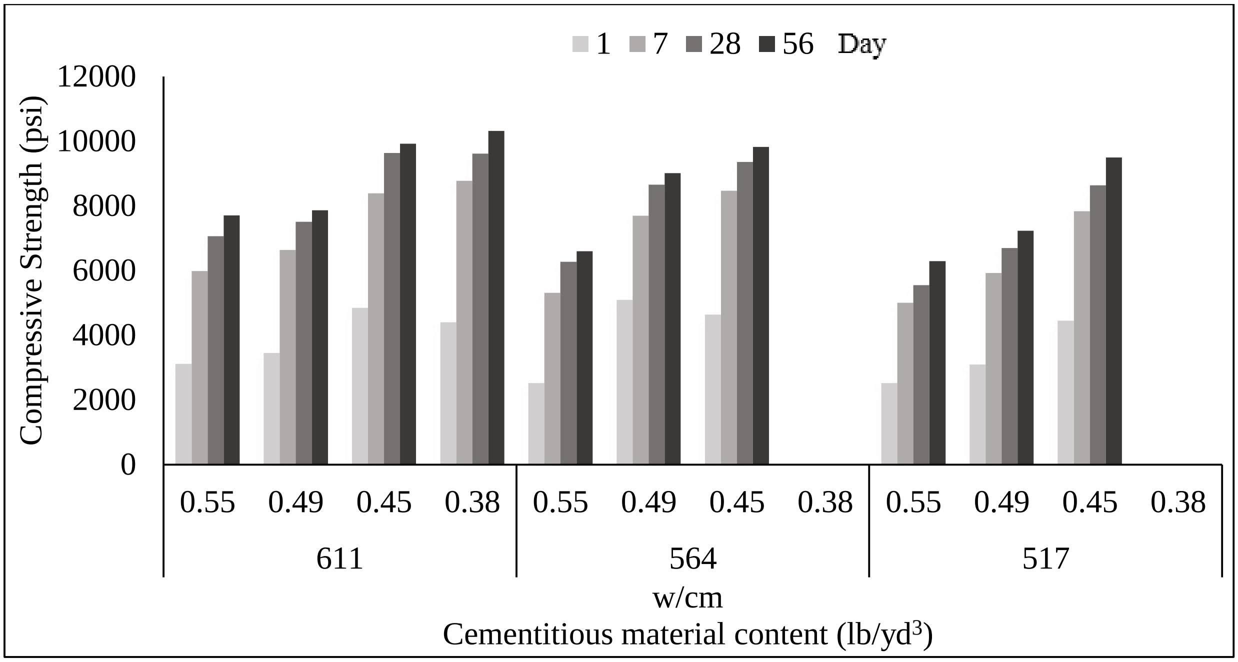

Figure 4.2. Compressive strength of concrete mixtures with cement only

4.3.1.2. Effect of Fly Ash on Strength

Figures 4.3, 4.4, and 4.5 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 4.3, 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 microcraks (Longarini 2014). As shown in Figures 4.3, 4.4, and 4.5, 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/yd^3, the compressive strength of 28 day 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 day; however, the compressive strength at 7 day achieved 3500 psi even 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 %.

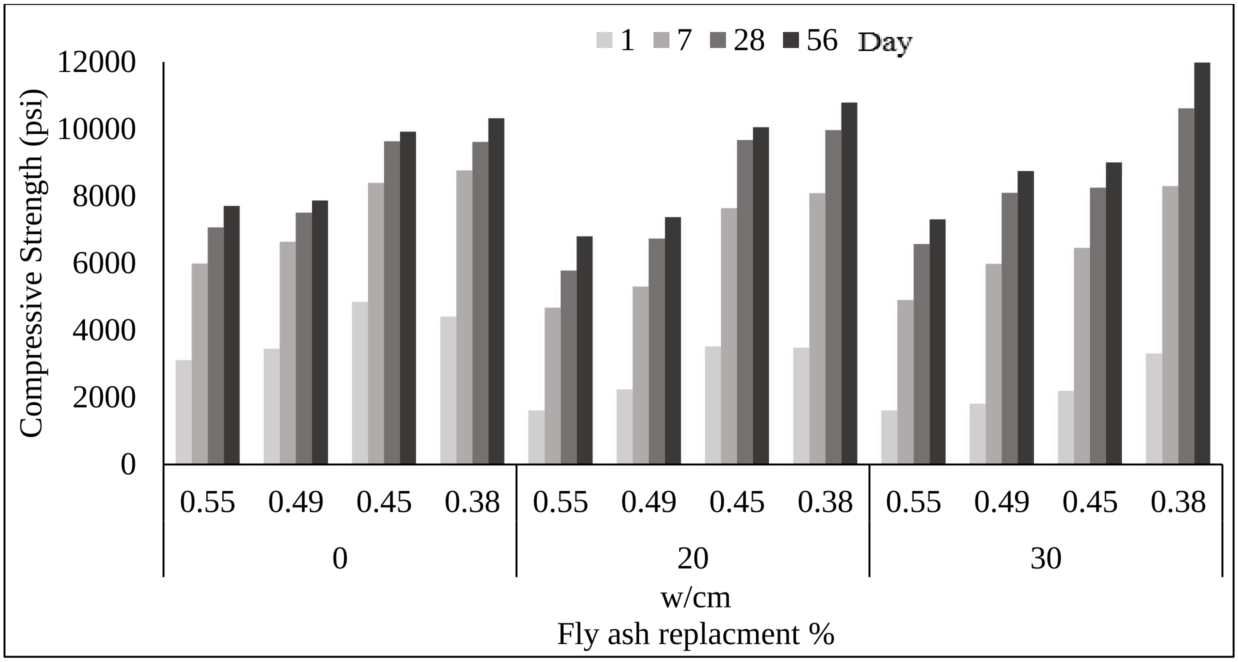

Figure 4.3. Compressive strength of concrete mixtures containing 611 lb/yd^3 cementitious content

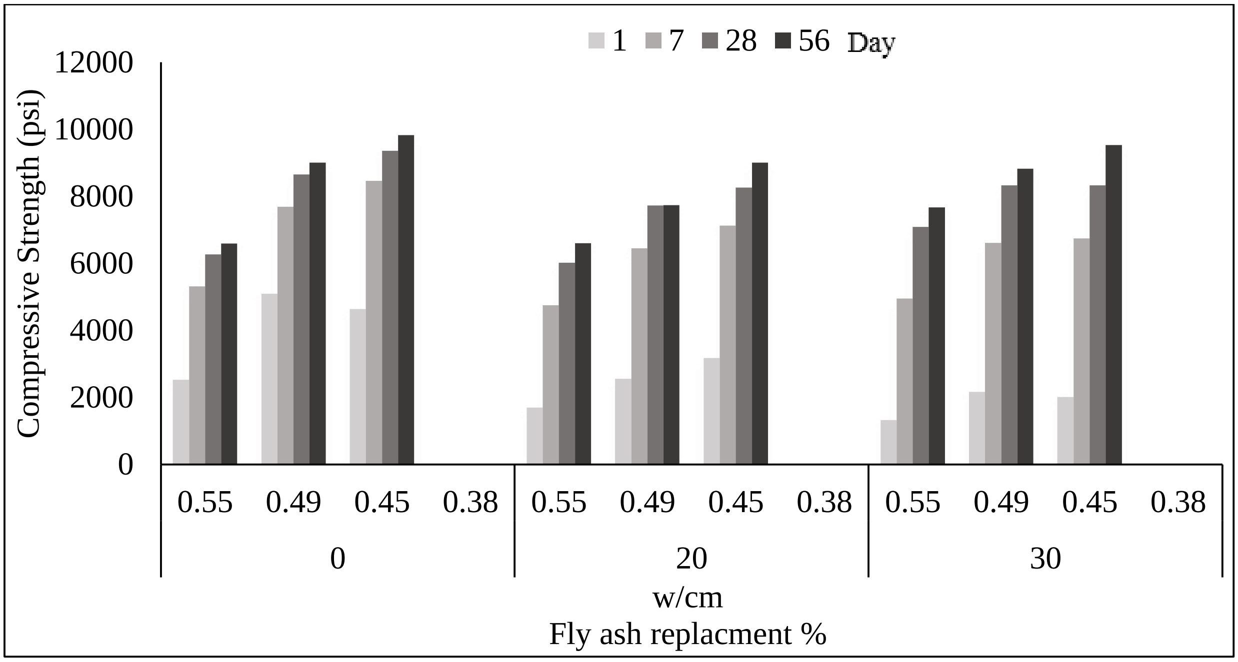

Figure 4.4. Compressive strength of concrete mixtures containing 564 lb/yd^3 cementitious content

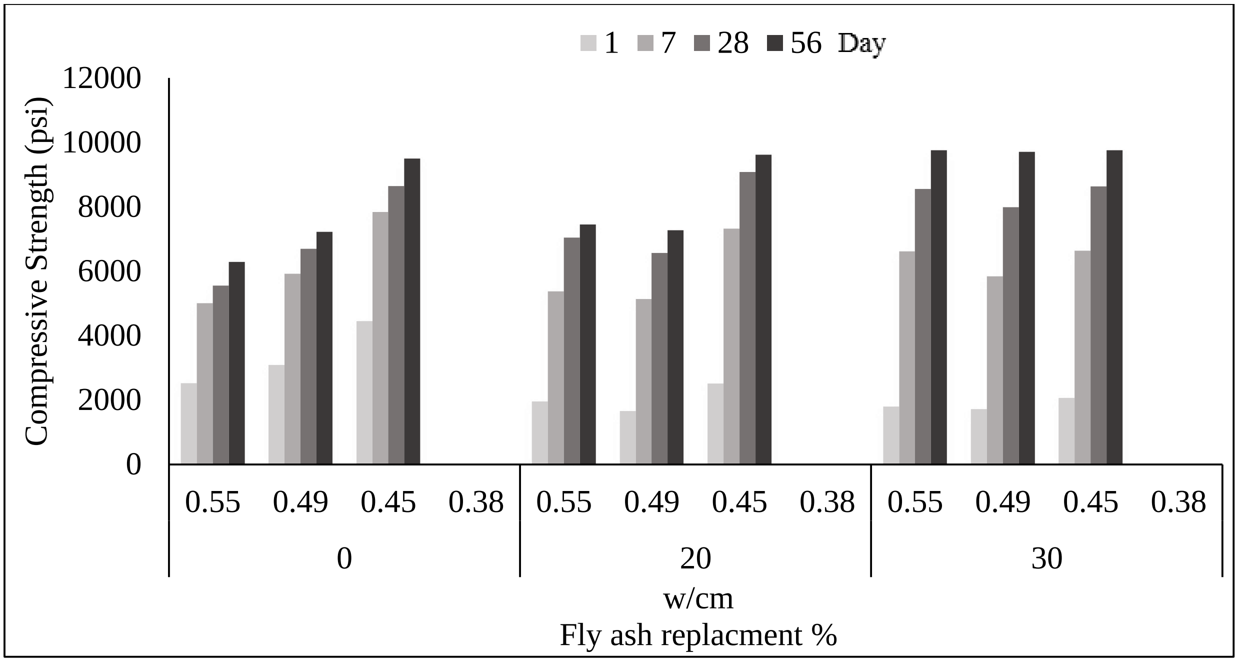

Figure 4.5. Compressive strength of concrete mixtures containing 517 lb/yd^3 cementitious content

4.3.1.3. Summary of Compressive Strength Results

All concrete mixtures tested in this research for compressive strength meet the 28 day required strength by AHTD of 3500 psi. 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 day 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. 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.

4.3.2.1. Effect of Cement Content on Drying Shrinkage

Figure 4.6, 4.7, and 4.8 show concrete strain (drying shrinkage) for mixtures having cement contents of 611, 564, and 517 lb/yd^3 respectively. The 16 weeks drying shrinkage ranged from approximately 100 to about 350x10^{-6} microstrains for all w/cms and cement contents. The strain of 350x10^{-6} is low because the higher limit of drying shrinkage to prevent shrinkage cracking is 700x10^{-6} (Babaei et al., 1995). 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.

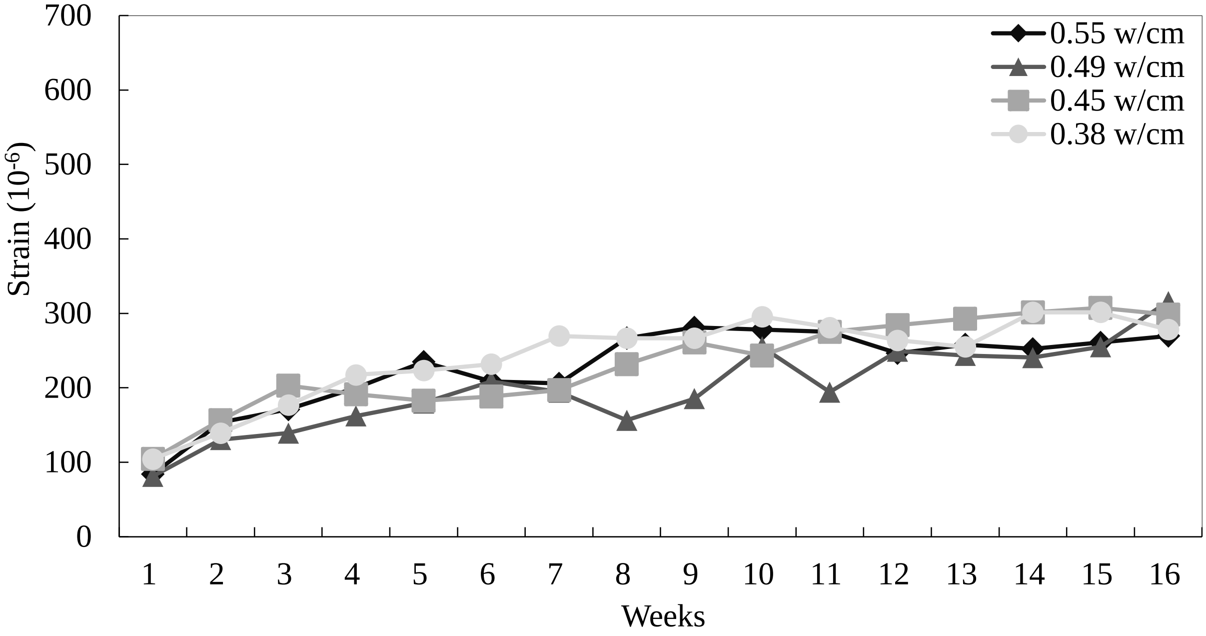

Figure 4.6. Concrete mixture with 611 lb/yd3 and 0% fly ash

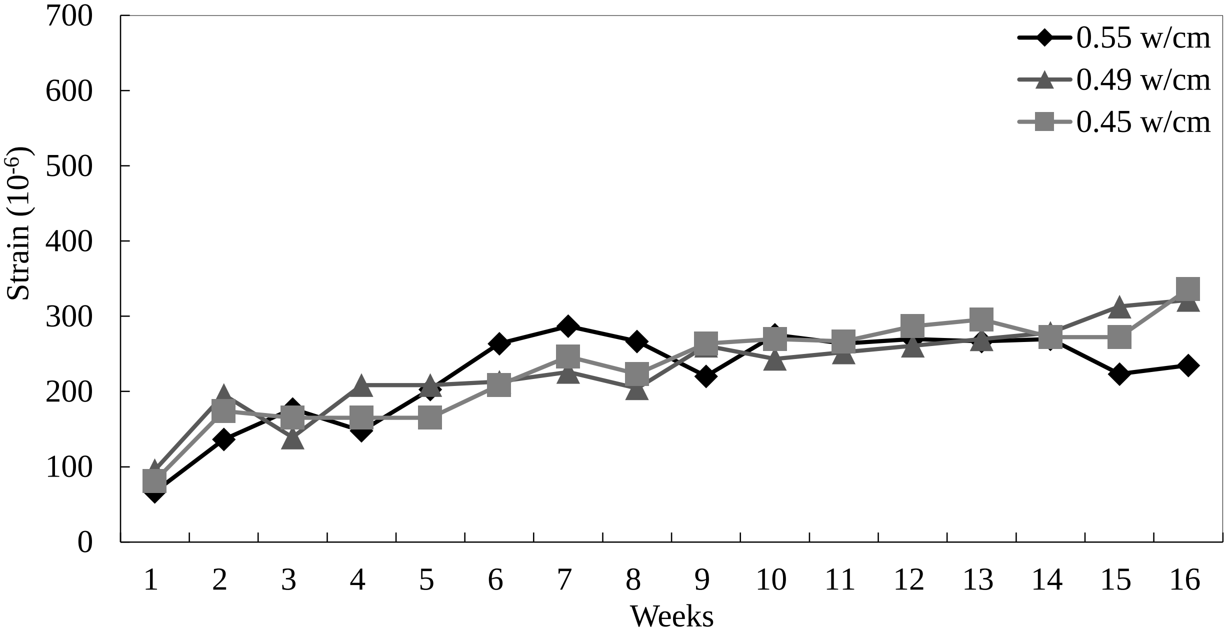

Figure 4.7. Concrete mixture with 564 lb/yd3 and 0% fly ash

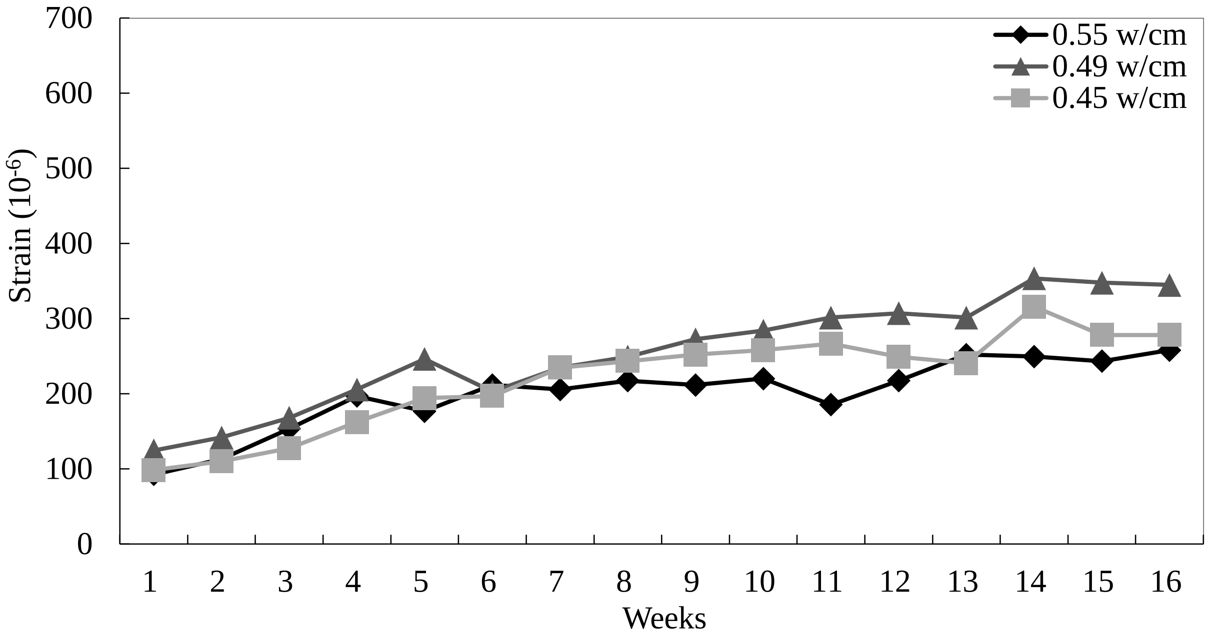

Figure 4.8. Concrete mixture with 517 lb/yd3 and 0% fly ash

4.3.2.2. Effect of Fly Ash on Drying Shrinkage

Figure 4.9, 4.10, and 4.11 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 may be 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 4.12, 4.13, and 4.14.

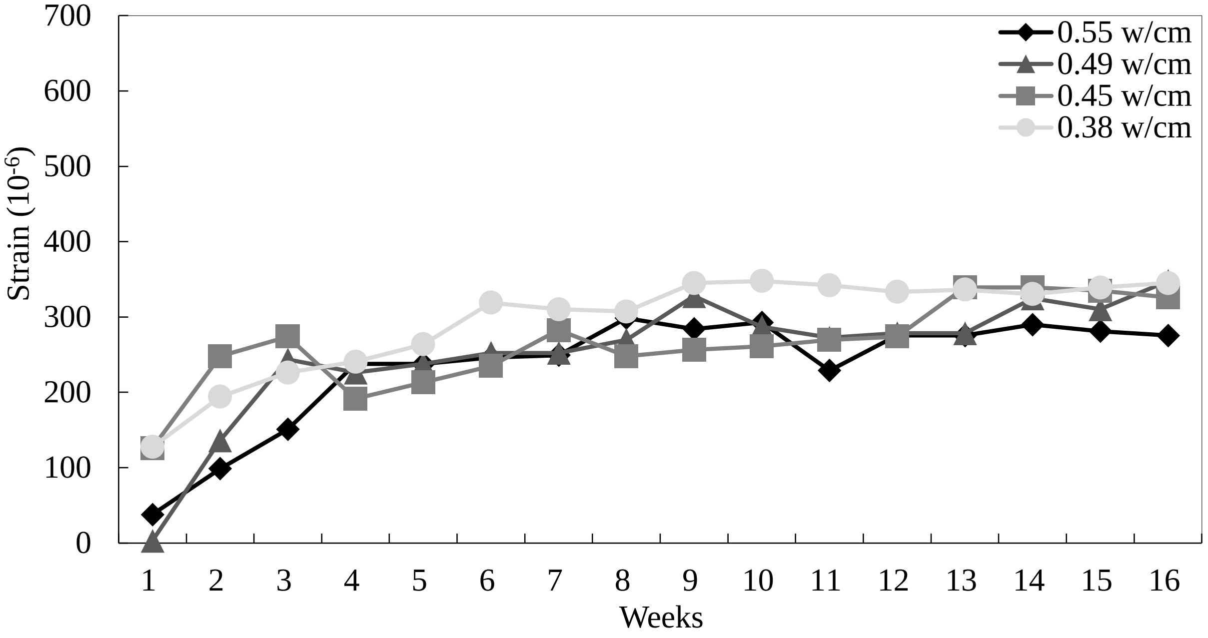

Figure 4.9. Concrete mixture with 611 lb/yd3 and 20% fly ash

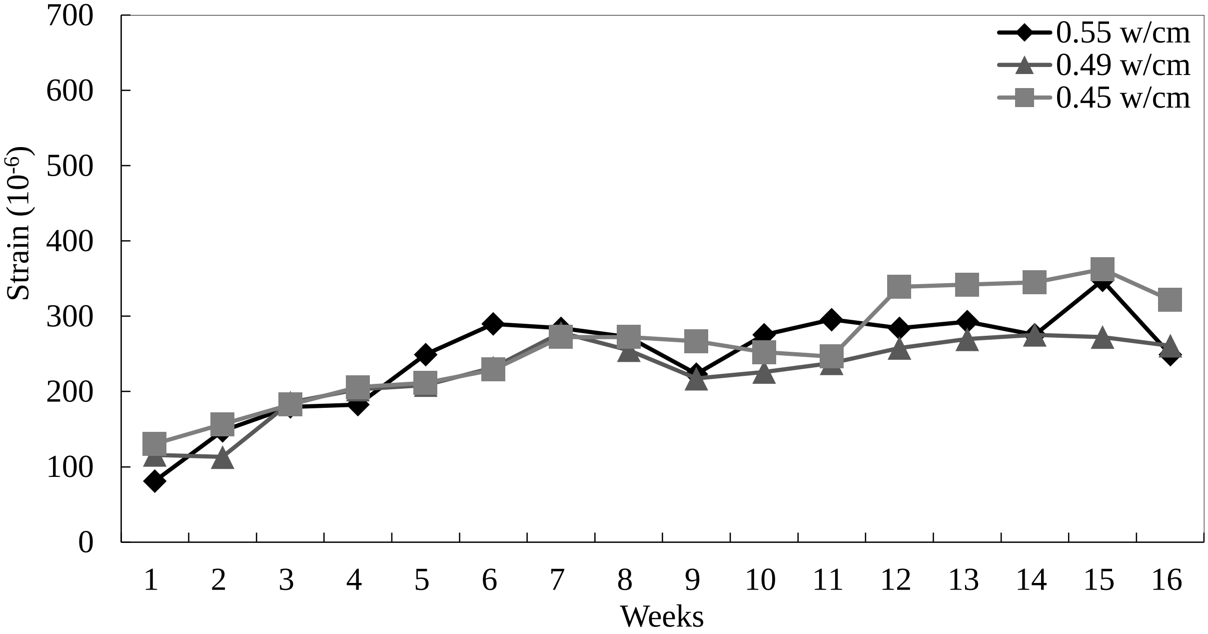

Figure 4.10. Concrete mixture with 564 lb/yd3 and 20% fly ash

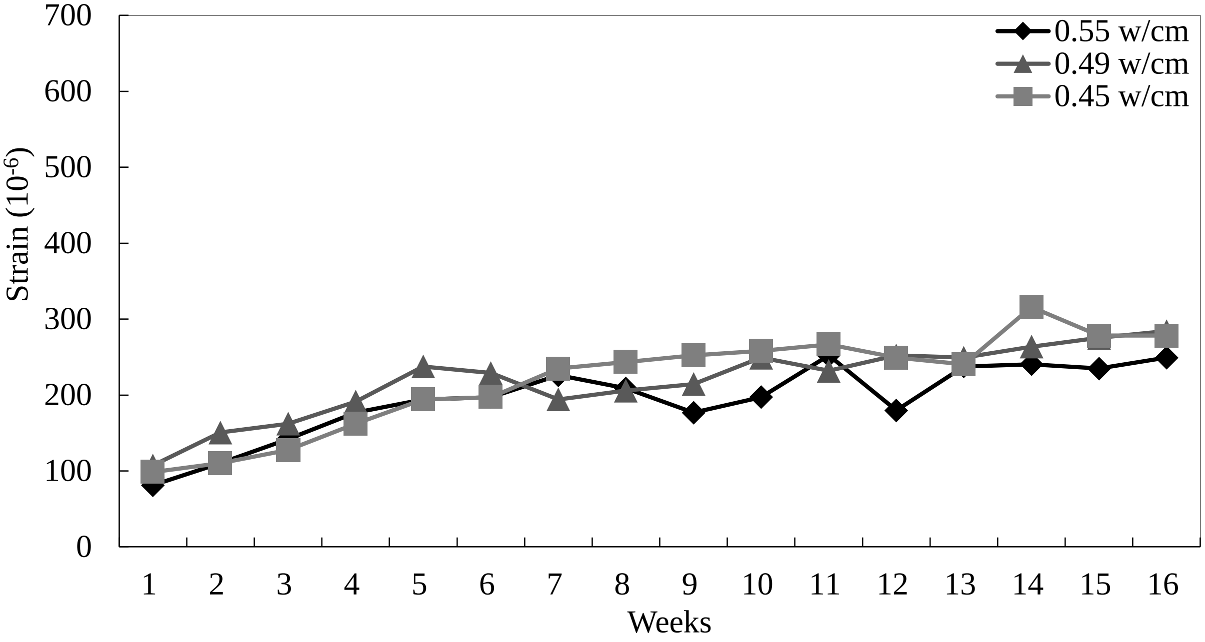

Figure 4.11. Concrete mixture with 517 lb/yd3 and 20% fly ash

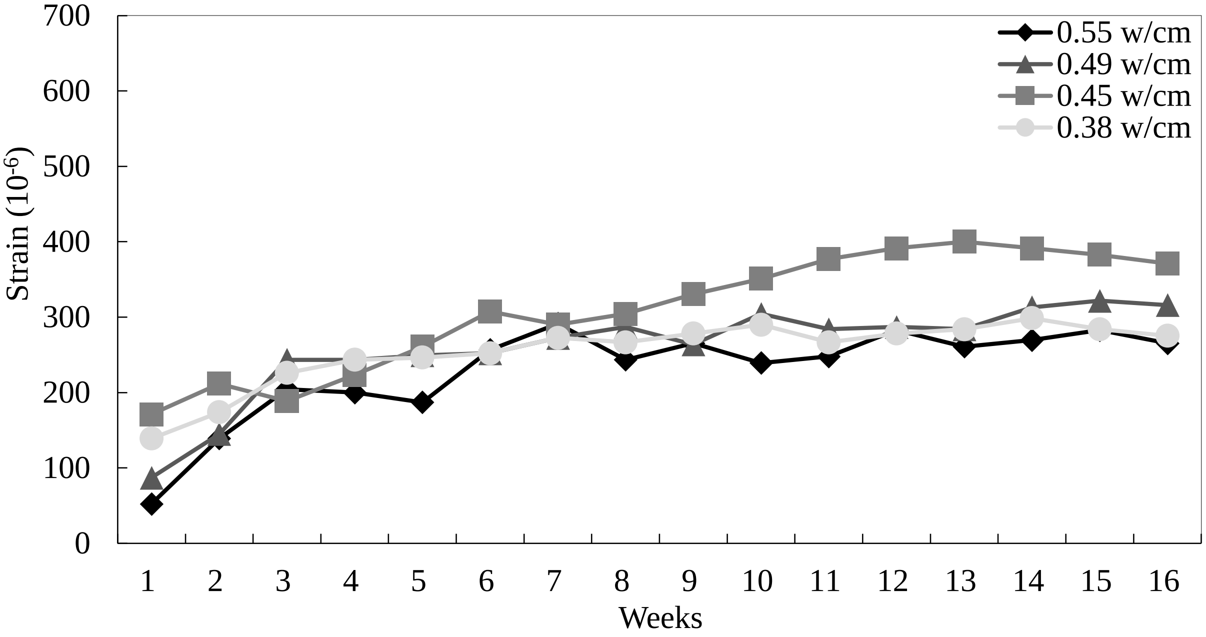

Figure 4.12. Concrete mixture with 611 lb/yd3 and 30% fly ash

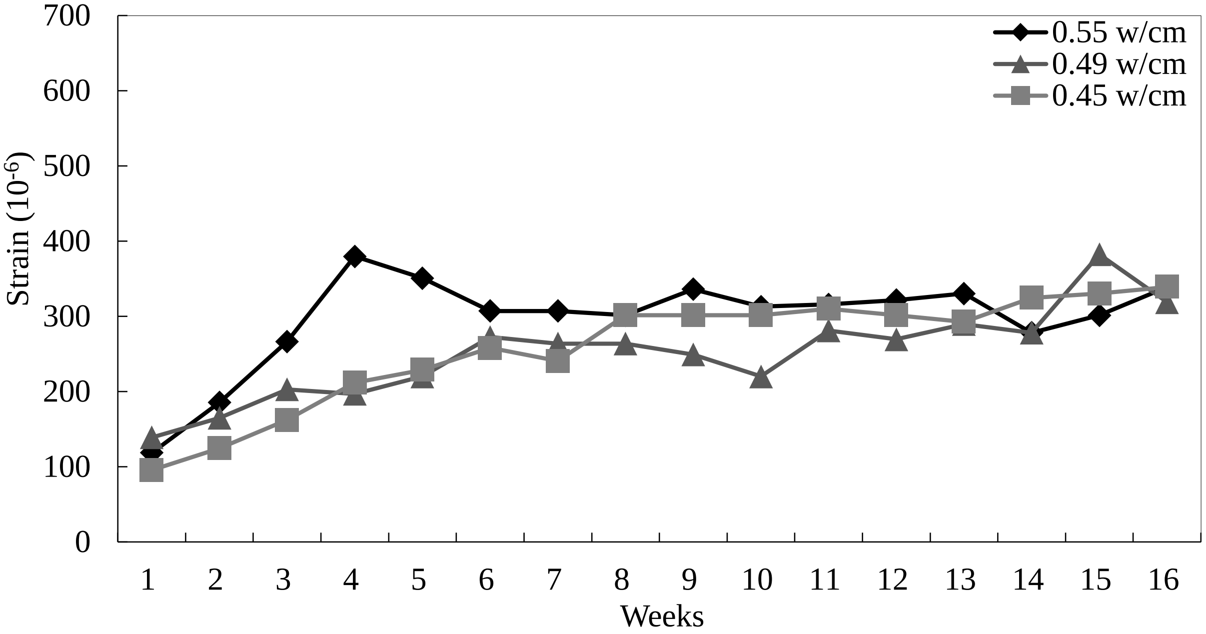

Figure 4.13. Concrete mixture with 564 lb/yd3 and 30% fly ash

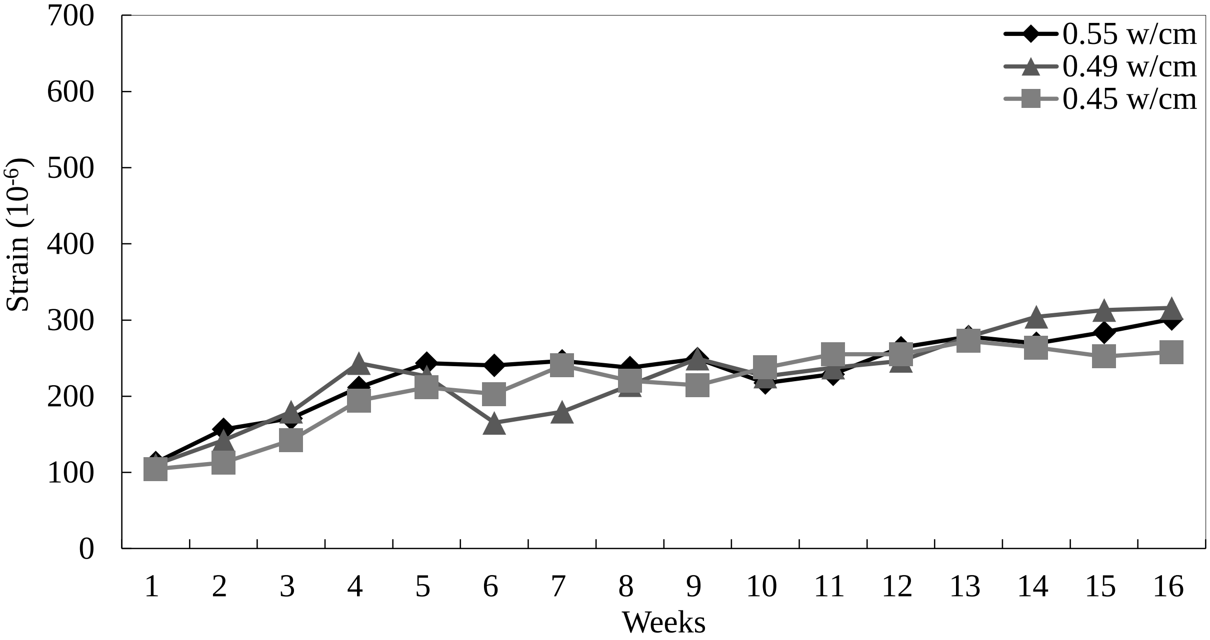

Figure 4.14. Concrete mixture with 517 lb/yd3 and 30% fly ash

4.3.2.3. Summary of Drying Shrinkage Results

Babaei et al (1995) states that shrinkage cracking may be reduced by limiting the 4 months drying shrinkage to 700 $\times 10^{-6}$ microstrains or less. As shown in Figure 4.15, the highest strain value of 16 weeks of age is approximately 350$\times 10^{-6}$ 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 affect cracking due to drying shrinkage. Also, replacement 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). Figure 4.15 represents the error bars to indicate the statistical significance of the data. The graph shows the standard deviation of each mixture for the final shrinkage at 16 weeks. The standard deviations for each mixture were plotted to show method is used to determine the distribution of the data around the mean values. In Figure 4.15, when the error bars overlap, it means the difference in drying shrinkage between mixtures is not statistically significant. Based on the results, no conclusions can be drawn from the differences in cement content, w/cm, or fly ash content.

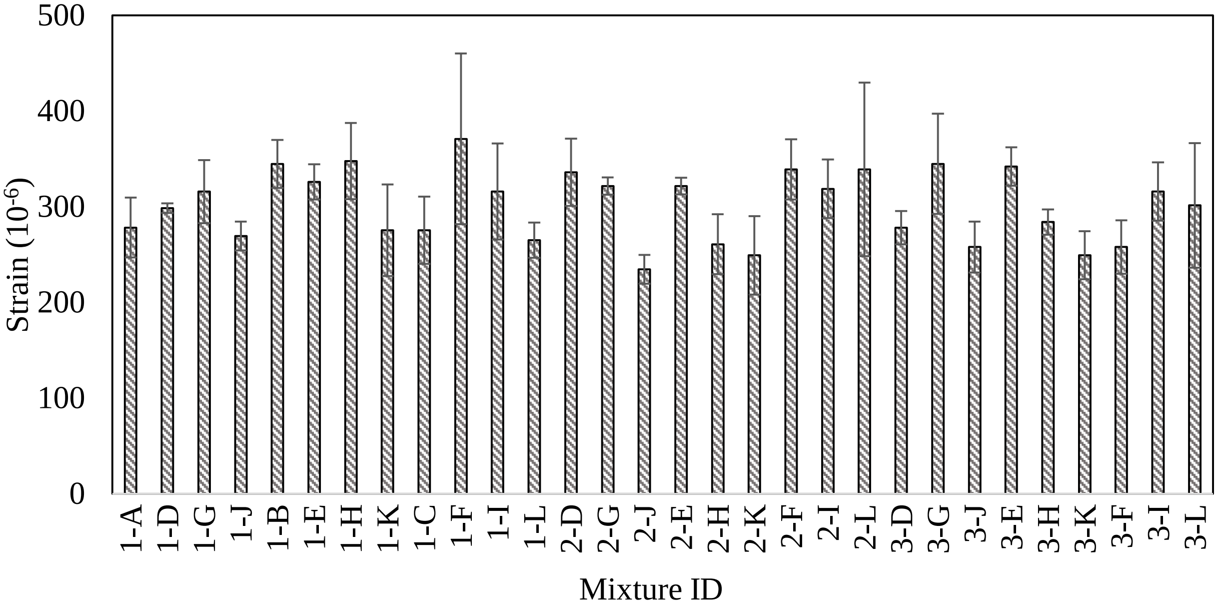

Figure 4.15. The ultimate drying shrinkage for all concrete mixtures

4.3.3. Modulus of Elasticity

Illustrated in Figure 4.16 is the relationship between modulus of elasticity and compressive strength. The modulus of elasticity was not determined for all mixtures. The modulus of elasticity was measured for only the mixtures with the lowest and highest compressive strength at 28 day. The predicted values from the standard ACI and AASHTO equations were compared to the measured data at 7, 28, 56 days. These equations are shown below as Equation 1 and 2.

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

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

The modulus of elasticity values estimated using the ACI and AASHTO equations provide a good agreement with the measured values. The modulus of elasticity of all concrete mixtures selected was within the range of 3000 to 6000 ksi. Based on the modulus elasticity data listed in Table 4.3, cement content and fly ash content did not considerably affect the modulus of elasticity. For example, for mixtures at a w/cm of 0.55 and fly ash content of 20%, the modulus of elasticity at 28 day slightly increased from 4290 to 4510 ksi as cementitious material content decreased from 611 lb/ to 564 lb/yd^3. When fly ash content increased from 20 to 30% for mixtures of 611 lb/yd^3 at w/cm of 0.38, the modulus of elasticity at 28 day decreased from 5710 to 5560 ksi. W/cm has a slightly higher effect on modulus of elasticity than cementitious material content and fly ash. As shown in Table 4.3, for mixtures having cementitious material content of 611 lb/yd^3 and 20% fly ash, the modulus of elasticity at 28 day decreased from 5190 to 4290 ksi as w/cm increased from 0.45 to 0.55.

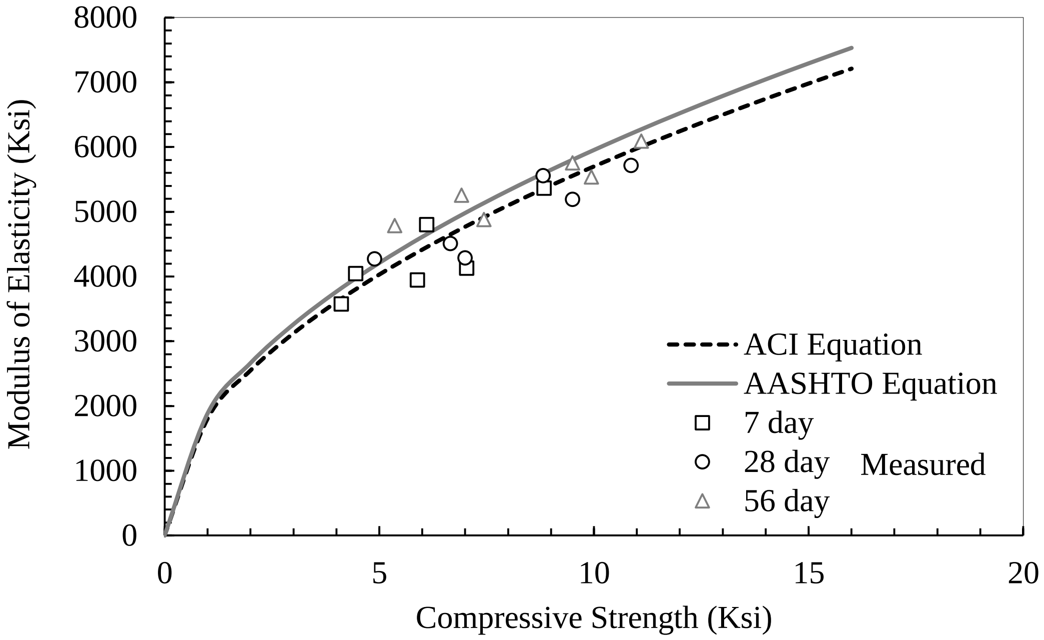

Figure 4.16. Modulus of Elasticity measured compared to the prediction equations

Table 4.3. Modulus of elasticity data

Day	611 lb/yd^3 - 20% -0.38	611 lb/yd^3 - 30% -0.38	611 lb/yd^3 - 20% -0.45
	Modulus of Elasticity (Ksi)		
7	5370	4800	4130
28	5710	5560	5190
56	6090	5760	5540
Day	517 lb/yd^3 - 0% -0.55	611 lb/yd^3 - 20% -0.55	564 lb/yd^3 - 20% -0.55
	Modulus of Elasticity (Ksi)		
7	3570	4040	3950
28	4270	4290	4510
56	4780	4880	5250

4.4. Cost Saving

In this section, the costs of a range of mixtures examined in this study were examined. According to information obtained from AHTD, the quantity of Class S concrete that was cast in Arkansas from year 2006 to 2015 was 147,577 yd^3. Using the cost data shown below in Table 4.4, the price of the concrete was determined. The prices for the materials used were from the receipts of the materials delivered to the laboratory.

Table 4.4. Local prices for the materials used

Material	Price ($)*
Cement	100
Fly Ash	35
Rock	16.5
Sand	23.8

* Prices listed above are per 2000 lbs

For a given w/cm of 0.49, the mixture having 611 lb/yd^3 cementitious content with 20% fly ash replacement is the least expensive mixture that meets current AHTD specifications. The material price of this the concrete is approximately $56.60/yd^3. It should be noted that this price excludes any costs associated with transportation from the concrete plant to the job site. For the same w/cm of 0.49, if the cement content was reduced to 517 lb/yd^3 cementitious and 30% of the cement was replaced with fly ash, the mixture would cost approximately $53.00/yd^3. The difference between the two mixtures is \$3.60/yd3 and based on the amount of Class S concrete cast from 2006 to 2015, the cost savings could have been \$518,733 as shown in Table 4.5.

Table 4.5. Estimated cost difference

Year	Quantity (yd^3)	Cost (\$)	
		611 lb/yd^3- 20% FA	517 lb/yd^3- 30% FA
2006	13939	789,547	740,553
2007	8545	484,012	453,977
2008	10972	621,522	582,954
2009	11108	629,223	590,177
2010	17420	986,722	925,492
2011	16302	923,413	866,111
2012	21307	1,206,913	1,132,019
2013	27396	1,551,797	1,455,502
2014	17324	981,314	920,420
2015	3264	184,890	173,417
Sum	147577	8,359,352	7,840,619
∑ Savings		\$518,733	

5. Conclusions

The goal of the research program was to determine if the cement content could be reduced in Class S concrete and to determine what effect reducing the cement content would have on the fresh and hardened properties. The testing variables included cement content, fly ash content, and w/cm. The fresh concrete properties such as slump and unit weight along with the hardened concrete properties (compressive strength and drying shrinkage) were measured for each mixture. The findings of the study are listed below.

- AHTD should allow their minimum required cementitious material content for Class S concrete to 517 lb/yd^3.
- Class C fly ash content is recommended to increase to 30%.
- 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 strength and had a small shrinkage value.
- Most concrete mixtures met the specified slump by AHTD of 1-4 in, but some mixtures with 0.55 w/cm had higher slump, and the concrete mixtures with 0.38 w/cm and 564 lb/yd^3 and 517 lb/yd^3 were not be able to be mix because of the low paste.
- All concrete mixtures achieved the required compressive strength of 3500 psi at 28 day and 7 day.
- 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.
- There was little change in drying shrinkage when varying w/cm and Class C fly ash content. This lack of change was due to the high amount of coarse aggregate of 1800 lb/yd^3.

- There was not a significant change in drying shrinkage when reducing cementitious content from 611 lb/yd^3 to 564 lb/yd^3 and 517 lb/yd^3.

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