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Effects of high volume fly ash and powder activators on plastic and hardened concrete properties

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EFFECTS OF HIGH VOLUME FLY ASH AND POWDER ACTIVATORS ON PLASTIC AND HARDENED CONCRETE PROPERTIES

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ABSTRACT

This study was performed to examine the effects of high volumes of Class C fly ash modified by powder activators upon the plastic and hardened properties of concrete. In a companion study, five Missouri area cements and five Class C fly ashes were examined for incompatibilities, with the most and least reactive combinations being scaled up to full scale concrete testing. Two baseline concrete mixtures were examined, the only difference in mixtures being the sources of portland cement and fly ash. Fly ash replacement was examined at 50% and 70% replacement (by total cementitious mass). Three powder activators were used in combination with the cement and fly ash mixtures: 4% gypsum, 10% hydrated lime, and 20% rapid set cement (by mass of fly ash). Gypsum was present in all concrete mixes, with either hydrated lime or rapid set cement acting as an activator in combination with it.

Both plastic concrete and hardened concrete properties were examined. The use of powdered activators in combination with fly ash resulted in the concrete exhibiting adequate 28 day strength, stiffer moduli, less drying shrinkage, lower chloride permeability, and improved resistance to freezing and thawing at 50% fly ash replacement when compared to a baseline mix, although the mixture suffered in abrasion resistance and salt scaling resistance. At 70% fly ash replacement, the mixtures performed poorly compared to their baseline counterparts, even with the addition of rapid set cement. The choice of activator primarily affected the early age strength and setting time, with rapid set cement mixtures exhibiting a quicker set and a higher earlier strength than the hydrated lime mixtures, though this did not correspond to improved characteristics in the long term. In applications where early properties are not important, the use of less expensive calcium hydroxide is recommended. In any applications, however, the specific cement and fly ash sources should be examined for possible incompatibilities.

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1. INTRODUCTION

1.1. STATEMENT OF PROBLEM

Partial fly ash substitution in concrete mixtures is not a new idea, and the benefits of increased workability, a less permeable microstructure, and improved long term strength have long been known. Substitution of cement with high volumes of fly ash (greater than 50% by mass of total cementitious materials), however, is not without problems, including delayed time of set, a decreased rate of strength gain, and certain durability issues. Because of this, substitution of cement with fly ash has been traditionally limited to around 25% by mass. A 2010 study by Bentz suggested the promise of two particular powdered activators in mitigating the delayed set and lowered strengths: calcium hydroxide and rapid set cement, used in combination with the addition of powdered gypsum (Bentz, 2010)

1.2. OBJECTIVES

The Missouri Department of Transportation (MoDOT) is interested in raising the current specification limit of 25% replacement of cement with fly ash. The objective of this study was to examine the effects of three powder activators upon high volume fly ash (HVFA) concrete mixes. Concrete properties examined included both fresh concrete and hardened concrete properties.

1.3. SCOPE OF INVESTIGATION

This project dealt with the effects of HVFA and powder activators. Initially, five Type I or Type I/II cements and five Class C fly ashes from the Missouri area were selected, representing both east and west sides of the state. Fly ash substitution levels were chosen as zero% replacement for a baseline mix, 25% replacement as a typical specified upper limit, 50% replacement, and 70% replacement. Three powder activators were chosen to mitigate potential problems with setting and strength gain: gypsum, hydrated lime, and rapid set cement. The paste study portion of this project focused on determining the most and least reactive combinations of cement and fly ash, and subsequently determining adequate dosages of the powder activators.

The concrete study focused on two different cement-fly ash combinations from the previous paste study: the most reactive combination and least reactive combinations, using the optimum dosages of powder activators determined previously in the paste study. A baseline mix for each combination with no fly ash was compared to both 50% and 70% replacement of cement with fly ash by mass. All concretes used in the study were air entrained to five percent air as per MoDOT standards, and included a varying dosage of a polycarboxylate water reducer in order to achieve a 5 in. slump.

Fresh concrete properties examined in the concrete study included slump, air content by pressure method, unit weight, water content by microwave method, and time of set. Hardened concrete properties examined in the concrete study included compressive strength, modulus of elasticity, flexural strength, splitting tensile strength, abrasion resistance, scaling resistance, freeze-thaw resistance, rapid chloride permeability, and shrinkage.

2. REVIEW OF LITERATURE

2.1. HIGH VOLUME FLY ASH MIXES

2.1.1. High Volume Fly Ash Hydration. HVFA concrete mixes are typically defined as concrete mixes containing larger than normal replacements of cement with fly ash. This replacement is typically greater than or equal to 30% replacement (Naik, et al., 1995) and often is defined as 50% or more. Replacing large volumes of cement with fly ash in this manner, however, drastically influences the hydration curve of the cement. Wang, et al. investigated the effects of fly ash and admixtures on the hydration curve of the cementitious system. They replaced Type I and II cement with 20% of Class F and Class C fly ash. Class F fly ash served only to reduce the heat release, while Class C fly ash reduced the heat release as well as delaying the peak of the hydration curve, effectively serving to retard the set of the concrete mixture. When combining substitution of fly ash with the addition of a water reducing admixture and a retarding admixture, the Class C mixes were more significantly affected than any other combination, impeding hydration for an extended time (Wang, et al., 2006)

Roberts and Taylor examined the effects of water reducing admixtures and Class C fly ash in terms of the root causes. Roberts and Taylor discussed the importance of sulfate in the hydration of cement. Sulfate is required in order to force the reaction of tricalcium aluminate (C_3A) and tetracalcium aluminoferrite (C_4AF) to ettringite. Ettringite requires a significant concentration of sulfate in order to form and remain stable—once the sulfate level drops below the level required to maintain stable formation of ettringite, it undergoes conversion to monosulfate. In addition, the sulfate level affects the reaction of the silicates (tricalcium silicate, C_3S and dicalcium silicate, C_2S) in cement, more fully hydrating the silicates and resulting in higher strengths. If not enough sulfate is present in the cement, ettringite will be unable to slow the reaction of C_3A, which will consume the calcium in solution, slowing or stopping the hydration of silicates, and resulting in retardation of set, or failure to set (Roberts & Taylor, 2007).

Roberts and Taylor then discuss the causes behind water reducing admixtures and Class C fly ash retarding or preventing set. They put forward evidence that as dosages of water reducing admixtures increase, the silicate hydration peak is retarded, resulting in retarded set. Beyond a point, the sulfate depletion occurs before the silicate hydration peak, resulting in the formation of monosulfate, and the consumption of calcium in C_3A hydration, leading the silicate peak to be severely retarded and depressed. Combining this effect with substitution of Class C fly ash, which depresses the silicate hydration peak, set may not occur (Roberts & Taylor, 2007).

Jiang, et al. investigated the hydration of HVFA pastes using replacement rates of 40% or greater. They found that as the fly ash content increased and as the w/cm increased, the total porosity increased. At a fly ash content of 70%, mixtures with a larger w/cm show a greater permeability, suggesting that the fly ash content should be limited to less than 70% in HFVA concrete. However, with increase of age, the porosity decreased, with pore volumes in HVFA mixes being of a smaller size. This is because the hydration of fly ash particles lends to a denser microstructure with an improved pore size distribution. However, using a scanning electron microscope, even at 90 days, many unreacted fly ash particles were found embedded in hydration products. This may imply that the fly ash in HVFA concrete cannot be fully hydrated (Jiang, et al., 1999).

Hübert, et al. examined the hydration products in HVFA binders. Three blended cements were examined containing 60%, 70%, and 85% replacement of portland cement by weight with two different fly ashes. Hydration was halted after 3, 7, 28, 90, and 300 days, to examine and characterize the hydration products. For every HVFA mixture, the calcium hydroxide content was lower than the baseline cement-only mixture at all ages. For several of the mixtures, complete depletion of calcium hydroxide occurred, likely due to the high reactivity of the fly ash. Ettringite content was also examined in the mixes, with evidence that ettringite was also a product of the hydration of the fly ash in these systems. The two different fly ashes showed that differing fly ash contents were required to attain the greatest amount of additional C-S-H. This is likely due to the varying consumption of calcium hydroxide. The reactivity of the fly ash used in a concrete mix needs to be adapted to the amount of available calcium hydroxide for optimal increase in strength (Hübert, et al., 2001).et al. This conclusion leads to an examination of supplemental powder activators.

2.1.2. Powder Activators. Bentz examined HVFA mixes with a 50% replacement of cement with fly ash. The author noted the lowered strength of 50% Class C fly ash cubes using a Class C fly ash with no additional source of calcium sulfate, and produced pastes with varying levels of gypsum between one and five percent. The addition of gypsum served to increase early age hydration and strength, however did nothing to influence the retardation in set seen in 50% fly ash mixtures. Bentz concludes that these additions are necessary to restore the “normal” hydration and strength development, though do not serve to mitigate the retardation influence of the fly ash (Bentz, 2010).

Bentz examined several powder additions with the intent of mitigating the retardation seen in mixes containing 50% Class C fly ash. The powder additions with the intent of restoring the hydration curve to the time observed at the zero percent fly ash substitution hydration curve. Dosages for these powders were in percentage of total solids of the mix. A dosage of five percent of the mass of total solids of limestone powder showed a minimal effect on the hydration curve. Ten percent aluminum hydroxide increased the heights of the hydration peaks, but did not accelerate the occurrence of the peaks. In particular, aluminum hydroxide increased the height of the second peak, corresponding to secondary aluminate hydration. A dosage of 10% cement kiln dust only accelerated the curves minimally, though Bentz notes that it increased the early-age hydration. Five percent condensed silica fume accelerated the hydration, but failed to restore the curve to the condition of the baseline curve. Of the powders examined, the two determined to show a marked degree of success in restoring the normal hydration were calcium hydroxide and rapid set cement (Bentz, 2010). In addition, a paper published by Bentz and Ferraris shows that dosages of these two activators serve to decrease set times of HVFA mixes back to set times similar to a control mix, or in some cases resulting in faster setting than the baseline, while still resulting in an initial set of greater than three hours, allowing for time to transport and place the concrete (Bentz & Ferraris, 2010).

2.1.2.1. Calcium hydroxide. As Roberts and Taylor pointed out, if insufficient calcium is available and is consumed by C_3A reactions, the silicate reactions will be slowed or halted. The addition of calcium hydroxide, then, provides a source of calcium ions to restore the normal silicate reactions. Bentz points out that calcium is already being restored to the mixture in the form of gypsum, however, it is likely that the calcium and sulfate provided by gypsum are both being utilized in aluminate reactions, leading to the formation of ettringite rather than aiding in the silicate hydration. In his study, Bentz employed calcium hydroxide at a dosage of five percent of the total mass of cementitious materials. Bentz notes that this accelerated the hydration curve by 1.5 hours and also that this acceleration increased when a high range water reducer was present in the mix, nearly restoring the curve to the same position as the control mix. He suggests that calcium hydroxide may reduce compressive strengths, however (Bentz, 2010).

2.1.2.2. Rapid set cement. Bentz discusses the composition of rapid set cement, which contains calcium sulfoaluminate, dicalcium silicate, and gypsum, and suggests that the chemistry of rapid set cement may be unaffected by the retarding action of the fly ash. Bentz suggests that this may contribute to a three-component blend, utilizing rapid set cement to contribute to early age strength development and set, while fly ash contributes to the longer term performance and strength gain. In this study, Bentz employed rapid set cement was used at a dosage of 10% of the total mass of cementitious materials. He writes that rapid set cement provides two separate contributions to the mix: both the hydration reactions of the rapid set cement, and the accelerated hydration of the cement/fly ash mixture due to the rapid set cement. With a dosage of high range water reducer, Bentz notes that the retardation was reduced by four hours, with the rapid set cement reacting nearly immediately after contact with water. In addition, he writes that initial compressive strengths were greater than those with no rapid set cement addition, 105% of similar mortar without rapid set cement at 28 days. Bentz cautions that at a replacement level of 20%, the hydration may be excessive, and lead to setting occurring too rapidly (Bentz, 2010).

2.1.3. Mixture Proportioning. Bentz, et al. present a method for optimizing HVFA concrete mixes. The method as consists of four stages: checking compatibility, attaining acceptable setting times, attaining acceptable strengths, and attaining acceptable autogenous shrinkage. After selecting potential fly ash and cement sources, Bentz et al. suggest determining compatibility by means of calorimetry. If the cement and fly ash combination are deemed incompatible, then this incompatibility must be rectified by addition of gypsum in order to optimize sulfate balance (Bentz, et al., 2010).

After optimizing sulfate balance, retardation should be mitigated by means of either powder addition to the mix, or admixture replacement. Bentz et al. note that calcium hydroxide and rapid set cement were both found to have potential for restoring setting time at levels of 5% to 10% per mass of binder. Adjustment of the dosage of water reducer, if applicable, may be necessary at this level (Bentz, et al., 2010).

Though long term strengths of HVFA mixtures may approach or exceed those of control mixtures, short term strengths may suffer. Bentz et al. note that if higher one day strengths are required from the HVFA mix, switching to a Type III cement may provide increased early strengths. The authors found switching from a Type II/V cement to a Type III cement resulted in a compressive strength increase of 60% at one day (Bentz, et al., 2010).

Finally, Bentz et al. write that for HVFA mixtures, it is critical to maintain saturation of the capillary pores in order to not only hydrate the long term strength products, but also to reduce autogenous shrinkage. The authors write that external curing may not be enough, due to the limited travel distance of water once the capillary porosity becomes severely limited due to hydration. Bentz et al. tout the effectiveness of internal curing in providing a long term source of hydration for pozzolanic reactions. The authors warn, however, if this method is chosen that the cost of materials will significantly increase. By following this method of proportioning HVFA concrete mixes, the authors write that benefits will include a lowered tendency toward thermal cracking due to the lower heat release of HVFA concrete mixes, as well as a cost savings at the time of placement as well as over a life-cycle. (Bentz, et al., 2010).

2.2. PLASTIC CONCRETE PROPERTIES

2.2.1. Slump. A study by Bouzoubaa, et al. involving laboratory-produced HVFA cements noted the influence of varying fly ash on slump and required dosage of superplasticizer. Of the two mixtures involving fly ashes, it was noticed that the mixture using unground fly ash required less superplasticizer to achieve a given slump than the mixture using fly ash which had been interground with the cement. The authors note that the increase in required superplasticizer was due primarily to the increased fineness of the interground fly ash (Bouzoubaa, et al., 2001).

Bouzoubaa, et al. investigated the use of 30%, 40%, and 50% by mass replacement of cement with fly ash. Bouzoubaa et al. created three concrete mixtures of different grades: 2900 psi, 5800 psi, and 8700 psi by varying the cement content, and made one control concrete without fly ash, and three at the various substitution levels.

They found that as fly ash content increased, the water requirement to attain a given slump decreased, and consequently the w/cm decreased as well (Bouzoubaa, et al., 2007).

2.2.2. Air Content. A study by Bouzoubaa, et al. involving laboratory-produced HVFA cements noted the influence of varying fly ash on air content and required dosage of air entraining agents. Of the two mixes containing fly ash, the authors note that the mix using a fly ash which had been interground with the cement required a higher dosage of air entraining agent than the mix using an unground fly ash. They note that this was also primarily due to the increased fineness of the interground fly ash (Bouzoubaa, et al., 2001).

A study by Bilodeau, Sivasundaram, Painter, and Malhotra notes that in air entraining HVFA concretes, the amount of air entraining agent required to attain the desired air content was greatly influenced by both the fly ash and the cement used in the mixture. The authors posit that the differing dosage is due to the carbon and alkali contents of the fly ash used, the fineness of the fly ash used, and the alkali content of the cement used (Bilodeau, et al., 1994).

2.2.3. Time of Set. Mehta and Monteiro note that the initial setting and final setting times are arbitrarily defined in test methods, and they do not mark a specific physical or chemical change in the cement paste, but rather “the former defines the limit of handling and the latter defines the beginning of development of mechanical strength”. Mehta and Monteiro also warn that when measured by a penetration method such as ASTM C 403, the penetration resistance does not indicate the compressive strength of the concrete. At the time of final set, when concrete shows a penetration resistance of 4000 psi, the compressive strength may only be around 100 psi (Mehta & Montiero, 1993).

A study by Bouzoubaa,et al. involving laboratory produced HVFA cements examined initial and final setting on concrete mixtures for both control and HVFA concrete mixtures. The authors found that the setting times for HVFA concrete mixtures were 30 minutes to 3 hours and 30 minutes longer than those baseline mixes. The fly ash mixes used in this study consisted of 45% by mass of cement, and 55% by mass of a Class F fly ash (Bouzoubaa, et al., 2001).

2.2.4. Microwave Water Content. The method used for determining water content of fresh concrete by microwave method comes from work done by Nagi and Whiting. The authors used a 900 W microwave oven to dry a 1500 g sample of concrete. Nagi and Whiting determined a schedule for microwaving the sample and breaking it up in order to achieve full recovery of water content within a reasonable amount of time. The authors found that a delay of up to 30 minutes from initial mixing showed no effect on the results of microwave water content determination, as well as developing a limited amount of precision data, showing that there was good agreement between multiple operators after only a brief instruction in the test method. Nagi and Whiting note that in addition to being reproducible, the test is also independent of absorption of aggregates or the consistency of the concrete, having tested it on mixes ranging from a 0.2 inch slump to a 6.6 inch slump (Nagi & Whiting, 1994).

2.3. HARDENED CONCRETE PROPERTIES

2.3.1. Compressive Strength. Compressive strength of HVFA mixtures typically suffers in the short term, as highly reactive cement is replaced with less reactive fly ash. A study by Bouzoubaa, et al. shows 55% Class F fly ash mixes obtaining around half the strength of regular portland cement mixes at one day. In the study by Bouzoubaa et al., fly ash mixes only begin to match or exceed the strength of control mixes between 14 and 28 days, with substantial strength gains still occurring out to one year. This is due to the pozzolanic activity of the fly ash present in the mix reacting to continue to form C-S-H (Bouzoubaa, et al., 2001).

A study by Galeota, Giammatteo, and Marino shows strengths of Class F fly ash mixes at 30%, 40%, and 50% replacement by mass of cement with fly ash lagging behind their control mix counterpart in strengths. The difference between the control mixture and the HVFA mixes lessens as the specimens age, and at one year of age, the 40% fly ash mix has exceeded the control mix in compressive strength (Galeota, et al., 1995).

A study by Naik, Ramme, Kraus, and Siddique examined long term effects of high volumes of both Class C and Class F fly ashes on concrete mixtures. The authors found that increasing volumes of both Class C and Class F fly ashes resulted in a similar decrease in early strengths, although Class F fly ashes show a better long term strength gain correlation with increased fly ash volume. Naik et al. also note that Class C fly ashes performed better at early age strength gain than Class F fly ashes, due to the pozzolanic activity imparted by the higher calcium content of Class C fly ashes (Naik, et al., 2003).

2.3.2. Flexural Strength. Bouzoubaa, Bilodeau, Sivasundaram, and Chakraborty investigated the use of 30%, 40%, and 50% by mass replacement of cement with fly ash. Bouzoubaa et al. created three concrete mixtures of different grades: 2900 psi, 5800 psi, and 8700 psi by varying the cement content, and made one control concrete without fly ash, and three at the various substitution levels. The authors found that in general, splitting tensile and flexural strength increased with age and with increasing grade of concrete, however, the effect of fly ash was more varied. At the 2900 psi grade, fly ash content did not seem to affect the flexural strength significantly until 91 days of age, however at 5800 psi there were noticeably higher flexural strengths compared to the control concrete, and at 8700 psi, higher fly ash content resulted in a general decrease in flexural strengths (Bouzoubaa, et al., 2007).

A study by Naik, Ramme, and Tews examined three different fly ash mixtures: 20% Class C fly ash, 50% Class C fly ash, and 40% Class F fly ash. The authors found that as fly ash content increased for Class C ashes, the flexural strength suffered at low ages, though as the age approached a year the flexural strength of the 50% Class C fly ash mix approached and then exceeded the flexural strength seen by the 20% Class C fly ash mix. Flexural strength development curves followed a similar curve shape as that of compressive strength (Naik, et al., 1995).

2.3.3. Splitting Tensile Strength. Bouzoubaa, Bilodeau, Sivasundaram, and Chakraborty investigated the use of 30%, 40%, and 50% by mass replacement of cement with fly ash. Bouzoubaa et al. created three concrete mixtures of different grades: 2900 psi, 5800 psi, and 8700 psi by varying the cement content, and made one control concrete without fly ash, and three at the various substitution levels. The authors found that in general, splitting tensile and flexural strength increased with age and with increasing grade of concrete, however, the effect of fly ash was more varied. At the 2900 psi grade, fly ash content did not seem to affect the splitting tensile strength significantly, however at 5800 psi there were noticeably higher splitting tensile strengths compared to the control concrete, and at 8700 psi, higher fly ash content resulted in a decrease in splitting tensile strengths, with lower splitting tensile strengths than the control concrete at 91 days of age (Bouzoubaa, et al., 2007).

A study by Rivest, Bouzoubaa, and Malhotra involved casting large monoliths of control concretes and of a 56% fly ash HVFA mix with accompanying specimens to test mechanical properties. The authors note that splitting tensile strengths were expected to fall in the range of 8% to 10% of the compressive strength as published data expected (Rivest, et al., 2004).

A study by Naik, Ramme, and Tews examined three different fly ash mixtures: 20% Class C fly ash, 50% Class C fly ash, and 40% Class F fly ash. The authors found that as fly ash content increased for Class C ashes, splitting tensile strengths decreased, following similar strength development curves as expected of compressive strength (Naik, et al., 1995).

2.3.4. Modulus of Elasticity. A study by Rivest, Bouzoubaa, and Malhotra involved casting large monoliths of control concretes and of a 56% fly ash HVFA mix, as well as a large number of specimens in order to test various properties. Rivest et al. found that the modulus of elasticity for the HVFA concrete mix was generally higher than both control concretes made with Type I and with Type II cement. They suggest that this is due to unreacted glassy fly ash particles acting as very fine aggregates rather than hydration products, thereby increasing the rigidity of the concrete. The authors also note that the "filler" effect of the fly ash contributes to a stronger transition zone, subsequently increasing the rigidity of the concrete (Rivest, et al., 2004).

2.3.5. Abrasion Resistance. An article by Cabrera and Atis discusses the major issues with abrasion testing. The authors present the fact that there are no guidelines on values from abrasion tests that ensure whether a concrete will perform adequately or not. Cabrera and Atis write that because of this, abrasion results may only be used on a comparative basis. The authors used a British abrasion standard typically used for abrasion characteristics of aggregates in their study, though mention that their findings confirm other studies that abrasion is closely related to compressive strength (Cabrera & Atis, 1999).

A study by Naik, Singh, and Ramme investigated the use of three Class C fly ashes in concrete mixtures at replacement rates of 40%, 50%, and 60%. The authors investigated abrasion resistance, using a modified version of ASTM C 944, involving the addition of silica sand to the surface at one minute intervals while abrading the specimen, and measuring the resulting depth of wear with time. Naik et al. noted that the resistance to abrasion increased with age, and decreased with both time abraded and fly ash content, though the authors also note that 40% replacement of cement with fly ash seemed to perform as well as the control mixture with no ash. Naik, Singh, and Ramme also point out a correlation between abrasion resistance and compressive strength, noting that with increased compressive strength, the specimens were subject to less wear. The source of fly ash showed a significant effect on hardened concrete properties, though no definite trend was established by the authors between fly ash properties and abrasion resistance (Naik, et al., 2002).

2.3.6. Rapid Chloride Permeability. Rapid Chloride Permeability was measured by means of ASTM C 1202, which notes that the test measures electrical conductance of concrete, which is a rapid method of indicating concrete's resistance to chloride ion penetration, not a direct measure of chloride ion penetration (American Society for Testing and Materials, 2012).

A HVFA concrete study by Gu, Beaudoin, Zhang, and Malhotra examined the performance of steel reinforcement in HVFA concretes when exposed to chloride solutions. Two HVFA mixtures in this study incorporated 58% by mass as a cement replacement: one containing Class F fly ash, and one with a Class C fly ash. The authors note greater resistance to chloride ion permeability than control concretes, even at only 28 days of age (Gu, et al., 1999).

Bilodeau, Sivasundaram, Painter, and Malhotra examined a number of HVFA concrete mixtures containing 58% replacement of cement by mass with fly ash. The authors examined the resistance of concrete to chloride ion penetration from 28 days out to one year, and found that all concretes showed high resistance to chloride ion penetration, with values at one year being rated 'very low', or less than 1000 coulombs passed. In addition, Bilodeau et al. note a relationship between chloride ion penetration and compressive strength of concrete. They state that differences between two mixtures using two different cements are likely due to differences in porosity as a result of differing rates of hydration and pozzolanic reaction in different cement and fly ash combinations (Bilodeau, et al., 1994).

Bouzoubaa, Bilodeau, Sivasundaram, and Chakraborty investigated the use of 30%, 40%, and 50% by mass replacement of cement with fly ash. Bouzoubaa et al. created three concrete mixtures of different grades: 2900 psi, 5800 psi, and 8700 psi by varying the cement content, and made one control concrete without fly ash, and three at the various substitution levels. What they found was that while satisfactory chloride ion permeability could be achieved simply by reducing the w/cm ratio, the addition of fly ash drastically reduced chloride ion permeability as soon as 28 days, with 91 day tests showing coulomb values of less than 300, or almost negligible permeability (Bouzoubaa, et al., 2007).

2.3.7. Freeze-Thaw Resistance. The mechanism by which freeze-thaw damage occurs is not solely due to the 9% expansion of water when freezing, according to research by Powers. Powers states that when water begins to freeze within pores in the concrete, the pore must dilate by 9% or else force some excess water out through the boundaries, generating hydraulic pressure. The magnitude of this hydraulic pressure is dependent upon the distance to an escape boundary, such as an air void. If the distance to an escape boundary is too great, disruptive pressures will form and damage the paste, resulting in freeze-thaw damage. This also serves to explain the beneficial effect of the use of air entrainment agent in concrete (Powers, 1958).

Bilodeau, Sivasundara, Painter, and Malhotra examined a number of HVFA concrete mixtures, consisting of 58% substitution by mass of cement with fly ash. In examining resistance of concrete prisms to freezing and thawing, the authors found that after 300 cycles of freezing and thawing, all combinations of cement and fly ash showed excellent durability, with durability factors of greater than or equal to 96. Bilodeau et al. extended the freezing and thawing tests to 1000 cycles, an extremely severe condition, and all but one mix retained durability factors of greater than or equal to 93. The one exception showed a durability factor of 67, which was still deemed acceptable (Bilodeau, et al., 1994).

Work by Galeota, Giammatteo, and Marino examined four concrete mixtures—one control mix with no fly ash, and three HVFA mixtures—at 30%, 40%, and 50% replacement of cement with fly ash. The authors used a Class F fly ash, and did not air entrain their concrete mixtures. The control mixture with no fly ash and the 30% fly ash mix failed earlier than did their counterparts containing more fly ash, showing that increased fly ash content seems to increase freeze-thaw resistance (Galeota, et al., 1995).

2.3.8. Scaling Resistance. The freeze-thaw resistance of concrete when in contact with deicing salts is generally lower than the resistance to freezing and thawing alone, with the most damage occurring to concrete surfaces at a salt concentration of 4-5 percent (Mehta & Montiero, 1993). Rosli and Harnik examined the possible reasons for scaling to occur when concrete is subjected to a combination of freezing and deicing salts. Rosli and Harnik discuss the inhomogeneity of concrete at the surface, namely that the cement gel, fine aggregate particles, and capillarity is more concentrated than through the rest of the concrete, and there are less coarse aggregate particles. This means that concrete properties differ at this ‘transitional zone’, including w/c, modulus of elasticity, and pore volume (Rosli & Harnik, 1980).

Rosli and Harnik also discuss the presence of several gradients in concrete, leading to a “layer by layer” freezing effect which can cause cracking and spalling of the concrete when subjected to deicing salts and freezing. The first gradient discussed is water content, with the highest concentration of water being present at the surface of the concrete, with the gradient tapering off further into the concrete due to the lowered permeability of concrete. The presence of this gradient means that a “water front” will form. This water front is the boundary between frozen and unfrozen concrete, as the outer saturated layer will freeze earlier than the less saturated inner layers. Ice formation, then, is restrained to the outer layer until the temperature drops enough to freeze the inner layers of the concrete, which contributes to surface damage of the concrete (Rosli & Harnik, 1980).

The second gradient discussed by Rosli and Harnik is the gradient of salt concentration. Salt concentration is typically low directly on the surface of the concrete, as salt is generally washed off of the surface of the concrete by rain. The peak salt concentration, then, exists within the concrete due to chloride diffusion through the concrete. Upon freezing, the outer layers will be able to freeze sooner, due to lower chloride content, and the higher chloride content inner layers will remain unfrozen. This freezing mechanism also contributes to damage of the outer layers (Rosli & Harnik, 1980).

The final gradient discussed by Rosli and Harnik is the thermal gradient through the concrete. Rosli and Harnik write that concrete surfaces undergo “temperature shock” when ice is rapidly thawed by salt, as the heat required for spontaneous melting of ice is extracted from the concrete. This “temperature shock” leads to the formation of a large thermal gradient within the concrete, and Rosli and Harnik conclude that this rapid cooling causes tensile stresses on the order of the tensile strength of the concrete, contributing to microcracking which could lead to macrocracks after occurring repeatedly. The inhomogeneous properties of the outer layers of the concrete, combined with the three gradients discussed lead to the deterioration of the concrete in the form of scaling (Rosli & Harnik, 1980).

Bilodeau, Sivasundara, Painter, and Malhotra examined a number of HVFA concrete mixtures, consisting of 58% substitution by mass of cement with fly ash. When examining resistance to deicer salt scaling, the authors found that all HVFA concretes showed a poor resistance to deicer salt scaling. All tested combinations of cement and fly ash by Bilodeau et al. showed a rating of 5 at 50 cycles, or severe scaling, with the exception of one mix showing a rating of 4, or moderate to severe scaling. The specimens were all air entrained, and showed good performance against repeated freezing and thawing, as well as showing good air void parameters in specimens cut from concrete prisms. The authors note no observable difference between concrete made with different cement brands, though they note that the scaling residue collected differed considerably depending upon the fly ash used (Bilodeau, et al, 1994).

A study by Naik, Kraus, Ramme, and Siddique investigated long term pavement performance of HVFA concrete pavements, containing up to 70% cement replacement with Class C fly ash, and up to 67% cement replacement with Class F fly ash. To the contrary of Bilodeau et al.'s results showing severe scaling in laboratory pavements containing 58% fly ash, Naik et al. examined several in use pavements and found comparatively less scaling. Naik et al. found through a visual observation of the surface of in use pavements that an 18 year old pavement containing 70% Class C fly ash rated at 3+, or moderate to heavy scaling, and a 12 year old pavement containing 50% Class C fly ash received a rating of 2, representing very slight to slight scaling. These results indicate a difference in field performance and laboratory scaling results (Naik, et al., 2003).

A study by Bouzoubaa, Zhang, Malhotra, and Golden consisting of 55% replacement by mass of cement with fly ash examined the scaling susceptibility of such a mix and concluded that HVFA concretes exhibited severe scaling, showing a visual rating of 5 according to ASTM C 672. The authors note, however, that experimental HVFA concrete sidewalks in Halifax, Canada were subjected to four winters and over 400 freezing and thawing cycles, combined with numerous applications of deicing salts, but show satisfactory performance. Bouzoubaa et al. suggest that ASTM C 672 may be overly severe in its assessment of concrete's performance in field applications (Bouzoubaa, et al, 2001).

2.3.9. Shrinkage. A study by Rivest, Bouzoubaa, and Malhotra involved casting large monoliths of control concretes and of a 56% fly ash HVFA mix with accompanying specimens to test mechanical properties. Rivest et al. recorded shrinkage strains out to one year for the HVFA concrete mix as well as control mixtures made with Type I and Type II cement. The authors found that the control concretes showed more shrinkage (strains of 0.069 and 0.059 mm/mm respectively) compared to the HVFA concrete, showing only a strain of 0.048 mm/mm. They suggest this to be due to the lower water content requirement of HVFA concretes, as well as greater unhydrated cementitious material in the HVFA mix which serves to act as aggregate, restraining shrinkage (Rivest, et al., 2004).

3. LABORATORY INVESTIGATION

3.1. EXPERIMENTAL DESIGN

3.1.1. Paste Study Screening Matrix. This study on the effects of HVFA and powder activators on fresh and hardened concrete properties was the culmination of a larger HVFA study. The initial two phases of the study focused on the effect of HVFA and powder activators on paste. The first phase of the study, the screening matrix, focused on examining all the possible combinations of cement and fly ash from the five cements and five fly ashes selected from the Missouri area. This screening matrix was intended to determine which combinations were more or less reactive by means of one day cube compressive strengths. The most and least reactive combinations of cement and fly ash, then, were used to move forward into the main effects paste matrix. The most reactive combination came from Cement 4 and Fly ash 1, hereafter known as combination "4-1". The least reactive combination came from Cement 1 and Fly ash 3, or combination "1-3".

3.1.2. Paste Study Main Effects Matrix. The purpose of the main effects paste matrix was to examine the effects of powder activators on the two selected cement/fly ash combinations. A water reducer dosage was chosen to be on the order of a typical water reducer dosage in a concrete mixture, 2.75 fluid ounces (oz) per hundred pounds of cementitious material (cwt). In a parallel study on HVFA concrete, this water reducer dosage was reported as being successful to achieve a required slump, so the dosage necessary to achieve the required design slump of the concrete control mix was defined as "low". A higher level of water reducer dosage was also investigated, 5.0 oz/cwt. The first powder activator examined in this part of the study was powdered gypsum. Gypsum was added to all mixtures in order to mitigate the loss of gypsum due to replacement of cement, which typically has some gypsum interground with it, with fly ash, which does not. This is an important balance to strike, as Class C fly ashes may contribute additional tricalcium aluminate (C_3A) to the cement paste. Gypsum is required to ensure that uncontrolled aluminate reactions do not lead to "flash set", nor do they consume the available calcium ions and retard silicate reactions, thus prolonging initial strength gain. After selecting a gypsum addition of 4% by weight of fly ash, this portion of the paste study looked at two different dosages of calcium hydroxide, 5% and 10% by weight of fly ash, and at two different dosages of rapid set cement, 10% and 20% by weight of fly ash. Dosages chosen to move forward into the concrete study were the higher of each, 10% calcium hydroxide and 20% rapid set cement.

3.1.3. Concrete Study Variables. Five mixtures were batched and tested for both the most reactive and least reactive combinations of cement and fly ash for a total of 10 mixtures. A baseline mix consisting of 100% cement was cast for each combination and used as a reference mix. At 50% replacement of cement with fly ash, two mixtures were batched: one using calcium hydroxide and gypsum as powder activators, the other using rapid set cement and gypsum as powder activators. Similarly, two mixtures were batched at 70% replacement of cement with fly ash: one using calcium hydroxide and gypsum.

3.1.4. Mix Design. The concrete mix design used in this project was determined based upon a combination of previous research and MoDOT specification requirements. Typical specified water to cementitious ratios for structural mixtures were around 0.45, although due to concerns that at 70% fly ash the mixtures would not exhibit enough strength, a w/cm of 0.40 was selected. The mixes used in this project were aimed at use in MoDOT class B structural concrete, while still retaining possible use as a paving mix, so a cement content of 564 lb/yd^3 was selected, exceeding the B specification and typical contractor mixes, but meeting typical contractor submitted paving mixes. This corresponds to six sacks of cement per cubic yard, and is a fairly typical specified cement content.

Due to the selected cement content and w/cm, without any water reducing admixtures, the concrete yielded a low slump. Glenium 7500, a water reducer/high range water reducer was selected from BASF for use in restoring the slump of the concrete. This water reducer/high range water reducer met requirements for both Type A water reducing admixtures and Type F high range water reducing admixtures, in accordance with ASTM C 494. Based upon previous research at Missouri S&T, at 70% fly ash replacement, the concrete would achieve a slump of 5 inches, so a slump target of 5±1 inches was selected for all levels of fly ash replacement. In addition, this slump target allows for a workable mix to be placed by hand, and meets MoDOT consistency requirements for Class B concrete when a water-reducer is used. Thus, for mixtures with less than 70% fly ash, a combination of WR and air entraining agent were used to restore the slump to 5 inches. MoDOT specifications for air entrained concrete require an air content of 5.0%, so mixtures were air entrained to 5.0±0.75% air using MB AE 90, an air entraining agent from BASF.

The concrete mixtures were designed by ACI 211's absolute volume method. A coarse aggregate/fine aggregate blend of 60% coarse aggregate and 40% fine aggregate was chosen because that is the typical proportion seen by MoDOT for both structural and pavement submitted mixture designs. A St. Louis Limestone Formation, Ledges 1-7, Gradation D from Bluff City Minerals at Alton, Illinois was used for coarse aggregate, based upon its high durability factor, and Missouri River sand was used for fine aggregate, based upon a good record as a natural, rounded sand, and local availability. Choice of a coarse aggregate gradation was gradation D in order to meet the 501 specification for a B concrete mixture, is used commonly for paving mixtures, and is readily available. Cement was replaced by mass with fly ash, resulting in more paste volume present in the fly ash mixtures, and activators were added as a percentage of the mass of fly ash. Table 3.1. comparing the nominal percentages (based on percentage of flyash) and actual percentages (based on percentage of total cementitious materials) of the mixtures is shown below.

Table 3.1. Nominal versus Actual Percentages of Cementitious Materials

	Nominal					Actual				
	Cement	Fly Ash	Gypsum	CH	RSC	Cement	Fly Ash	Gypsum	CH	RSC
Baseline	100%	0%	0%	0%	0%	100%	0%	0%	0%	0%
50% FA w/CH	50%	50%	4%	10%	0%	46.7%	46.7%	1.9%	4.7%	0.0%
50% FA w/RSC	50%	50%	4%	0%	20%	44.5%	44.5%	1.9%	0.0%	9.1%
70% FA w/CH	30%	70%	4%	10%	0%	27.4%	63.9%	2.4%	6.3%	0.0%
70% FA w/RSC	30%	70%	4%	0%	20%	25.8%	59.8%	2.4%	0.0%	12.0%

A number of trial batches were conducted in order to determine proper dosages of both water reducer and air entraining admixture to achieve both a 5±1 inch slump and an air content of 5.0±0.75%. Initially, a large number of trial batches were needed in order to achieve adequate slump and air content of a mix, though as the mixing procedure was refined and dosages for various mixtures were determined, predicted dosages of water reducer and air entrainment agent became very close to what was required. For instance, the initial mixture required 16 trial batches in order to determine adequate dosages, while several later batches required only one or two trial batches in order to confirm that dosages were adequate. During these trial batches, several refinements were made to the sequence of mixing. The size of trial batches was increased from 1.0 cubic foot to 2.0 cubic feet in order to minimize the effects of moisture content variations in the bins. In addition to this, in order to control moisture contents more closely, the aggregates to be used in trial batching were prepared a day in advance, mixed in a drum to be uniform, and stored in a mortar box beneath a plastic sheet in order to retain the moisture content. These steps greatly improved the chances of obtaining a representative sample. The moisture content was then determined in order to adjust the batch water to maintain the mixture design w/cm.

Initially, the water was split into equal portions; the WR was mixed into one portion and the air entraining agent (AEA) was placed into another portion, with the water containing the water reducing admixture added to the mixer first, followed by the water containing air entraining agent. This mixing order was changed based upon a conversation with a BASF technical representative, who recommended the addition of a Type A water reducer before the addition of Glenium 7500 in order to increase the Glenium 7500's effectiveness ('loosen up the mixture" before adding the HRWR). As an additional water reducer was not being added to the concrete mixtures in this study, 2/3 of the water containing the air entraining agent was added before the remaining water with the Glenium 7500. The reasoning for this change was that air entraining agent generates very small, round air bubbles, which can serve to increase the slump, and it was thought that this action along with an increased first water portion may contribute to the effectiveness of the Glenium 7500 in place of a Type A water reducer.

3.1.5. Replicates. The majority of hardened concrete testing—flexural strength, splitting tensile strength, modulus of elasticity, abrasion, rapid chloride permeability, freeze-thaw resistance, and scaling resistance—consisted of at least three replicate tests in order to perform an ASTM E 178 "t-critical" outlier analysis. In other tests—temperature, slump, air, unit weight, time of set, microwave water content, and compressive strength—less replicate tests were conducted, and therefore an E 178 outlier analysis could not be conducted.

3.2. EQUIPMENT

This section covers the major pieces of equipment used in each test. Except where noted, equipment was set up and used at the Missouri University of Science and Technology (Missouri S&T).

3.2.1. Mixing of Fresh Concrete. Concrete was mixed in a 6 cubic foot capacity, variable speed mixer, pictured below in Figure 3.1.

3.2.2. Slump of Fresh Concrete. Slump of the concrete mixtures was measured by means of a standard ASTM C 143 slump cone. Concrete was consolidated in the cone by a 5/8 inch diameter slump rod, and measured with a plastic ruler. The slump equipment is pictured below in Figure 3.2.

Figure 3.1 Six Cubic Foot Variable Speed Mixer

Figure 3.2. Slump Testing Equipment

3.2.3. Unit Weight and Air Content of Fresh Concrete. Air content of the concrete mixtures was measured by means of a Type B pressure meter, manufactured by Hogentogler. Concrete was consolidated in the bowl by means of a 5/8 inch diameter slump rod, and struck off with an aluminum plate. The equipment used in determining unit weight and air content is pictured below in Figure 3.3.

Figure 3.3. Air Content and Unit Weight Equipment

3.2.4. Temperature of Fresh Concrete. Temperature of the concrete mixtures was measured with an analog thermometer with a 5 inch probe length, and a resolution of one degree.

3.2.5. Microwave Water Content of Fresh Concrete. A 1250 watt microwave from Panasonic was used to determine the microwave water content of fresh concrete. The sample was wrapped in a fiberglass cloth sheet approximately 20 by 20 inch, and placed in a microwave-safe baking dish. A 1 inch wide metal scraper and a 2 inch diameter ceramic pestle were used to break up the concrete sample. The microwave water content equipment is pictured below in Figure 3.4.

Figure 3.4. Microwave Water Content Station

3.2.6. Concrete Time of Set. The concrete time of set test was performed using an Acme penetrometer from Humboldt. The concrete sample was passed over a #4 sieve, and collected in a 6 inch diameter cylinder mold, cut to a 6 inch depth. Needles of varying diameter (1 in, ½ in, ¼ in, 1/10 in, 1/20 in, and 1/40 in) are attached to a loading arm, and the load required to penetrate the concrete is recorded upon a dial gauge on the penetrometer. The concrete time of set setup is pictured below in Figure 3.5.

3.2.7. Curing Equipment. With the exception of freeze-thaw prisms, concrete specimens were cured in a moist cure room at MST. The moist cure room mists water over the specimens in such a manner as to maintain at least 95% relative humidity at all times. Freeze-thaw prisms were cured in a saturated limewater bath, as were flexural strength beams for the final 24 hours before testing.

3.2.8. Compressive Strength. A 400 k load frame from Forney was used in determining the compressive strength of 4 inch diameter concrete cylinders. Cylinders were capped with sulfur in accordance with ASTM 617 prior to testing. Cylinder diameter measurements were taken using calipers.

Figure 3.5. Concrete Time of Set Setup

3.2.9. Flexural Strength. A 200 k load frame from Tinius Olsen was used in determining the flexural strength of concrete beams. An alignment jig constructed at Missouri S&T (Richardson, 1990) was used to ensure that the beam testing apparatus was aligned properly with the top load being applied at third points. The alignment jig is pictured below in Figure 3.6. The flexural strength specimens were tested on a Test Mark third point loading beam testing apparatus. The testing apparatus is pictured in Figure 3.7.

3.2.10. Modulus of Elasticity. A 200 k capacity, servo controlled universal testing load frame from Tinius Olsen was used in determining the modulus of elasticity of concrete specimens, with data collected by a computer controlling the testing program.

The cylinder was secured in a yoke, which held an LVDT to measure axial compression during the test. This test setup can be seen below in Figure 3.8.

Figure 3.6. Beam Alignment Jig

Figure 3.7. Beam Testing Apparatus

Figure 3.8. Modulus of Elasticity Test Setup

3.2.11. Splitting Tensile Strength. A 400k load frame from Forney was used in determining the splitting tensile strength of concrete cylinders. A marking jig pictured below in Figure 3.9 was used to mark diametral lines upon the specimens. The testing jig pictured in Figure 3.10 was used to center and load the specimens for testing. The testing jig was not available at the start of testing; therefore early testing was conducted by manually centering the specimen below the crosshead, and using a piece of steel stock as a supplementary bearing block.

3.2.12. Abrasion Resistance. Abrasion testing according to ASTM C 944 was conducted upon a drill press rotating at 300 rpm. A specialized abrasion head, constructed at Missouri S&T was used to abrade the concrete, and a weight was hung from the arm of the drill press, corresponding to a 44 pound double load as noted in ASTM C 944. The abrasion testing setup is pictured below in Figure 3.11.

Figure 3.9. Cylinder Marking Jig

Figure 3.10. Splitting Tensile Testing Jig

Figure 3.11. Abrasion Testing Setup

3.2.13. Shrinkage of Concrete. Linear shrinkage of concrete was determined in a modified version of ASTM C 157, using a cylindrical specimen with DEMEC points attached. Molds for the specimens consisted of 4 inch PVC pipe cut to length, with three equally spaced grooves cut longitudinally along the PVC mold in order to ease removal after casting. DEMEC points were attached with a metal and concrete epoxy 24 hours after casting. A DEMEC gauge was used in order to measure shrinkage of the specimens. The specimens and DEMEC gauge are pictured below in Figure 3.12.

3.2.14. Vicat Set Time of Paste. Set time of paste according to ASTM C 191 and normal consistency according to ASTM C 187 were conducted with the same Vicat device. This device consists of a double-ended needle, with one end 10 mm in diameter used for determination of normal consistency, and the other end a removable needle with a 1 mm diameter, used in determining Vicat setting time. The paste is held in a plastic conical ring, and set upon a glass base plate.

Paste was mixed with a Hobart N50 mixer, bowl, and paddle in conformation with ASTM C 305. The mixer is a planetary type mixer, moving the paddle in planetary and revolving motions at three different speeds. A semi-rigid rubber spatula was used to scrape the bowl, and a rectangular steel trowel with a length of 4.25 inches and a width of 2 inches was used to strike off the paste. The Vicat apparatus and mixing equipment are pictured below in Figure 3.13.

Figure 3.12. DEMEC Gauge and Specimen

Figure 3.13. Vicat Apparatus and Mixing Equipment

3.3. MATERIALS

3.3.1. Cement. Five Type I and Type I/II cements from Missouri area producers were selected for use in the paste study, encompassing both eastern and western parts of the state. Of these five cements, two were selected for continued examination in the concrete study, corresponding to the most and least reactive cement/fly ash combinations.

3.3.2. Fly Ash. Five Class C fly ashes produced from Missouri area power plants were selected for use in the paste study, encompassing both eastern and western parts of the state. Of these five fly ashes, two were selected for continued examination in the concrete study, corresponding to the most and least reactive cement/fly ash combinations.

3.3.3. Powder Activators. Three powder activators were used in this study: powdered gypsum, calcium hydroxide in the form of hydrated lime, and rapid set cement. These powder additions were blended in with the cement and fly ash prior to concrete mixing. Dosages for these powder additions were determined during the paste study, and were 4% by weight of fly ash of powdered gypsum, 10% by weight of fly ash of calcium hydroxide, and 20% by weight of fly ash of rapid set cement. The powdered gypsum used was Ultrafine Gypsum from USA Gypsum. The rapid set cement used in this study was CTS Rapid Set Cement, and the source of calcium hydroxide was Mississippi Lime's Standard Hydrated Lime.

3.3.4. Admixtures. Concrete mixtures were air entrained with BASF's MB-AE-90 air entraining admixture, and slump was adjusted by use of Glenium 7500, a polycarboxylate water reducer from BASF.

3.3.5. Water. Deionized water was used in determining normal consistency and set time by the Vicat method. Tap water was used in the mixing of fresh concrete.

3.3.6. Aggregates. The coarse aggregate used in mixing fresh concrete was a Bluff City limestone, which was known to have a high durability factor based upon previous studies and knowledge from MoDOT. The sand used was a Missouri River sand, based upon a good service record as a rounded sand, and local availability. The aggregate properties are summarized below in Table 3.2. "DRUW" and "FM" refer to Dry Rodded Unit Weight of the coarse aggregate and Fineness Modulus of the sand, respectively. Gradations for both the coarse and fine aggregate are provided in Table 3.3, and Table 3.4 respectively.

Table 3.2. Aggregate Properties

	Coarse Aggregate	Fine Aggregate
Bulk Specific Gravity (OD)	2.62	2.62
Bulk Specific Gravity (SSD)	2.66	2.64
Absorption	1.4%	0.7%
Flat and Elongated (5:1)	1%	NA
DRUW	97 lb/ft^3	NA
FM	NA	2.73

Table 3.3. Coarse Aggregate Sieve Analysis

Sieve Size	Total Percent Passing
1 in.	100%
¾ in.	92%
½ in.	53%
3/8 in.	26%
#4	6%
#8	4%
#30	3%
#100	3%
#200	2.6%

Table 3.4. Fine Aggregate Sieve Analysis

Sieve Size	Total Percent Passing
3/8 in.	100%
#4	99%
#8	92%
#16	79%
#30	48%
#50	9%
#100	1%
#200	0.2%

3.4. TEST PROCEDURES

This section covers relevant details pertaining to test procedures. Significant deviations to standardized test procedures will be discussed. Complete procedures for each test may be found in Appendix A.

3.4.1. Aggregate Preparation. In order to assure uniform moisture contents in the aggregate used to mix fresh concrete, an aggregate preparation schedule was developed. First, roughly 25 lbs of Jefferson City dolomite were tumbled in the concrete mixer for 5 minutes in order to clean the drum out and knock loose any hardened concrete on the fins or in the drum. This aggregate was disposed of after tumbling. Coarse and fine aggregate were both weighed out, exceeding the estimated amount needed by roughly 50 to 100 lbs. Coarse aggregate was mixed first, and then fine aggregate. Both aggregates were mixed at a speed of 9 in the concrete drum for five minutes. Upon completion of the mixing time, each aggregate was discharged into a separate mortar box, mixed with a square pointed shovel, and then tightly covered with plastic sheeting.

Three hours prior to mixing, the plastic sheet was momentarily removed in order to take moisture content samples. A shovel was used to mix the aggregate again, taking a moisture content sample from each aggregate bin. Aggregate was dried for three hours in a forced air drying oven at 235 F. The plastic sheet was then replaced until it was time to batch out aggregates for the mix. Immediately prior to mixing, the moisture content samples were removed from the drying oven, weighed, and used to determine the necessary moisture content adjustments to be made to aggregate and batch water.

3.4.2. Mixing of Fresh Concrete. The mixing procedure used was a modified version of ASTM C 192. Prior to mixing fresh concrete, the mixer was 'buttered' by adding several pounds of cementitious materials matching the mix design to the drum, adding water, and allowing this fluid to flow in the drum for at least five minutes, coating all surfaces of the inside of the drum. This fluid was discharged and wasted just prior to the beginning of fresh concrete mixing.

Batch water was separated into two buckets, one containing two thirds of the total batch water plus the total amount of air entraining agent, the other containing one third of the water plus the water reducer. The total amount of coarse aggregate was added to the drum, and the mixer was started on a speed setting of 12. The bucket of water containing air entrainment agent was then added, taking care to flush any fines on the sides of the mixer back into the aggregate. The sand was then added, and the mixer was run until the aggregates appeared well blended. Cement and the remaining water containing water reducer were then metered in so that the mix appeared uniform. After completion of addition of the mix constituents, the concrete was mixed at a speed setting of 15 for three minutes, subjected to a rest period of three minutes, and then remixed for a period of two minutes before discharging. Notably, the mixer was not covered during the 3 minute rest period as dictated in ASTM C 192 as this provision was not discovered until after test batches had been conducted without the use of a cover. By not covering the mixer during the rest period, it is possible that some water in the mixures may have evaporated, lowering the w/c.

Due to the capacity limitations of the 6.0 cubic foot mixer, concrete was mixed in three batches, with specimens cast in order to determine similar properties coming from the same batch. The three batches and specimens cast from each are shown below in Table 3.5. The concrete mix designs per cubic foot under SSD conditions are presented below in Table 3.6.

3.4.3. Temperature of Fresh Concrete. Temperature measurement of fresh concrete was conducted in accordance with ASTM C 1064. The temperature was taken in a wheelbarrow immediately after discharge of the concrete from the drum.

3.4.4. Slump of Fresh Concrete. Slump of fresh concrete was conducted in accordance with ASTM C 143. The test was conducted on a dampened sheet of plastic.

3.4.5. Unit Weight of Fresh Concrete. Unit weight of fresh concrete was conducted in accordance with ASTM C 138. The same measure and concrete sample were used for the air content test immediately after determining the unit weight.

Table 3.5. Concrete Batches

Batch	Test	Specimen	Number
Strength Batch	Strength	4 x 8 Cyl.	12
	Modulus of Elasticity	6 x 12 Cyl.	3
	Splitting Tensile	6 x 12 Cyl.	3
	Flexural Strength	6 x 6 x 24 Beam	3
Durability Batch	Abrasion	6 x 16 x 3.5 Slab	2
	Freeze/Thaw	3.5 x 4.5 x 16 Beam	3
	Scaling	12 x 12 x 3 Slab	3
	RCP	4 x 8 Cyl.	2
Shrinkage/Time of Set	Shrinkage	4 x 24 Cyl.	2
	Time of Set	6 x 6 Cyl.	1

Table 3.6. Mix Design in SSD (per cubic foot)

	Baseline	50% FA,CH	50% FA,RSC	70% FA,CH	70% FA,RSC
water	8.4 lbs	8.4 lbs	8.4 lbs	8.4 lbs	8.4 lbs
PC	20.9 lbs	9.8 lbs	9.3 lbs	5.7 lbs	5.4 lbs
Flyash	-	9.8 lbs	9.3 lbs	13.3 lbs	12.5 lbs
Gypsum	-	0.4 lbs	0.4 lbs	0.5 lbs	0.5 lbs
Lime	-	1.0 lbs	-	1.3 lbs	-
RSC	-	-	1.9 lbs	-	2.5 lbs
Coarse Agg.	69.5 lbs	69.0 lbs	69.0 lbs	69.0 lbs	69.0 lbs
Fine Agg.	46.3 lbs	44.0 lbs	43.8 lbs	43.3 lbs	43.1 lbs

3.4.6. Air Content by Pressure Method. The air content of fresh concrete was determined in accordance with ASTM C 231, using a type B pressure meter. This test was run upon the same measure and concrete sample used previously to determine unit weight. This often meant cleaning the rim of the bowl a second time after transporting it to a scale and back.

3.4.7. Microwave Water Content. Microwave water content of fresh concrete was determined in accordance with AASHTO 318. The sample for microwave water content was taken halfway through discharge of the drum and weighed immediately. The test was then conducted after the other fresh concrete tests had been completed.

In addition to determining the water content by the microwave method, it was also calculated based upon the yield determined in the unit weight test. The design water was divided by the calculated yield in order to arrive at the 'adjusted' water content per cubic foot. Similarly, the cementitious materials were divided by the calculated yield to arrive at the 'adjusted' cementitious content per cubic foot. Using these two adjusted values, the w/cm can be calculated.

3.4.8. Concrete Time of Set. Concrete time of set was conducted in accordance with ASTM C 403. Samples were wet sieved over a #4 sieve after fresh concrete testing was completed, and remixed by hand after a suitable amount of concrete had been sieved for the test.

3.4.9. Compressive Strength of Concrete Cylinders. Concrete cylinders for compressive strength were cast in accordance with ASTM C 192. Placement consisted of two lifts, each being consolidated with 25 roddings with a 3/8 inch tamping rod, and 10 taps. Compressive strength of the 4 in x 8 in concrete cylinders was determined in accordance with ASTM C 39. A sulfur capping system was used to ensure planeness of the cylinder ends when testing.

3.4.10. Flexural Strength of Concrete Beams. Concrete beams were cast in accordance with ASTM C 192. Placement consisted of two layers, each layer rodded 72 times, tapped 12 times, and then spaded around the edges. Flexural strength of the concrete beams was determined in accordance with ASTM C 78. Beams were cured in saturated limewater for the last 24 hours of curing prior to testing.

3.4.11. Modulus of Elasticity of Concrete. Modulus of elasticity was determined on 6 in diameter cylinders, cast in accordance with ASTM C 192. Placement consisted of three layers, each being consolidated with 25 roddings with a 5/8 in tamping rod, and 10 taps. Modulus of elasticity was determined in accordance with ASTM C 469.

Prior to testing, the concrete cylinders were sulfur capped to ensure planeness of loading surfaces. Three replicate cylinders were used to determine the modulus of elasticity.

3.4.12. Splitting Tensile Strength. Splitting tensile strength was determined on 6" diameter cylinders, cast in accordance with ASTM C 192. Placement consisted of three layers, each being consolidated with 25 roddings with a 5/8 in tamping rod, and 10 taps. Splitting tensile strength was determined in accordance with ASTM C 496 on three replicate cylinders.

3.4.13. Abrasion Resistance. Specimens for abrasion resistance were cast in one lift, consolidated with 96 rods with a 5/8 in diameter tamping rod, 10 taps with a rubber mallet, and finally spaded around the edges. Abrasion testing was conducted in accordance with ASTM C 944, using the 44 pound double load, however the test was conducted at 300 rotations per minute instead of 200 rotations per minute, due to limitations of the drill press.

3.4.14. Linear Shrinkage of Concrete. Specimens used to determine linear shrinkage of concrete were cast in 4 in inner diameter PVC molds, each 24 in long. Concrete was placed in two layers in these molds, and consolidated by internal vibration, with one insertion per layer. The next day, specimens were demolded by use of a Dremel tool with a cutting head. The PVC molds were cut laterally down the three pregrooved sections, and the molds removed without damaging the specimens. DEMEC points were attached with a metal and concrete epoxy, and initial readings were taken as soon as was feasible. Subsequent readings were taken initially daily, with increasing periods of time between readings as the rate of shrinkage of the specimens decreased. Data was then adjusted for the reference bar; the shrinkage was calculated in microstrain and plotted on a figure. A detailed procedure for calculating microstrain from the shrinkage readings is provided with the test methods in the Appendix.x

3.4.15. Scaling Resistance. Specimens for scaling resistance were cast in molds 12 in by 12 in by 4 in deep. Initially, specimens were cast at a full 4 in depth with a broomed finish, and a 1 in high, 1 in wide mortar dam was built atop the finished surface with the aid of an angle iron backer. After a consultation with technicians from MoDOT, however, the casting procedure was revised. The molds for scaling resistance specimens were underfilled, and the concrete surface finished approximately an inch below the top surface of the mold. This surface was broomed, and a 1 in high, 1 in wide mortar dam was built atop the finished surface against the steel mold.

Scaling specimens were cured in the moist cure room for 14 days, after which they were subject to a 14 day drying period prior to testing. Between 14 days and 21 days, the scaling specimens were transported to MoDOT central testing laboratories for testing in accordance with ASTM C 672.

3.4.16. Freeze-Thaw Resistance of Concrete. Concrete prisms measuring 4.5 in deep, 3.5 in wide, and 16 in long were cast with gauge studs at either end to determine freeze-thaw resistance of concrete in accordance with ASTM C 666. Specimens were cast in two layers, and consolidated by means of 28 roddings, 10 tappings, and spading around the perimeter of the specimens. After demolding, freeze-thaw prisms were cured in a saturated limewater tank until the date of testing. Freeze-thaw prisms were transported to MoDOT's central testing laboratory between 14 and 21 days of age, and were tested by a technician there at 35 days of age. Testing was conducted according to ASTM C 666 Method B.

3.4.17. Rapid Chloride Permeability. Concrete cylinders 4 in in diameter were cast for use in the rapid chloride permeability test. These cylinders were placed and consolidated in the same manner that the compressive strength cylinders were. Concrete was placed in two lifts, and each lift was rodded 25 times with a 3/8 in diameter tamping rod before being tapped 10 times. Samples were transported to MoDOT Central Testing Laboratory between 14 and 21 days of age for testing by a technician there according to ASTM C 1202.

3.5.18. Vicat Setting Time of Cement Paste. Vicat setting time was conducted as a two part test: first, normal consistency was determined according to ASTM C 187. A notable deviation in this testing method is that both the mixing bowl and the mixing paddle were dampened with water before mixing the paste to provide a more consistent surface condition between mixtures, which may have contributed to some variability in normal consistency when compared to other labs or literature. After normal consistency was achieved, the same specimen was used to determine Vicat setting time on the paste in accordance with ASTM C 191. One deviation was present in determining Vicat setting time. The specimen was kept in the moist cure room between penetration measurements, and covered with a plastic sheet to prevent damage to the specimen from dripping water. Other researchers have used similar modifications to the test method in order to prevent evaporation from the specimen. (Bentz & Ferraris, 2010) For specimens that underwent initial set prior to the initial penetration reading at 30 minutes, a penetration of 40 mm, corresponding to full penetration of the vicat specimen, was assumed to occur at a time of zero minutes, making it possible to interpolate the initial set at a penetration of 25 mm.

4. RESULTS AND DISCUSSION

4.1. FRESH CONCRETE TESTS

The fresh concrete tests included slump, air content, microwave water content, and time of set.

4.1.1. Slump. Glenium 7500 water reducer was used in all 10 concrete mixtures in order to adjust the slump to 5±1 inches. Table 4.1, below, shows the dosages used for each mix in fluid ounces per hundredweight of cementitious material. For the 4-1 combination, as would be expected, less water reducer was required to achieve a 5 inch slump as the amount of fly ash in the mix increased. Mixtures with rapid set cement as an activator required more water reducer than did those with calcium hydroxide as an activator. This reason could be two-fold: the rapid hydration of rapid set cement led to a more rapid rate of slump loss than calcium hydroxide, and the dosage of rapid set cement was 20% by weight of fly ash, or twice that of the dosage used for calcium hydroxide.

For the 1-3 combination, the trend is not as clear. Mixtures using rapid set cement as an activator require higher dosages of water reducer than those using calcium hydroxide for the same reasons outlined before. However, increasing fly ash content in these mixtures led to an increase in the required dosage of water reducer. Rapid slump loss was noticed during mixing for fly ash mixtures in the 1-3 combination, so it is possible that rapid aluminate reactions due to the fly ash meant that a higher dosage of water reducer was necessary in order to achieve a target slump.

4.1.2. Air Content. BASF's MB-AE-90 air entrainment admixture was used in all 10 concrete mixtures in order to adjust the air content to 5±0.75%. Table 4.1, below, shows the required dosages in oz/cwt to achieve this air content. For the 4-1 combination, the required dosage of air entrainment agent was lower at higher percentages of fly ash replacement. This is likely tied to the increased workability seen with these mixtures, therefore requiring a lower dosage to entrain the same amount of air. No difference was noted in air entrainment dosages between those mixtures utilizing calcium hydroxide as an activator and those utilizing rapid set cement as an activator.

For the 1-3 combination, again, no difference was noted in air entrainment dosages between those utilizing calcium hydroxide and those utilizing rapid set cement as activators. As in the case of the water reducer, fly ash mixtures initially required less air entrainment agent to achieve a given air content, though the required dosage increased as the fly ash content increased from 50% to 70%. Again, this is likely due to the more rapid rate of slump loss. The fly ash used in the 1-3 combination was also darker in color than that used in the 4-1 combination, possibly indicating higher carbon content. This assumption was verified by examining the loss on ignition (LOI) data for the five fly ashes received for the paste study. This LOI data is provided below in Table 4.2. Fly ash mixtures with higher carbon content typically require more air entrainment admixture to achieve a given air content.

4.1.3. Microwave Water Content. To ensure that the w/cm of freshly mixed concrete remained constant at 0.40, water content of the mixtures was determined by the microwave method as specified in AASHTO 318. This water content was then used to calculate the w/cm of the mix. In addition to calculating w/cm in this manner, w/cm was also calculated by means of the yield, and these two values were compared. The values of w/cm determined by both methods are summed up below in Table 4.3. As can be seen, the average difference seen between the two methods is 0.019. In research by Nagi and Whiting, the most significant difference measured at a pavement repair site was a w/c difference of 0.0319 (Nagi & Whiting, 1994). This value was exceeded 3 times out of the 20 tests run. Error may have been introduced into the test by not microwaving the sample immediately after collecting it from the mixer, but rather waiting until other fresh concrete tests had been conducted before beginning the microwave water content test. Nevertheless, the microwave water content test appears to give a good ballpark result of the w/cm of the mix.

Table 4.1. Required Admixture Dosages

	WR Dose (oz/cwt)	AE Dose (oz/cwt)
Mix 4-1		
Baseline	5.3	4.7
50% FA w/CH	2.8	2.1
50% FA w/RSC	3.6	1.9
70% FA w/CH	1.9	2.1
70% FA w/RSC	2.8	1.9
Mix 1-3		
Baseline	5.0	8.1
50% FA w/CH	4.0	6.5
50% FA w/RSC	5.3	6.5
70% FA w/CH	4.9	7.3
70% FA w/RSC	6.2	7.3

Table 4.2. Fly Ash LOI

Sample	Loss On Ignition (%)
Fly Ash 1	0.37%
Fly Ash 2	0.49%
Fly Ash 3	3.05%
Fly Ash 4	0.57%
Fly Ash 5	0.26%

Table 4.3. w/cm by Yield and Microwave Water Content

From Yield	From Microwave	Difference
0.402	0.429	0.027
0.402	0.399	0.003
0.4	0.408	0.008
0.4	0.418	0.018
0.404	0.422	0.018
0.404	0.441	0.037
0.4	0.43	0.03
0.4	0.396	0.004
0.4	0.436	0.036
0.4	0.415	0.015
0.402	0.426	0.024
0.402	0.428	0.026
0.4	0.42	0.02
0.4	0.401	0.001
0.404	0.437	0.033
0.404	0.39	0.014
0.4	0.427	0.027
0.4	0.379	0.021
0.4	0.397	0.003
0.4	0.388	0.012
	Average:	0.019

4.1.4. Time of Set. Substitution of cement with fly ash, a slower reacting material, typically should increase the time of set, even with Class C ashes which serve as cementitious as well as pozzolanic. Time of set was determined on each of the 10 concrete mixtures tested for this project. Figure 4.1 below details the initial and final set times determined for the 4-1 combination.

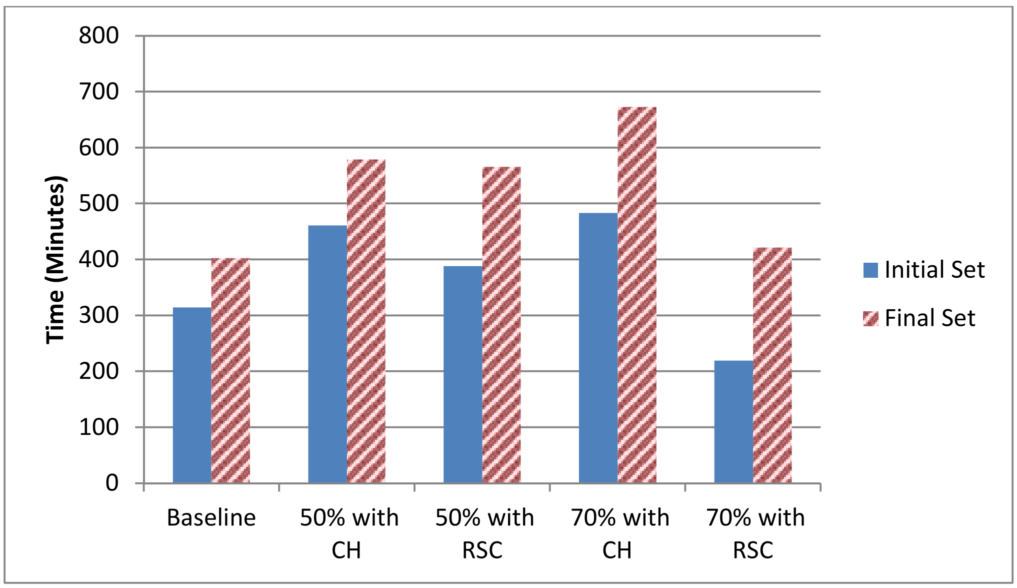

Figure 4.1. Initial and Final Set Times for the 4-1 Combination

As is expected, the addition of fly ash causes both the initial and final set to increase for mixtures incorporating calcium hydroxide as an activator. Mixtures incorporating rapid set cement as an activator fared better than their calcium hydroxide counterparts in reducing the lengthened time of set due to fly ash substitution. Notably, at 70% replacement of cement with fly ash, the rapid set cement mix brings the time of set down considerably more than at 50% replacement of cement with fly ash. This discrepency is likely due to the fact that since activator levels are determined as a percentage of fly ash, more rapid set cement is present in the 70% fly ash mix than the 50% fly ash mix, resulting in a decreased time of set.

The results of time of set tests on combination 1-3 are pictured below in Figure 4.2. Results on the 1-3 combination are very similar to those found for the 4-1 combination. Increasing fly ash content of the concrete tends to lengthen the set times greatly. At 50% fly ash replacement the rapid set cement mix responds in a similar way to the calcium hydroxide mix, whereas at 70% fly ash replacement, the rapid set cement mix exhibits a marked decrease in set time from the calcium hydroxide mix.

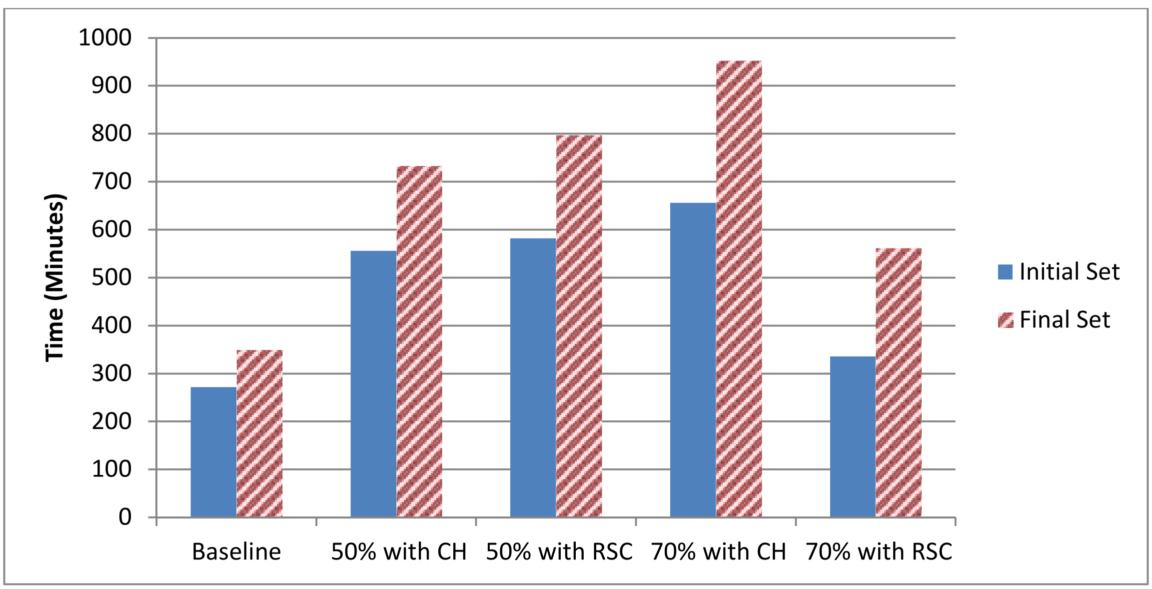

Figure 4.2. Initial and Final Set Times for the 1-3 Combination

4.2. HARDENED CONCRETE TESTS

4.2.1. Compressive Strength. Compressive strength was determined on 4 in.x 8 in. concrete cylinders at 1, 7, 28, and 56 days of age. Three cylinders were broken for each test, and the data was thereafter examined for outliers using an outlier identification method laid out in ASTM E 178. A common flaw in this outlier identification method is that it may falsely identify an outlier if two out of the three values are identical or very similar. Judgment was used in this case in determining whether or not to label the identified value as an outlier. For compressive strength, three outliers were identified, one of them being a false positive due to two of the three values being identical. The precision statement in ASTM C 39 allows for a maximum %1s of 3.2%, though it also notes that this is only applicable for strengths between 2500 psi and 4700 psi. Taking into account only the compressive strengths between 2500 and 4700 psi, 11 of the 40 compressive strengths do not meet this precision statement. The precision and outlier analysis is presented below in Tables 4.4 through 4.7. However, looking at ACI 214 ratings for precision for laboratory mixtures, of the 40 mixtures, 33 were Excellent, one Very Good, 1 Good, 3 Fair, and 2 Poor (ACI 214, 2011).

Results from the 4-1 combination are presented in Figure 4.3., below. All fly ash mixtures, regardless of replacement percentage, suffered in terms of short term strength gain compared to the baseline mix. By 7 days of age, however, the 50% fly ash mixtures had begun to exhibit more reasonable strengths, exceeding 3000 psi. They continued to gain strength, approximating the baseline mix strengths by 28 days and at 56 days exceeding baseline strengths. Mixtures with 70% fly ash replacement exhibited greatly lowered strengths when compared to baseline mixtures, or even their 50% fly ash replacement counterparts at all ages. The difference in strength due to activator selection was small at most ages, though mixtures using rapid set cement were always stronger than mixtures using calcium hydroxide as an activator.

Results from the 1-3 combination are presented in Figure 4.4., below. All fly ash mixtures for this combination exhibited lower strengths than the baseline concrete mix at all ages. For the 50% fly ash replacement mixtures, mixtures using calcium hydroxide as an activator showed slightly greater strengths than mixtures using rapid set cement as an activator. The 70% fly ash mixtures displayed lower strengths than the 50% fly ash mixtures, as expected.

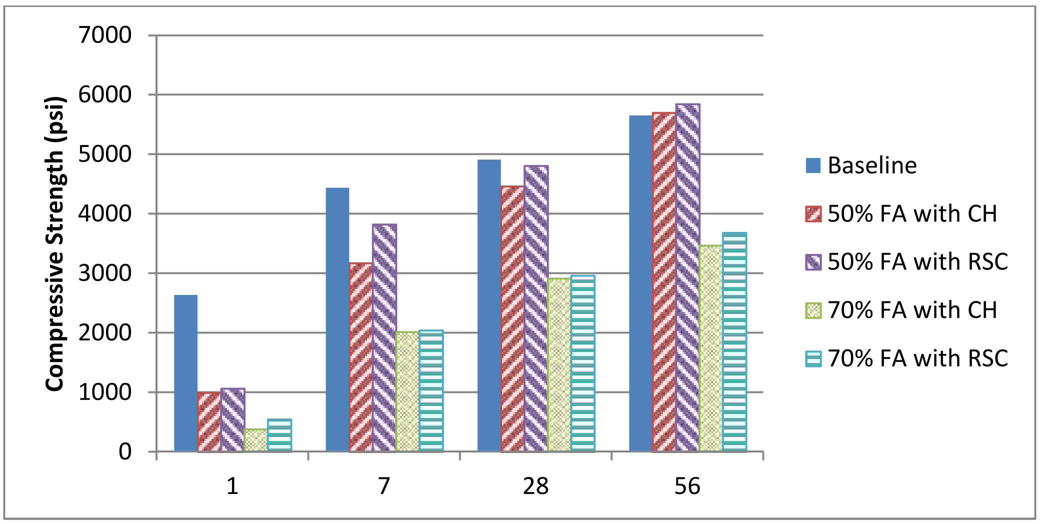

Figure 4.3. Compressive Strengths for Combination 4-1

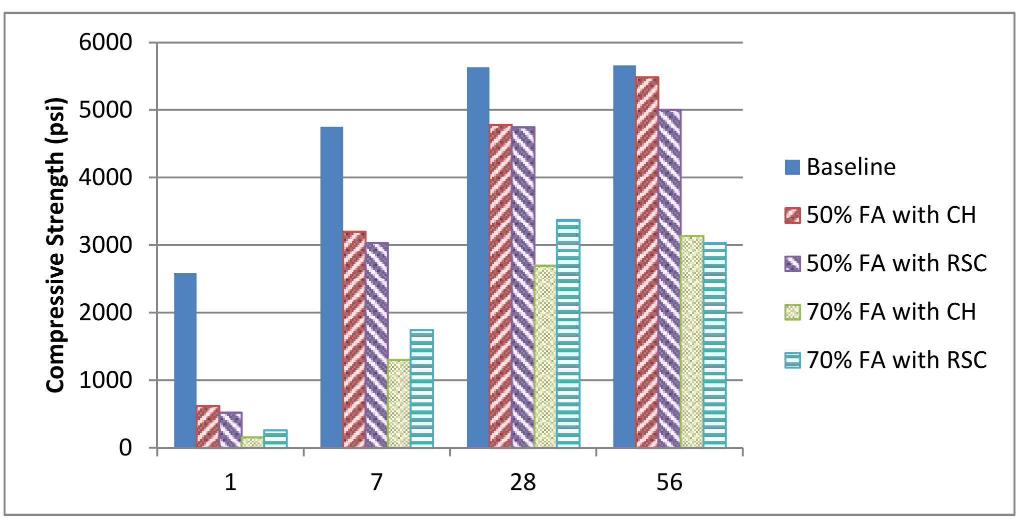

Figure 4.4. Compressive Strengths for Combination 1-3

Table 4.4. Outlier Analysis of 1 Day Compressive Strengths

Comp. Strengths	Combination 4-1					Combination 1-3				
1 Day	Baseline	50% FA with CH	70% FA with CH	50% FA with RSC	70% FA with RSC	Baseline	50% FA with CH	70% FA with CH	50% FA with RSC	70% FA with RSC
Rep. 1	2520	925	355	1132	531	2451	586	161	535	260
Rep. 2	2712	988	392	1042	538	2730	637	159	489	266
Rep. 3	2676	1067	408	1016	575	2577	649	155	551	266
Average	**2636**	**993**	**385**	**1063**	**548**	**2586**	**624**	**158**	**525**	**264**
Standard Dev.	102.1	71.2	27.2	60.9	23.6	139.7	33.5	3.1	32.2	3.5
tmax	0.745	1.035	0.846	1.128	1.142	1.031	0.747	0.873	0.808	0.577
tmin	1.137	0.960	1.104	0.778	0.719	0.966	1.136	1.091	1.118	1.155
tcrit	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153
Outlier?	**No**	**No**	**No**	**No**	**No**	**No**	**No**	**No**	**No**	**No***
New Average	**2636**	**993**	**385**	**1063**	**548**	**2586**	**624**	**158**	**525**	**264**
Standard Dev.	**102.1**	**71.2**	**27.2**	**60.9**	**23.6**	**139.7**	**33.5**	**3.1**	**32.2**	**3.5**
CV (%)	**3.87**	**7.16**	**7.06**	**5.72**	**4.31**	**5.40**	**5.36**	**1.93**	**6.13**	**1.31**

Table 4.5. Outlier Analysis of 7 Day Compressive Strengths

Comp. Strengths	Combination 4-1					Combination 1-3				
7 Day	Baseline	50% FA with CH	70% FA with CH	50% FA with RSC	70% FA with RSC	Baseline	50% FA with CH	70% FA with CH	50% FA with RSC	70% FA with RSC
Rep. 1	4338	3107	2200	3681	1866	4641	3104	1218	3181	1699
Rep. 2	4211	3084	1873	3928	2218	4819	3271	1388	2818	1726
Rep. 3	4771	3330	1978	3859	2050	4790	3230	1305	3113	1818
Average	**4440**	**3174**	**2017**	**3823**	**2045**	**4750**	**3202**	**1304**	**3037**	**1748**
Standard Dev.	293.6	135.9	167.0	127.4	176.1	95.5	87.0	85.0	193.0	62.4
tmax	1.127	1.151	1.096	0.826	0.985	0.722	0.797	0.992	0.745	1.127
tmin	0.780	0.660	0.863	1.112	1.015	1.141	1.122	1.008	1.137	0.780
tcrit	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153
Outlier?	**No**	**No**	**No**	**No**	**No**	**No**	**No**	**No**	**No**	**No**
New Average	**4440**	**3174**	**2017**	**3823**	**2045**	**4750**	**3202**	**1304**	**3037**	**1748**
Standard Dev.	**293.6**	**135.9**	**167.0**	**127.4**	**176.1**	**95.5**	**87.0**	**85.0**	**193.0**	**62.4**
CV (%)	**6.61**	**4.28**	**8.28**	**3.33**	**8.61**	**2.01**	**2.72**	**6.52**	**6.35**	**3.57**

Table 4.6. Outlier Analysis of 28 Day Compressive Strengths

Comp. Strengths	Combination 4-1					Combination 1-3				
28 Day	Baseline	50% FA with CH	70% FA with CH	50% FA with RSC	70% FA with RSC	Baseline	50% FA with CH	70% FA with CH	50% FA with RSC	70% FA with RSC
Rep. 1	5059	4408	2866	4819	2354	5688	4173	2723	4628	3386
Rep. 2	4863	4372	2956	5727	3451	5958	5204	2611	4697	3419
Rep. 3	4806	4617	2927	4795	3081	5257	4957	2755	4912	3324
Average	**4909**	**4466**	**2916**	**5114**	**2962**	**5634**	**4778**	**2696**	**4746**	**3376**
Standard Dev.	132.7	132.3	45.9	531.3	558.1	353.6	538.3	75.6	148.1	48.2
tmax	1.128	1.144	0.863	1.154	0.876	0.915	0.791	0.776	1.123	0.885
tmin	0.779	0.708	1.096	0.600	1.089	1.067	1.124	1.129	0.794	1.085
tcrit	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153
Outlier?	**No**	**No**	**No**	**Yes, Max**	**No**	**No**	**No**	**No**	**No**	**No**
New Average	**4909**	**4466**	**2916**	**4807**	**2962**	**5634**	**4778**	**2696**	**4746**	**3376**
Standard Dev.	**132.7**	**132.3**	**45.9**	**17.0**	**558.1**	**353.6**	**538.3**	**75.6**	**148.1**	**48.2**
CV (%)	**2.70**	**2.96**	**1.58**	**0.35**	**18.84**	**6.28**	**11.27**	**2.80**	**3.12**	**1.43**

Table 4.7. Outlier Analysis of 56 Day Compressive Strength

Comp. Strengths	Combination 4-1					Combination 1-3				
56 Day	Baseline	50% FA with CH	70% FA with CH	50% FA with RSC	70% FA with RSC	Baseline	50% FA with CH	70% FA with CH	50% FA with RSC	70% FA with RSC
Rep. 1	5807	5699	3337	5546	4075	6054	5625	3219	4855	2872
Rep. 2	5709	5116	3496	5757	3870	5537	5512	2944	4900	3127
Rep. 3	5436	5707	3576	6243	3114	5399	5317	3253	5249	3100
Average	**5651**	**5507**	**3470**	**5849**	**3686**	**5663**	**5485**	**3139**	**5001**	**3033**
Standard Dev.	192.3	338.9	121.7	357.4	506.1	345.3	155.8	169.4	215.7	140.1
tmax	0.813	0.589	0.874	1.103	0.768	1.131	0.901	0.675	1.148	0.671
tmin	1.117	1.155	1.091	0.847	1.131	0.766	1.076	1.149	0.679	1.149
tcrit	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153
Outlier?	**No**	**Yes, Min**	**No**	**No**	**No**	**No**	**No**	**No**	**No**	**No**
New Average	**5651**	**5703**	**3470**	**5849**	**3686**	**5663**	**5485**	**3139**	**5001**	**3033**
Standard Dev.	**192.3**	**5.7**	**121.7**	**357.4**	**506.1**	**345.3**	**155.8**	**169.4**	**215.7**	**140.1**
CV (%)	**3.40**	**0.10**	**3.51**	**6.11**	**13.73**	**6.10**	**2.84**	**5.40**	**4.31**	**4.62**

4.2.2. Flexural Strength. Flexural strength was determined by third point loading on three replicates for each mix. An E 178 outlier analysis was conducted on the resultant data, and one outlier was found. This was found to be a falsely identified outlier, as the remaining two values were only 1 psi in difference. The precision statement in ASTM C 78 specifies a maximum allowable %1s of 5.7%. Only two tests exceeded this value. The outlier and precision analysis is presented below in Table 4.8.

Results from the 4-1 combination are presented below in Figure 4.5. As can be seen, both calcium hydroxide and rapid set cement served well to prevent excessive loss of flexural strength at 50% replacement of cement with fly ash. At the 70% replacement level, there was a notable loss in flexural strength, more so with the calcium hydroxide mix than the rapid set cement mix.

Results from the 1-3 combination are presented below in Figure 4.6. At 50% replacement of cement with fly ash, calcium hydroxide and rapid set cement mixtures performed similarly, though a greater loss of strength was observed here than with combination 4-1. At 70%, another drop in strength is seen, with the rapid set cement mix providing a greater flexural strength than the calcium hydroxide mix.

The loss of flexural strength moving from 50% fly ash replacement to 70% fly ash replacement is consistent with work by Naik, Ramme, and Tews, showing that as Class C fly ash content increases, the flexural strength suffers. It is possible, however, if the flexural strength testing had been conducted at later ages, that higher volume fly ash mixtures may have exhibited greater flexural strength in the longer term (Naik, et al., 1995).

Table 4.8. Flexural Strength Outlier Analysis

	Combination 4-1					Combination 1-3				
Flexural Strength	Baseline	50% FA with CH	70% FA with CH	50% FA with RSC	70% FA with RSC	Baseline	50% FA with CH	70% FA with CH	50% FA with RSC	70% FA with RSC
Rep. 1	734	648	475	704	555	842	594	392	622	463
Rep. 2	760	700	436	711	554	769	649	390	602	441
Rep. 3	686	738	468	680	530	777	668	404	643	460
Average	*727*	*695*	*460*	*698*	*546*	*796*	*637*	*395*	*622*	*455*
Standard Dev.	37.5	45.2	20.8	16.3	14.2	40.0	38.4	7.6	20.5	11.9
tmax	0.888	0.944	0.737	0.779	0.612	1.149	0.807	1.145	1.008	0.698
tmin	1.083	1.048	1.138	1.128	1.154	0.674	1.119	0.704	0.992	1.146
tcrit	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153
Outlier?	**No**	**No**	**No**	**No**	**No***	**No**	**No**	**No**	**No**	**No**
New Average	**727**	**695**	**460**	**698**	**546**	**796**	**637**	**395**	**622**	**455**
Standard Dev.	**37.5**	**45.2**	**20.8**	**16.3**	**14.2**	**40.0**	**38.4**	**7.6**	**20.5**	**11.9**
CV (%)	**5.16**	**6.50**	**4.52**	**2.33**	**2.59**	**5.03**	**6.03**	**1.92**	**3.30**	**2.62**

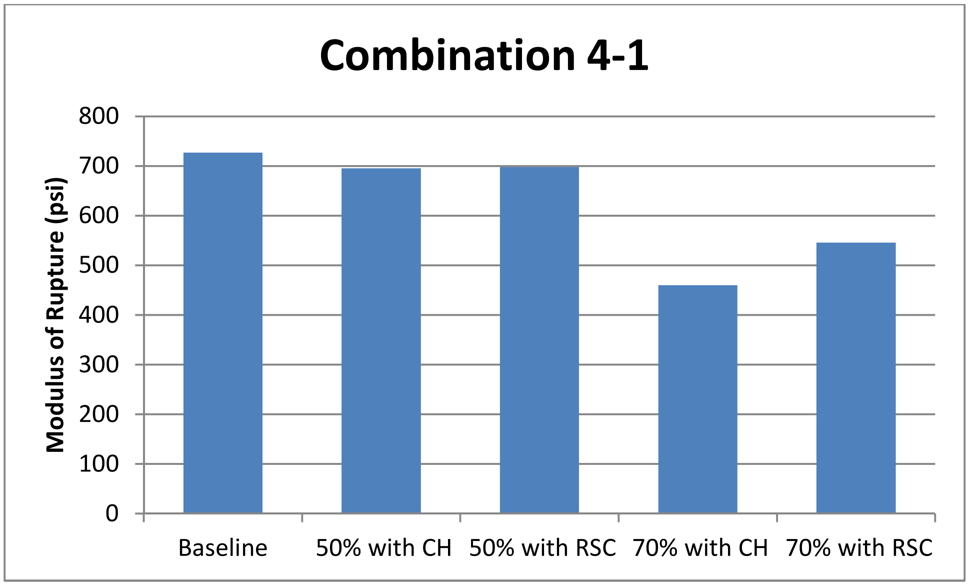

Figure 4.5. Flexural Strength of Combination 4-1

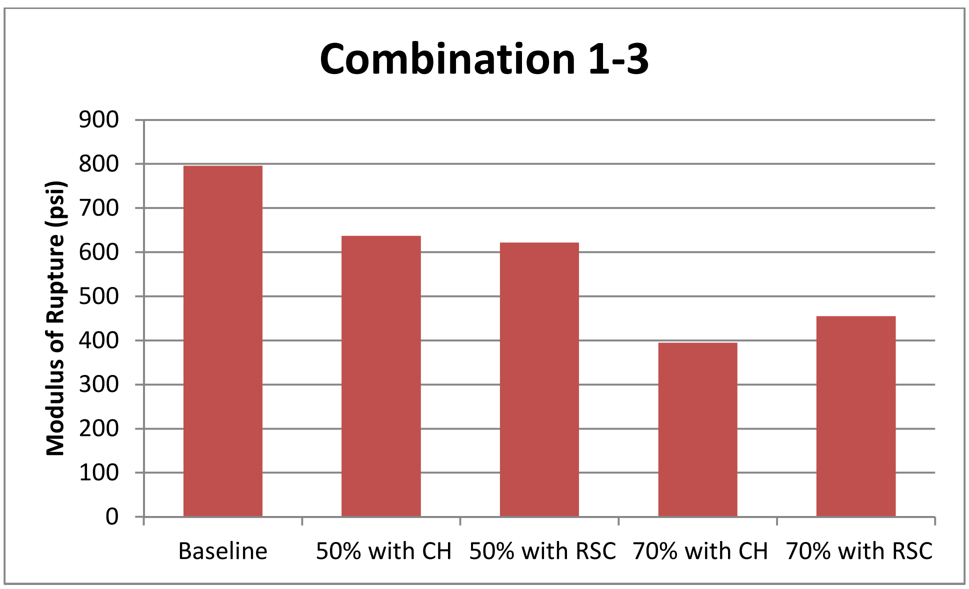

Figure 4.6. Flexural Strength of Combination 1-3

4.2.3. Splitting Tensile Strength. Three replicates of each mix were tested for splitting tensile strength at 28 days of strength, and an E 178 outlier analysis conducted for each test. Only one outlier was found for this test. To check the precision of testing, the coefficient of variation for each mix was checked against the allowable %1s of 5% as set by ASTM C 496, and it was found that six of the ten mixtures did not meet this. Three of the mixtures from combination 4-1—the baseline and both 50% fly ash replacement mixtures—were not tested using the testing jig. Looking at the coefficients of variation for those three mixtures tested without the testing jig, and the 7 tested with it, the pattern is less clear. The highest coefficient of variation, 14.8% comes from a mixture tested without the testing jig (4-1, 50% FA with CH), however, the other tested mixes (4-1 Baseline and 4-1, 50% with RSC) fall in line with observed coefficient of variations from mixtures tested with the use of the testing jig. Therefore, it is unclear if any improvement was derived from the use of the testing jig or not, although the use certainly simplified the conduction of the test. The outlier and precision analysis is presented below in Table 4.9.

Results from the 4-1 combination are shown below in Figure 4.7. At 50% fly ash substitution, splitting tensile strength results were similar or greater than the baseline mix, while at higher levels of fly ash substitution, the splitting tensile strength was reduced. Results from the 1-3 combination are shown in Figure 4.8. and show similar trends. The 50% fly ash replacement mixtures show a small loss in splitting tensile strength, with a larger loss present at 70% fly ash replacement. In both 4-1 and 1-3 combinations, rapid set cement appears to be a more effective activator at 70% replacement.

The drop in splitting tensile strength from 50% fly ash replacement to 70% fly ash replacement falls in line with previous research by Naik, Ramme, and Tews, showing a lowered splitting tensile strength with increased Class C fly ash content (Naik, et al., 1995). The majority of the splitting tensile strengths at 28 days fall within 8.9% to 10.7%

of the compressive strength at 28 days, with one mix exhibiting a splitting tensile strength 12.8% of the compressive strength. Rivest, Bouzoubaa, and Malhotra mention that splitting tensile strengths are expected to fall within 8% to 10% of the compressive strength of concrete, and this appears to be fairly true (Rivest, et al., 2004).

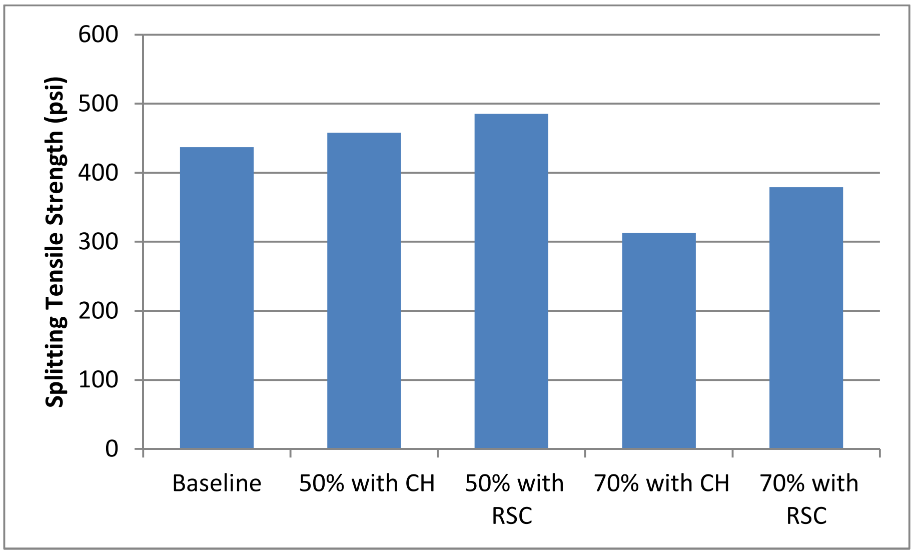

Figure 4.7. Splitting Tensile Strength of Combination 4-1

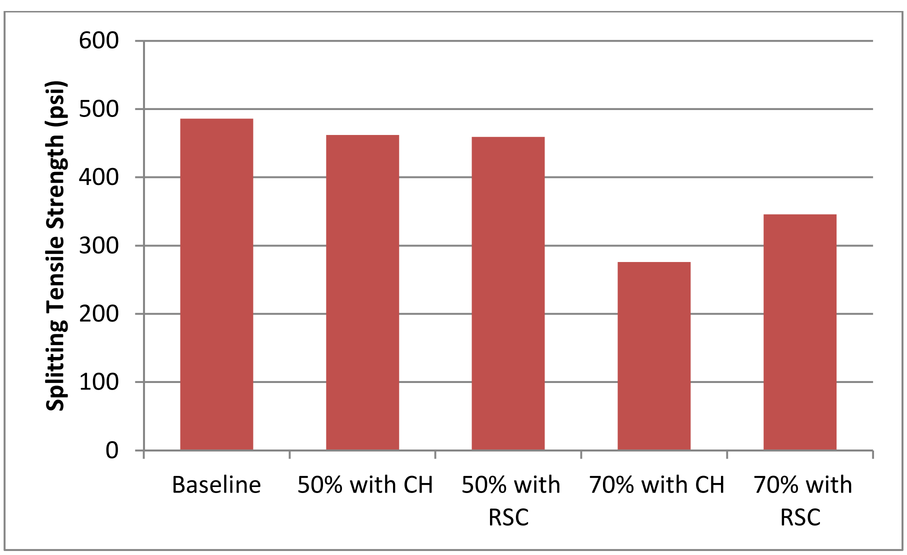

Figure 4.8. Splitting Tensile Strength of Combination 1-3

Table 4.9. Splitting Tensile Strength Outlier Analysis

	Combination 4-1					Combination 1-3				
Splitting Tensile Strength	Baseline	50% FA with CH	70% FA with CH	50% FA with RSC	70% FA with RSC	Baseline	50% FA with CH	70% FA with CH	50% FA with RSC	70% FA with RSC
Rep. 1	469	523	313	507	405	462	415	271	487	363
Rep. 2	425	388	235	453	361	493	500	273	463	334
Rep. 3	417	462	312	494	371	503	471	284	427	341
Average	*437*	*458*	*287*	*485*	*379*	*486*	*462*	*276*	*459*	*346*
Standard Dev.	28	68	45	28	23	21	43	7	30	15
tmax	1.143	0.966	0.588	0.792	1.127	0.795	0.879	1.143	0.927	1.123
tmin	0.714	1.031	1.155	1.124	0.780	1.123	1.088	0.714	1.060	0.793
tcrit	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153
Outlier?	**No**	**No**	**Yes, Min**	**No**	**No**	**No**	**No**	**No**	**No**	**No**
New Average	**437**	**458**	**313**	**485**	**379**	**486**	**462**	**276**	**459**	**346**
Standard Dev.	**28.0**	**67.6**	**0.7**	**28.2**	**23.1**	**21.4**	**43.2**	**7.0**	**30.2**	**15.1**
CV (%)	**6.4**	**14.8**	**0.2**	**5.8**	**6.1**	**4.4**	**9.4**	**2.5**	**6.6**	**4.4**

4.2.4. Modulus of Elasticity. Modulus of Elasticity was conducted upon three replicate specimens. An E 178 outlier analysis was then conducted upon the measured moduli. This outlier analysis determined that there were no outliers in the data set. The outlier and precision analysis is shown below in Table 4.10.

Results from the 4-1 combination are shown in Figure 4.9., and from the 1-3 combination in Figure 4.10. In both 4-1 and 1-3 combinations, the 50% fly ash mixtures show a similar or slightly increased modulus of elasticity, indicating a stiffer concrete. At 70% replacement of cement with fly ash, all concretes exhibit a lowered modulus of elasticity, with those 70% fly ash mixtures using rapid set cement as an activator suffering the smallest loss in modulus.

The increased modulus of elasticity of the HVFA concretes could be due to unreacted particles acting as fine aggregates to contribute to the rigidity of the concrete, as suggested by Rivest, Bouzoubaa, and Malhotra (Rivest, et al., 2004). This could likely explain why even the 70% fly ash concrete mixtures exhibited a modulus of elasticity around 4 million psi, despite a drastically lowered compressive strength.

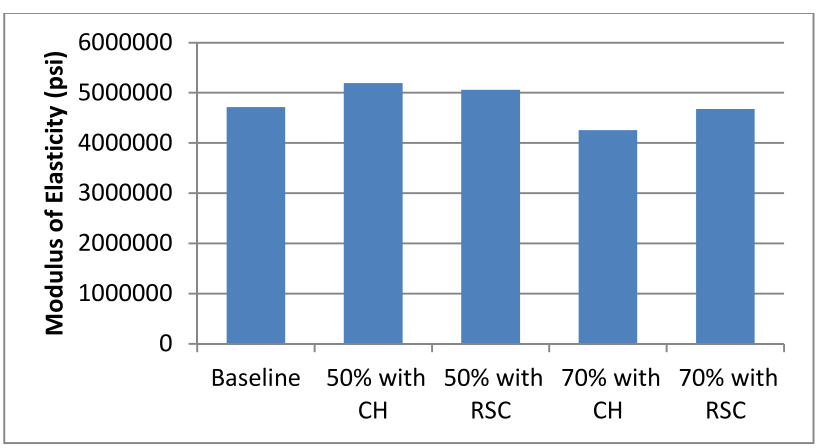

Figure 4.9. Combination 4-1 Modulus of Elasticity

Table 4.10. Modulus of Elasticity Outlier Analysis

	Combination 4-1					Combination 1-3				
Modulus of Elasticity	Baseline	50% FA with CH	70% FA with CH	50% FA with RSC	70% FA with RSC	Baseline	50% FA with CH	70% FA with CH	50% FA with RSC	70% FA with RSC
Rep. 1	4683473	5186851	4052402	5033237	4794737	5221024	5053628	3868545	5208054	4433333
Rep. 2	4759207	5293907	4437500	5048711	4521739	5020460	4920732	4095000	5325260	4545064
Rep. 3	4706704	5098976	4273148	5093567	4715789	4897756	4966565	3895455	5304795	4676856
Average	**4716461**	**5193245**	**4254350**	**5058505**	**4677422**	**5046413**	**4980308**	**3953000**	**5279370**	**4551751**
Standard Dev.	38798	97623	193236	31335	140485	163189	67506	123709	62603	121899
tmax	1.102	1.031	0.948	1.119	0.835	1.070	1.086	1.148	0.733	1.026
tmin	0.850	0.966	1.045	0.806	1.108	0.911	0.883	0.683	1.139	0.971
tcrit	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153
Outlier?	**No**	**No**	**No**	**No**	**No**	**No**	**No**	**No**	**No**	**No**
New Average	**4716461**	**5193245**	**4254350**	**5058505**	**4677422**	**5046413**	**4980308**	**3953000**	**5279370**	**4551751**
Standard Dev.	**38798**	**97623**	**193236**	**31335**	**140485**	**163189**	**67506**	**123709**	**62603**	**121899**
CV (%)	**0.8**	**1.9**	**4.5**	**0.6**	**3.0**	**3.2**	**1.4**	**3.1**	**1.2**	**2.7**

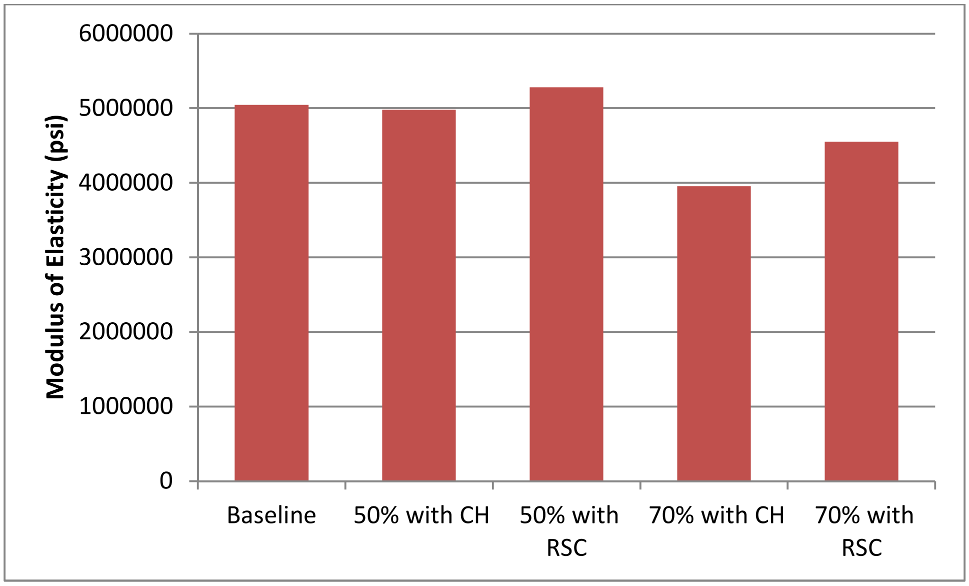

Figure 4.10. Combination 1-3 Modulus of Elasticity

4.2.5. Abrasion Resistance. Abrasion resistance was measured in both mass loss and depth of wear of the abrasion specimens in three replicates. Figure 4.11. shows a strong correlation between the two measured methods of abrasion resistance. An E 178 outlier analysis was conducted on both depth of wear and mass loss data. Four outliers were found by this method, all in the 28 day abrasion testing data, but it was determined that two of these were false positives, due to two data points being in close proximity to each other. The coefficient of variation for each mix was compared to the allowable %1s of 12.6% as noted in ASTM C 944. Eight instances of the coefficient of variation exceeding this allowable value were found. The outlier analysis and examination of precision statements can be seen in Tables 4.11 through 4.14.

In all cases, HVFA concrete mixtures showed less resistance to abrasion than their baseline counterparts. Between 28 days and 56 days of age, the HVFA concrete mixtures did gain some abrasion resistance, though in every case they still fared poorer than their baseline counterparts. This is as expected, as increased compressive strength correlates well with increased abrasion resistance. This correlation between compressive strength and mass loss is illustrated in Figure 4.12., and between compressive strength and depth of wear in Figure 4.13. For both combinations 4-1 and 1-3, the 50% fly ash mix using calcium hydroxide as an activator came closest to matching the performance of the baseline concrete. Mass loss for each mix at 28 and 56 days is plotted in Figure 4.14. for combination 4-1, and in Figure 4.15. for combination 1-3. Some scatter is evident in the data, as made apparent by 56 day abrasion tests of the baseline mixtures being quite similar or higher than 28 day abrasion tests despite having higher compressive strengths at 56 days. Figures 4.16. and 4.17. detail the depth of wear for each mix and show a similar correlation as the mass loss data. This data seems in agreement with research by Naik, Singh, and Ramme on abrasion resistance of high volume Class C fly ash concretes. In their work, Naik et al. note that replacement of cement with fly ash at low dosages (20% to 50%) fly ash seems to not greatly influence abrasion resistance of the concrete, while higher cement replacements show lowered resistance to abrasion. The authors also note the significant effect of varying fly ash sources on abrasion resistance (Naik, et al., 2002).

Table 4.11. Outlier Analysis of 28 Day Mass Loss

	Combination 4-1					Combination 1-3				
Abrasion	Baseline	50% FA with CH	70% FA with CH	50% FA with RSC	70% FA with RSC	Baseline	50% FA with CH	70% FA with CH	50% FA with RSC	70% FA with RSC
28 Day										
Weight Loss										
Rep. 1	10.2	24.2	41.9	25.7	45.3	15.8	23.7	44.5	25.4	45.6
Rep. 2	13.2	18.3	45.6	20.5	41.3	14.6	24.3	46.1	21.8	42.8
Rep. 3	10.2	16.4	44.8	23.9	46	11.0	26.8	53.9	23.3	38.6
Average	**11.2**	**19.6**	**44.1**	**23.4**	**44.2**	**13.8**	**24.9**	**48.2**	**23.5**	**42.3**
Standard Dev.	1.7	4.1	1.9	2.6	2.5	2.5	1.6	5.0	1.8	3.5
tmax	1.155	1.123	0.770	0.884	0.710	0.801	1.135	1.140	1.051	0.927
tmin	0.577	0.795	1.130	1.086	1.144	1.121	0.750	0.729	0.940	1.060
tcrit	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153
Outlier?	**Yes, Max**	**No**	**No**	**No**	**No**	**No**	**No**	**No**	**No**	**No**
New Average	**10.2**	**19.6**	**44.1**	**23.4**	**44.2**	**13.8**	**24.9**	**48.2**	**23.5**	**42.3**
Standard Dev.	**0.0**	**4.1**	**1.9**	**2.6**	**2.5**	**2.5**	**1.6**	**5.0**	**1.8**	**3.5**
CV (%)	**0.0**	**20.7**	**4.4**	**11.3**	**5.7**	**18.1**	**6.6**	**10.4**	**7.7**	**8.3**

Table 4.12. Outlier Analysis of 28 Day Depth of Wear

	Combination 4-1					Combination 1-3				
Abrasion	Baseline	50% FA with CH	70% FA with CH	50% FA with RSC	70% FA with RSC	Baseline	50% FA with CH	70% FA with CH	50% FA with RSC	70% FA with RSC
28 Day										
Depth of Wear										
Rep. 1	0.73	1.33	1.91	1.62	2.76	0.96	1.69	2.87	1.49	2.13
Rep. 2	0.92	1.07	2.29	1.5	2.53	0.96	1.65	2.66	1.6	2.41
Rep. 3	0.80	1.06	2.35	1.74	2.63	0.83	1.68	2.88	1.52	2.16
Average	**0.82**	**1.15**	**2.18**	**1.62**	**2.64**	**0.92**	**1.67**	**2.80**	**1.54**	**2.23**
Standard Dev.	0.10	0.15	0.24	0.12	0.12	0.08	0.02	0.12	0.06	0.15
tmax	1.075	1.154	0.698	1.000	1.041	0.577	0.801	0.617	1.114	1.149
tmin	0.902	0.610	1.146	1.000	0.954	1.155	1.121	1.154	0.821	0.672
tcrit	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153
Outlier?	**No**	**Yes, Max**	**No**	**No**	**No**	**No***	**No**	**No***	**No**	**No**
New Average	**0.82**	**1.07**	**2.18**	**1.62**	**2.64**	**0.92**	**1.67**	**2.80**	**1.54**	**2.23**
Standard Dev.	**0.10**	**0.01**	**0.24**	**0.12**	**0.12**	**0.08**	**0.02**	**0.12**	**0.06**	**0.15**
CV (%)	**11.77**	**0.66**	**10.93**	**7.41**	**4.37**	**8.19**	**1.24**	**4.43**	**3.70**	**6.88**

Table 4.13. Outlier Analysis of 56 Day Mass Loss

	Combination 4-1					Combination 1-3				
Abrasion	Baseline	50% FA with CH	70% FA with CH	50% FA with RSC	70% FA with RSC	Baseline	50% FA with CH	70% FA with CH	50% FA with RSC	70% FA with RSC
56 Day										
Weight Loss										
Rep. 1	13.1	16.2	41.6	19.8	41.6	13.5	18.4	30.1	24.9	42.9
Rep. 2	11.4	15.5	39.3	18.6	28.4	16.2	17.3	37.6	22.8	32.2
Rep. 3	13.6	14.4	38.7	15.1	23.5	13	18.1	34	17.4	28.5
Average	**12.7**	**15.4**	**39.9**	**17.8**	**31.2**	**14.2**	**17.9**	**33.9**	**21.7**	**34.5**
Standard Dev.	1.15	0.91	1.53	2.44	9.36	1.72	0.57	3.75	3.87	7.48
tmax	0.780	0.918	1.132	0.805	1.114	1.142	0.821	0.986	0.827	1.119
tmin	1.127	1.065	0.762	1.119	0.819	0.716	1.114	1.013	1.111	0.807
tcrit	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153
Outlier?	**No**	**No**	**No**	**No**	**No**	**No**	**No**	**No**	**No**	**No**
New Average	**12.7**	**15.4**	**39.9**	**17.8**	**31.2**	**14.2**	**17.9**	**33.9**	**21.7**	**34.5**
Standard Dev.	**1.2**	**0.9**	**1.5**	**2.4**	**9.4**	**1.7**	**0.6**	**3.8**	**3.9**	**7.5**
CV (%)	**9.1**	**5.9**	**3.8**	**13.7**	**30.0**	**12.1**	**3.2**	**11.1**	**17.8**	**21.7**

Table 4.14. Outlier Analysis of 56 Day Depth of Wear

	Combination 4-1					Combination 1-3				
Abrasion	Baseline	50% FA with CH	70% FA with CH	50% FA with RSC	70% FA with RSC	Baseline	50% FA with CH	70% FA with CH	50% FA with RSC	70% FA with RSC
56 Day										
Depth of Wear										
Rep. 1	0.92	1.09	2.49	1.27	2.31	0.99	1.34	2.07	1.42	2.14
Rep. 2	0.82	1.10	2.31	1.32	1.81	1.25	1.27	2.16	1.66	2.1
Rep. 3	1.00	1.07	2.04	1.68	1.56	1.17	1.31	2.05	1.37	2.17
Average	**0.91**	**1.09**	**2.28**	**1.42**	**1.89**	**1.14**	**1.31**	**2.09**	**1.48**	**2.14**
Standard Dev.	0.09	0.02	0.23	0.22	0.38	0.13	0.04	0.06	0.16	0.04
tmax	0.961	0.873	0.927	1.147	1.091	0.851	0.949	1.138	1.140	0.949
tmin	1.035	1.091	1.060	0.685	0.873	1.101	1.044	0.740	0.731	1.044
tcrit	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153
Outlier?	**No**	**No**	**No**	**No**	**No**	**No**	**No**	**No**	**No**	**No**
New Average	**0.91**	**1.09**	**2.28**	**1.42**	**1.89**	**1.14**	**1.31**	**2.09**	**1.48**	**2.14**
Standard Dev.	**0.09**	**0.02**	**0.23**	**0.22**	**0.38**	**0.13**	**0.04**	**0.06**	**0.16**	**0.04**
CV (%)	**9.87**	**1.41**	**9.93**	**15.72**	**20.17**	**11.72**	**2.69**	**2.80**	**10.45**	**1.64**

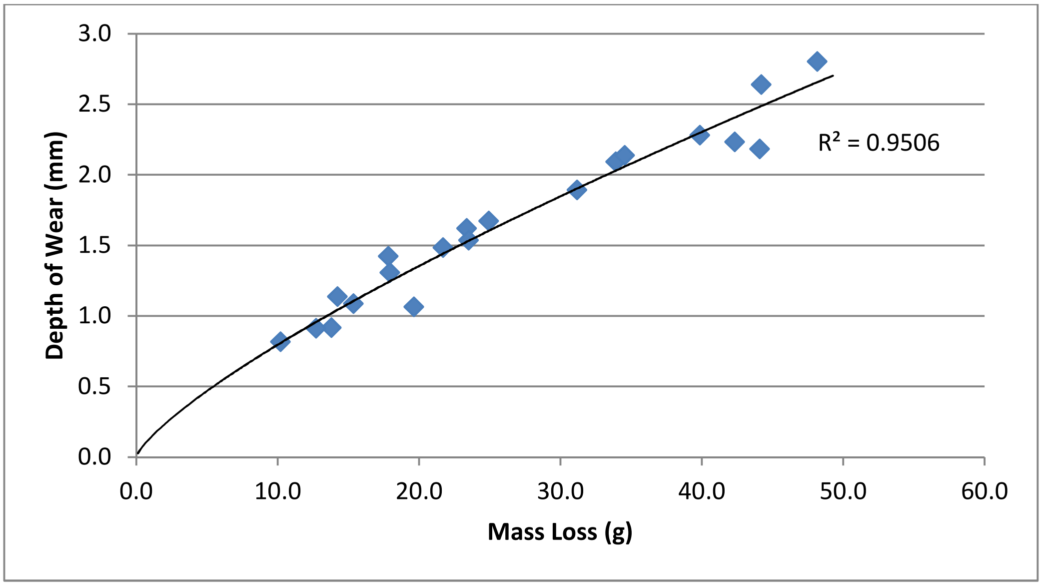

Figure 4.11. Mass Loss/Depth of Wear Correlation

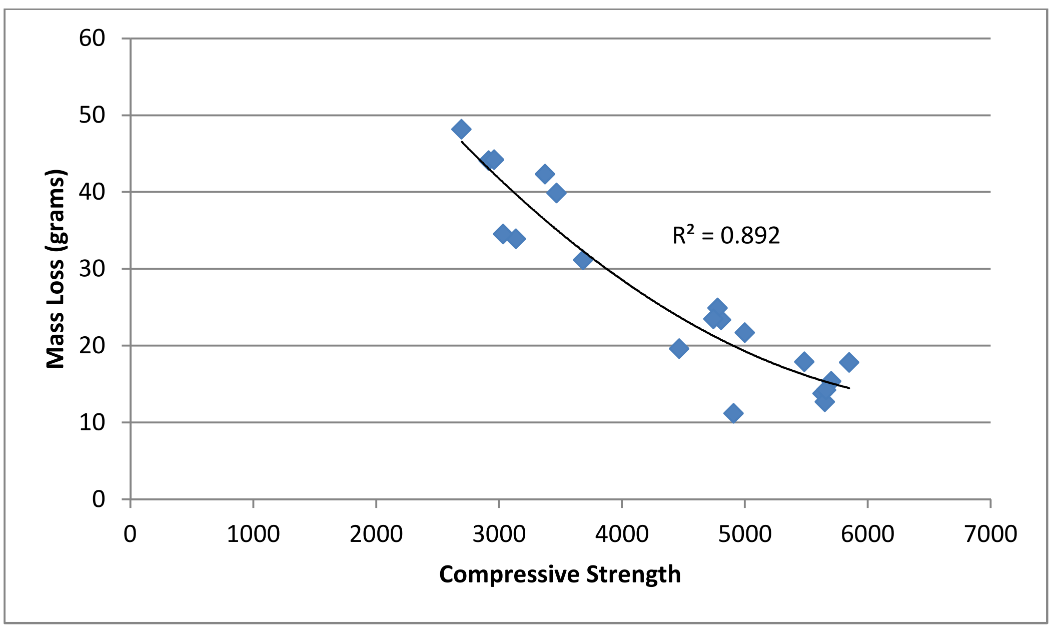

Figure 4.12. Mass Loss versus Compressive Strength

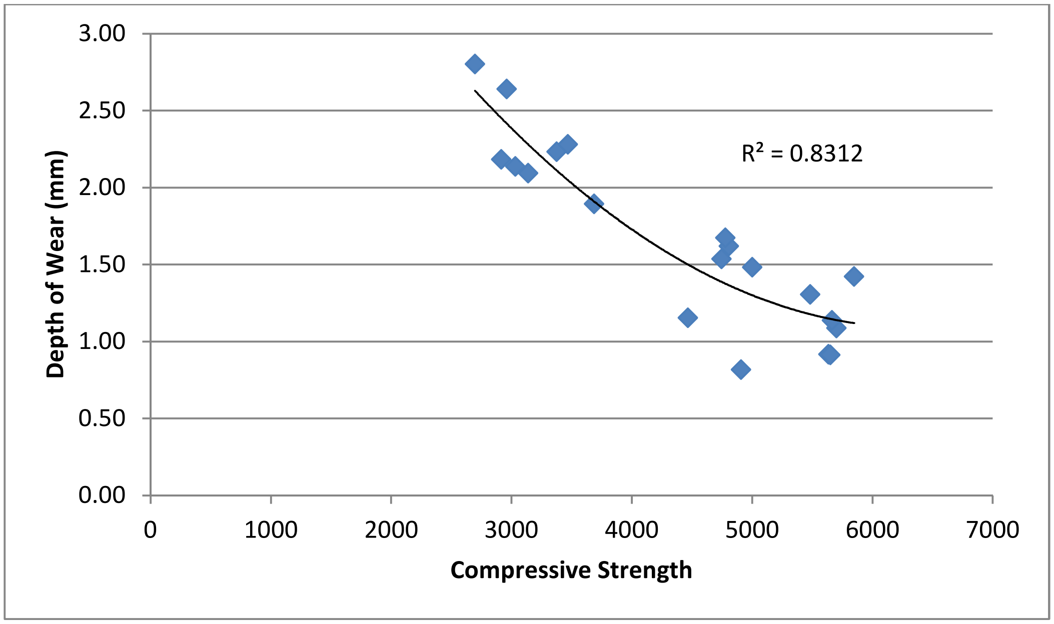

Figure 4.13. Depth of Wear versus Compressive Strength

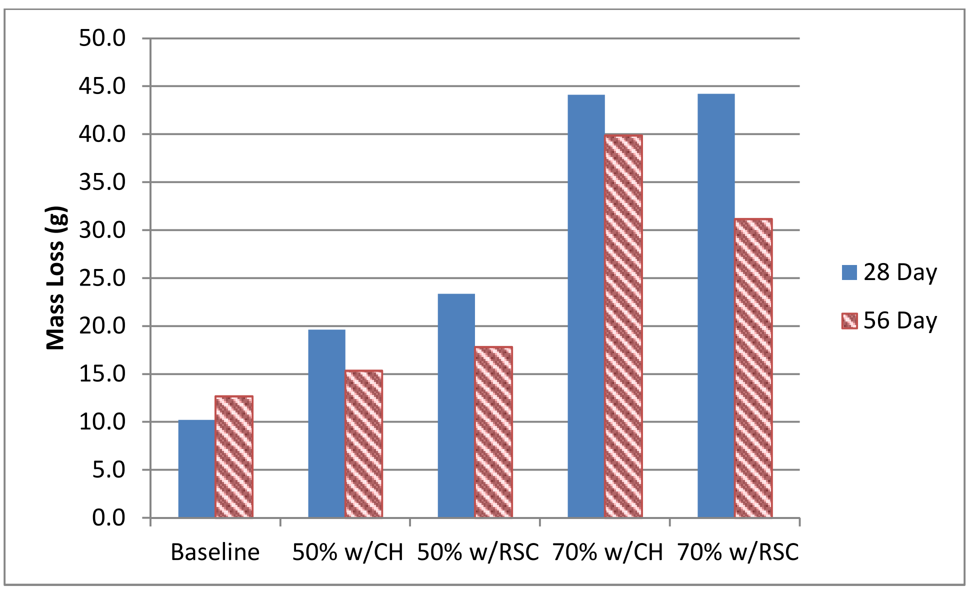

Figure 4.14. 4-1 Abrasion Resistance Mass Loss

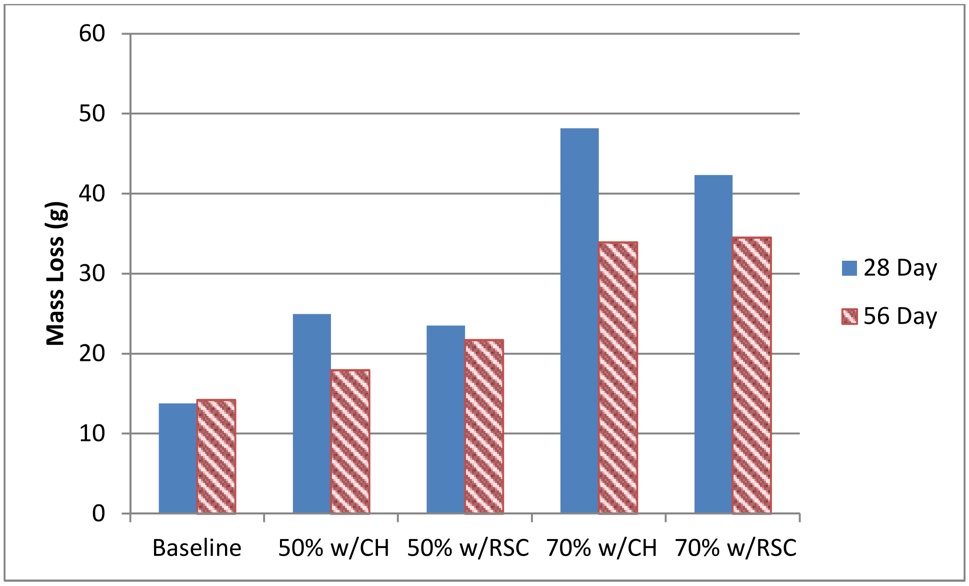

Figure 4.15. 1-3 Abrasion Resistance Mass Loss

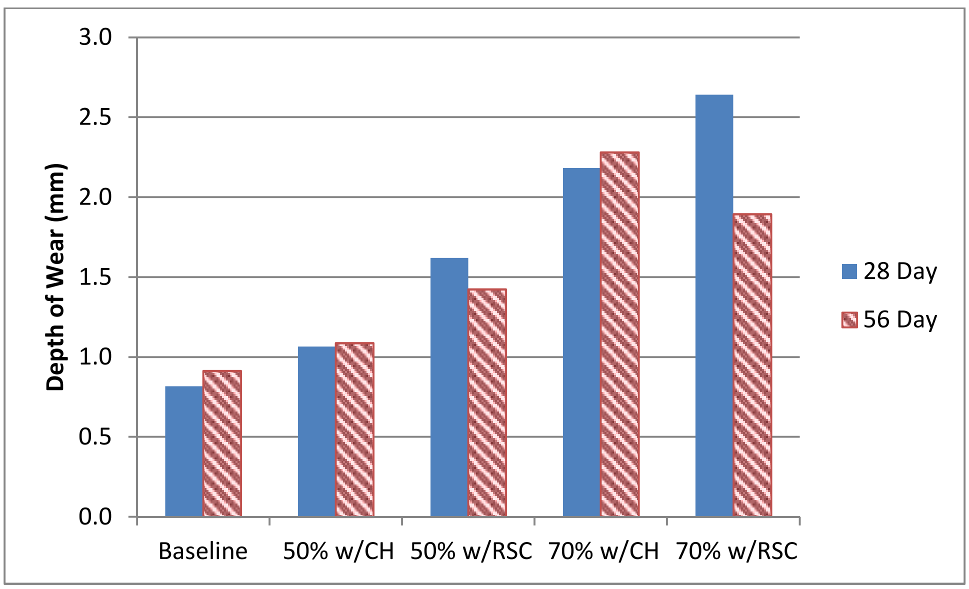

Figure 4.16. 4-1 Abrasion Resistance Depth of Wear

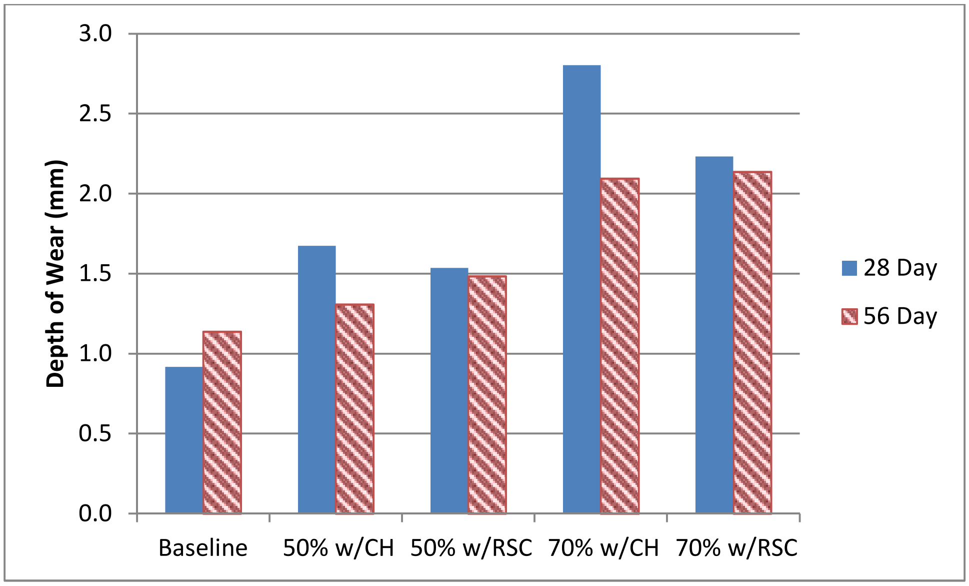

Figure 4.17. 1-3 Abrasion Resistance Depth of Wear

4.2.6. Rapid Chloride Permeability. The rapid chloride permeability (RCP) test is a direct measure of electrical conductivity rather than an actual permeability test. However, this test shows good correlation with more intensive chloride ponding tests. This test was conducted on two cylinders for each concrete mix at 28 days of age. Two slices were taken of each cylinder, for a total of four measurements of charge passed. These four measurements were subject to an E 178 outlier analysis, and only one outlier was found. ASTM C 1202 sets an allowable coefficient of variation, or %1s of 12.3%. In all but one case, this precision statement is met. Permeability classes for each mix were determined in accordance with Table X1.1 from ASTM C 1202. The results of these tests and outlier analyses are shown below in Table 4.15.

Figure 4.18, below, shows the RCP test results for the most reactive combination, 4-1. At 50% replacement of cement with fly ash, both calcium hydroxide and rapid set cement mixtures exhibited greatly decreased permeability, with an adjusted charge passed of less than half of that exhibited by the baseline mix. At 70% replacement, however, both calcium hydroxide and rapid set cement mixtures proved to be more permeable than the baseline mix. It is important to note, however, that this test was conducted at 28 days, and as the 70% fly ash mixtures approach 100% hydration, they may exhibit a more impermeable microstructure. In both cases, rapid set cement mixtures had a more drastic effect on the permeability than calcium hydroxide.

Figure 4.19 shows the results of the RCP test on the least reactive combination, 1-3. Results for this combination are less clear cut, with 50% fly ash mixtures exhibiting similar permeability to the baseline mix. The 50% fly ash mix utilizing rapid set cement as an activator decreased the permeability from the baseline mix by a slight amount, while the mix utilizing calcium hydroxide was more permeable than the baseline mix. At 70%, both mixtures exhibited high permeability, with the mix utilizing calcium hydroxide as an activator passing too high a charge to finish the test. Therefore, as the test could not run for the full 6 hours, no data for this test is provided.

Previous research by Bilodeau, Sivasundaram, Painter, and Malhotra shows fly ashes at 58% replacement exhibiting fairly low charges passed, with values falling off drastically at 91 days and 1 year (Bilodeau, et al., 1994). The most reactive mix combination, 4-1, shows a similar decreased chloride ion permeability at 50%. Possible reasons for the higher charge passed at 70% for the 4-1 combination, and for both 50% and 70% fly ash replacement of the 1-3 mix could be due to the test being conducted at the relatively early age of 28 days, when pozzolanic activity of the fly ash may not contribute significantly until 56 or 90 days of age, and therefore unreacted fly ash particles act as filler rather than hydration products, increasing the porosity of the paste microstructure.

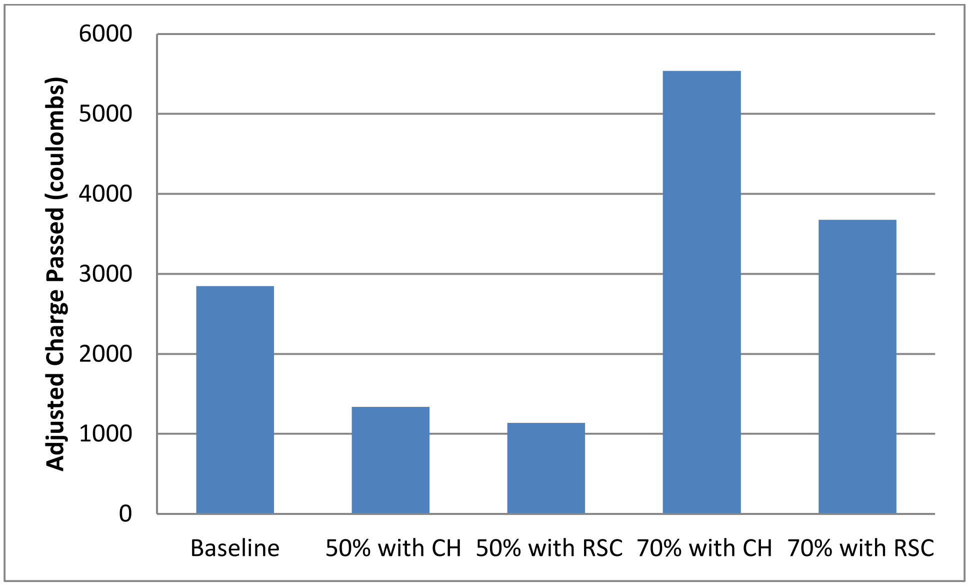

Figure 4.18. Rapid Chloride Permeability Results for 4-1 Mixtures

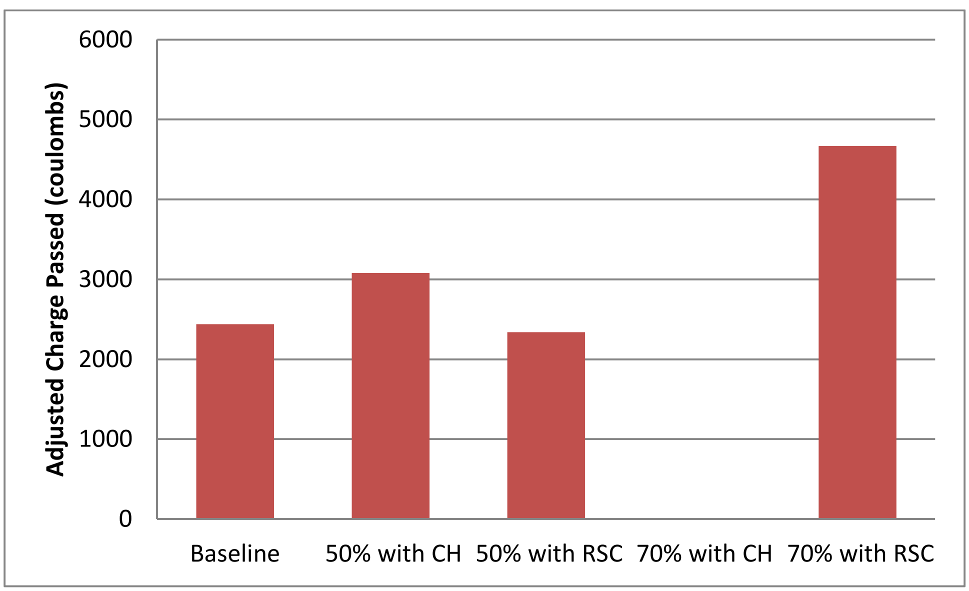

Figure 4.19. Rapid Chloride Permeability Results for 1-3 Mixtures

Table 4.15. RCP Data and Outlier Analysis

	4-1 Combinations					1-3 Combinations				
RCP Adjusted Charge	Baseline	50% FA with CH	70% FA with CH	50% FA with RSC	70% FA with RSC	Baseline	50% FA with CH	70% FA with CH	50% FA with RSC	70% FA with RSC
Top 1	2698	1350	5407	976	3394	2389	3198	NA	2559	4817
Middle 1	2760	1323	5701	1428	3602	2445	3162	NA	2434	4392
Top 2	3109	1039	5479	1047	3685	2615	3107	NA	2042	4926
Middle 2	2816	1344	5559	1103	4030	2304	2856	NA	2319	4540
Average	**2846**	**1264**	**5537**	**1139**	**3678**	**2438**	**3081**	**NA**	**2339**	**4669**
Standard Dev.	182.00	150.45	126.02	199.87	264.82	131.32	154.44	NA	220.63	245.85
tmax	1.446	0.572	1.305	1.448	1.330	1.346	0.759	NA	0.999	1.046
tmin	0.812	1.496	1.028	0.813	1.071	1.022	1.455	NA	1.344	1.126
tcrit	1.463	1.463	1.463	1.463	1.463	1.463	1.463	NA	1.463	1.463
Outlier?	**No**	**Yes, Top 2**	**No**	**No**	**No**	**No**	**No**	**NA**	**No**	**No**
New Average	**2846**	**1339**	**5537**	**1139**	**3678**	**2438**	**3081**	**NA**	**2339**	**4669**
Standard Dev.	**182.0**	**14.2**	**126.0**	**199.9**	**264.8**	**131.3**	**154.4**	**NA**	**220.6**	**245.8**
CV (%)	**6.39**	**1.06**	**2.28**	**17.55**	**7.20**	**5.39**	**5.01**	**NA**	**9.43**	**5.27**
Permeability Class	**Moderate**	**Low**	**High**	**Low**	**Moderate**	**Moderate**	**Moderate**	**High/NA**	**Moderate**	**High**

4.2.7. Freeze-Thaw Resistance. Three replicate beams were cast and tested for freeze-thaw resistance at 35 days of age, thereby making it possible to conduct an E 178 outlier analysis upon the results. Freeze-thaw resistance for this study was measured by means of the durability factor, and no outliers were found in this data. ASTM C 666 specifies variable allowable %1s values depending upon the number of replicate specimens, the average durability factor, and whether Method A or Method B are used. For this study, Method B was used, and all tests were found to fall within the allowable %1s. The outlier and precision analysis can be seen below, in Table 4.16.

Freeze-thaw results for combination 4-1 may be seen in Figure 4.20., below. Durability factor (DF) is a relative measure, adjusting the relative dynamic modulus for the number of cycles that the specimen has undergone, relative to the total number of cycles it will undergo. A text written by Mindess, Young, and Darwin suggests that there are not hard limits on whether or not a concrete will fail based upon freeze-thaw data, only suggesting that concrete with a DF of more than 60 will perform adequately (Mindess, et al., 2003). MoDOT uses a durability factor of 75, which all concrete mixtures in this study exceeded. The data for combination 4-1 suggests that the inclusion of fly ash, regardless of which powder activator is used in the mix, greatly improves the durability factor from that of the baseline mix, with 70% fly ash mixtures showing a higher durability factor than those containing 50% fly ash. The same conclusions can be drawn from combination 1-3, the results of which are shown in Figure 4.21, below. Though the baseline mix for this combination showed higher freeze thaw resistance than did combination 4-1, the fly ash mixtures all improve upon this freeze thaw durability, with 70% fly ash mixtures showing a higher durability factor than those containing 50%

fly ash. This is likely due to the decreased permeability of HVFA concretes, resulting in a less continuous pore structure, and therefore improved resistance to freezing and thawing.

While their concretes were not air entrained, this increased durability of HVFA concretes seems to be in line with Galeota, Giammatteo, and Marino's work showing that higher volume fly ash concretes resist freezing and thawing more than their cement only counterparts (Galeota, et al., 1995), and it shows high durability factors for fly ash mixtures, in line with work by Bilodeau, Sivasundaram, Painter, and Malhotra, which showed HVFA mixtures being able to withstand severe freezing and thawing conditions (Bilodeau, et al., 1994).

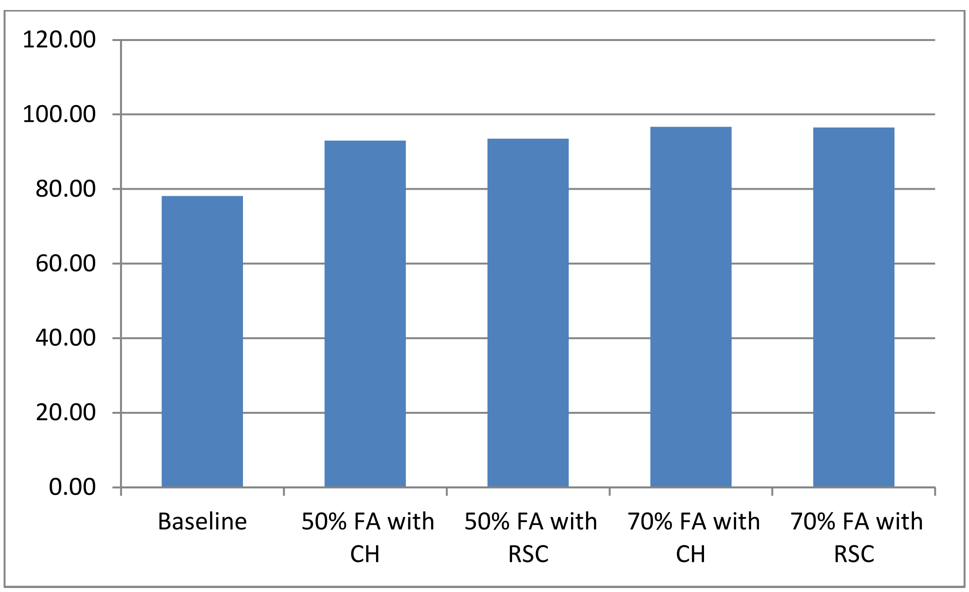

Figure 4.20. Durability Factors of 4-1 Combinations

Table 4.16. Outlier and Precision Analysis for Freeze/Thaw Resistance

Freeze Thaw	Combination 4-1					Combination 1-3				
Durability Factor	Baseline	50% FA with CH	70% FA with CH	50% FA with RSC	70% FA with RSC	Baseline	50% FA with CH	70% FA with CH	50% FA with RSC	70% FA with RSC
Rep. 1	72.11	94.94	95.57	94.18	96.76	86.92	90.67	96.4	92.19	95.24
Rep. 2	82.59	91.38	97.01	91.52	96.44	84.25	92.87	96.63	90.29	95.89
Rep. 3	79.79	92.58	97.4	94.71	96.28	90.59	93.39	97.11	90.11	95.01
Average	**78.16**	**92.97**	**96.66**	**93.47**	**96.49**	**87.25**	**92.31**	**96.71**	**90.86**	**95.38**
Standard Dev.	5.43	1.81	0.96	1.71	0.24	3.18	1.44	0.36	1.15	0.46
t_{max}	0.816	1.090	0.768	0.725	1.091	1.048	0.748	1.095	1.151	1.117
t_{min}	1.116	0.876	1.131	1.141	0.873	0.944	1.136	0.865	0.654	0.811
t_{crit}	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153	1.153
Outlier?	**No**	**No**	**No**	**No**	**No**	**No**	**No**	**No**	**No**	**No**
New Average	78.16	92.97	96.66	93.47	96.49	87.25	92.31	96.71	90.86	95.38
Standard Dev.	5.43	1.81	0.96	1.71	0.24	3.18	1.44	0.36	1.15	0.46
Allowable 1s	9.9	2.3	1.2	2.3	1.2	5.0	2.3	1.2	2.3	1.2
CV (%)	6.94	1.95	1.00	1.83	0.25	3.65	1.56	0.37	1.27	0.48

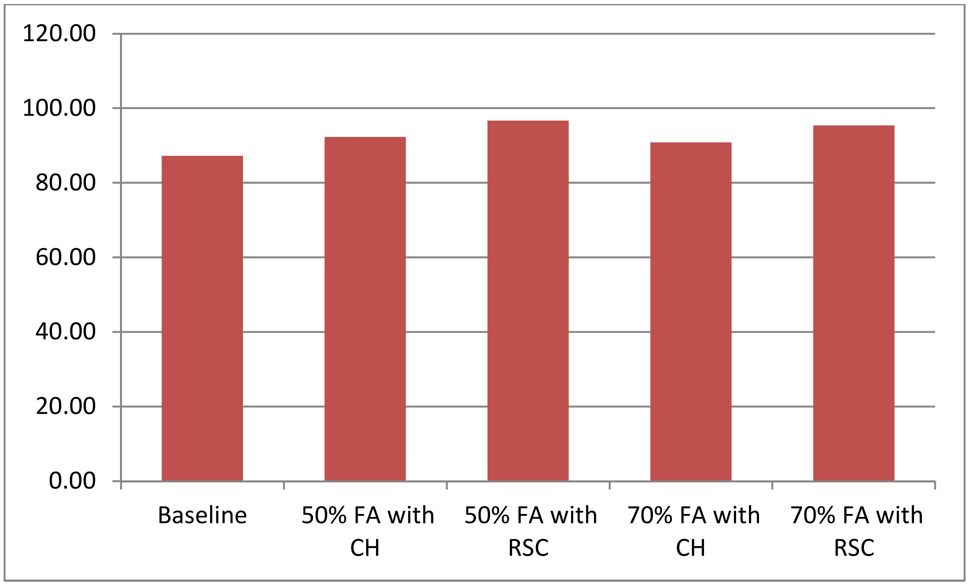

Figure 4.21. Durability Factors of 1-3 Combinations

4.2.8. Scaling Resistance. Three replicates of each mix were tested for scaling resistance. As the scaling method is based upon visual rankings, it cannot be subjected to a method to determine precision appropriately. Specimens were visually rated every 5 cycles, and rankings typically matched across all three specimens. Small variations in finishing procedure may have led to differing rankings between specimens. Table 4.17., below, shows scaling ratings alongside pictures of scaling slabs meeting those rankings.

The scaling results for combination 4-1 are presented below in Table 4.18. As the baseline mix performs adequately, showing only very slight scaling (defined by ASTM C 672 as 3 mm depth maximum, and no coarse aggregate visible), this suggests that the molding and finishing procedures are adequate. Fly ash concretes show severe scaling, defined by ASTM C 672 as coarse aggregate being visible over the entire surface of the specimen. The mixtures containing 70% replacement of cement with fly ash show a much more rapid scaling than those containing 50%, albeit with the same end result.

Calcium hydroxide appears to perform better than rapid set cement as an activator in resisting deicer scaling, though all fly ash mixtures exhibit severe scaling at the end of 50 cycles. This tendency toward severe scaling seems to mirror the findings of Bilodeau, Sivasundaram, Painter, and Malhotra, who examined 8 different fly ashes with both high calcium contents and low calcium contents (corresponding to Class C and Class F). At 58% fly ash replacement, all 16 of their mixtures showed severe scaling after 50 cycles according to ASTM C 672 (Bilodeau, et al., 1994).

Scaling results for combination 1-3 follow in Table 4.19., and are similar in nature to the results from combination 4-1. Again, the baseline concrete mix performs the best, with increasing fly ash content resulting in more severe scaling. Rapid set cement performs better than calcium hydroxide as an activator for this combination, though still shows more severe scaling than baseline mixtures.

Table 4.17. Visual Scaling Rankings

0	No Scaling	
1	Very Slight Scaling	
2	Slight to Moderate Scaling	

Table 4.17 Visual Scaling Rankings (cont.)

3	Moderate Scaling	
4	Moderate to Severe Scaling	
5	Severe Scaling	

Table 4.18. Scaling Results for Combination 4-1

	5 Cycles	10 Cycles	15 Cycles	20 Cycles	25 Cycles	30 Cycles	35 Cycles	40 Cycles	45 Cycles	50 Cycles
Baseline										
Rep. 1	1	1	1	1	1	1	1	2	2	2
Rep. 2	1	1	1	1	1	1	1	1	1	1
Rep. 3	1	1	1	1	1	1	1	1	1	1
50% with CH										
Rep. 1	1	1	2	3	3	3	4	4	4	5
Rep. 2	1	1	2	3	3	3	4	4	4	5
Rep. 3	1	1	2	3	3	3	4	4	4	4
70% with CH										
Rep. 1	3	4	5	5	5	5	5	5	5	5
Rep. 2	3	4	5	5	5	5	5	5	5	5
Rep. 3	3	4	5	5	5	5	5	5	5	5
50% with RSC										
Rep. 1	3	3	4	4	4	4	4	5	5	5
Rep. 2	3	3	4	4	4	4	4	5	5	5
Rep. 3	3	3	4	4	4	4	4	5	5	5
70% with RSC										
Rep. 1	4	4	4	4	4	4	4	5	5	5
Rep. 2	4	4	4	4	4	4	4	5	5	5
Rep. 3	4	4	4	4	4	4	4	5	5	5

Table 4.19. Scaling Results for Combination 1-3

	5 Cycles	10 Cycles	15 Cycles	20 Cycles	25 Cycles	30 Cycles	35 Cycles	40 Cycles	45 Cycles	50 Cycles
Baseline										
Rep. 1	0	1	*	*	*	*	*	*	*	*
Rep. 2	0	1	1	2	2	2	2	2	2	2
Rep. 3	0	1	1	1	1	1	1	2	2	2
50% with CH										
Rep. 1	3	3	3	3	3	3	4	5	5	5
Rep. 2	3	3	3	3	3	3	4	5	5	5
Rep. 3	3	3	3	3	3	3	4	5	5	5
70% with CH										
Rep. 1	3	3	4	5	5	5	5	5	5	5
Rep. 2	3	3	4	5	5	5	5	5	5	5
Rep. 3	3	3	4	5	5	5	5	5	5	5
50% with RSC										
Rep. 1	2	3	3	3	3	3	3	4	4	4
Rep. 2	2	2	2	3	3	3	3	4	4	4
Rep. 3	2	2	2	3	3	3	3	4	4	4
70% with RSC										
Rep. 1	2	2	2	3	3	3	3	3	3	3
Rep. 2	2	2	2	3	3	3	3	3	3	3
Rep. 3	2	2	2	3	3	3	3	3	3	3

4.2.9. Linear Shrinkage. Linear shrinkage was measured on cylindrical specimens with two lines of DEMEC points applied at 180 degrees from each other. Two specimens were cast for each mix, and only in one case did one specimen break during demolding (combination 4-1 with 70% fly ash and rapid set cement as an activator).

Figure 4.22. below shows the shrinkage curves for combination 4-1, and Figure 4.23. shows the shrinkage curves for combination 1-3. In all cases, fly ash mixtures plotted below the baseline mix, meaning that these mixtures incurred less shrinkage. The slopes of the lines parallel the baseline curve closely, making it unlikely that the fly ash mixtures will ever cross the baseline curve and incur greater shrinkage. This lessened shrinkage could be due to the decreased amount of water reducer needed in fly ash mixtures, though this explanation is unlikely to explain the reduced shrinkage in combination 1-3, due to the need for increased water reducer dosages from the baseline in some cases. The lessened shrinkage of HVFA concrete mixtures falls in line with results from Rivest, Bouzouubaa, and Malhotra, suggesting that unhydrated cementitious material within the HVFA mixtures may be acting as aggregate and restraining the specimens from shrinkage. While Rivest et al. used a lower w/cm for fly ash concretes and attributed the lower water content to decreased shrinkage of the HVFA mixtures, it is clear that other factors are at work (Rivest, et al., 2004).

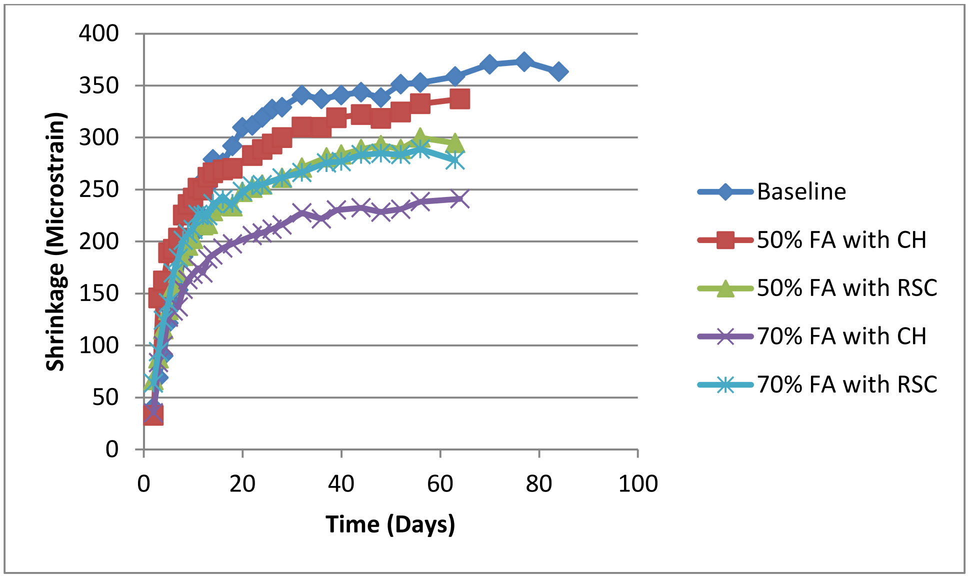

Figure 4.22. Shrinkage Curves for Combination 4-1

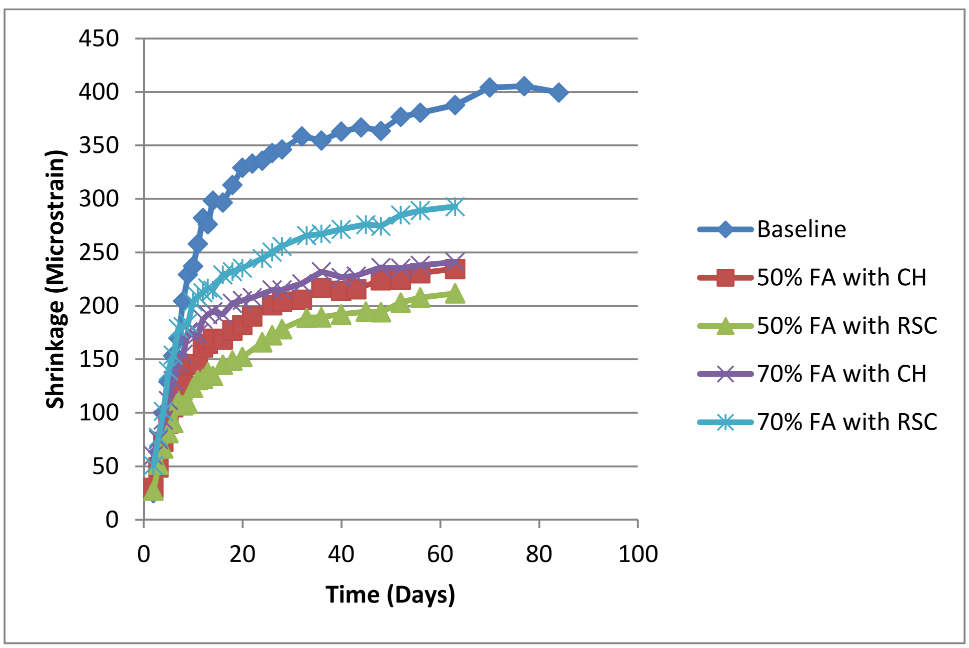

Figure 4.23. Shrinkage Curves for Combination 1-3

4.2.10. Vicat Setting Time. Vicat setting time was measured on all of the mixtures in the paste study in order to compare setting times, and measure the effects of the activators on setting time. Before the addition of any powder activators, two water reducer dosages were used in the paste study—a low dose of 2.75 fl oz/cwt, and a high dose of 5.0 fl oz/cwt. The effects of water reducer dosages upon setting times are presented below in Figure 4.24. for combination 4-1, and in Figure 4.25. for combination 1-3. For the 4-1 combination, setting time is increased by the addition of water reducer as cementitious particles are dispersed. For the 1-3 combination, setting time is increased at low levels of fly ash replacement, but as higher volumes of fly ash are used in the paste, the set time decreases drastically. This could be due to increased dispersion of the aluminates in combination with a lack of sulfate, leading to the rapid reaction of aluminates with calcium in the mix to cause flash set.

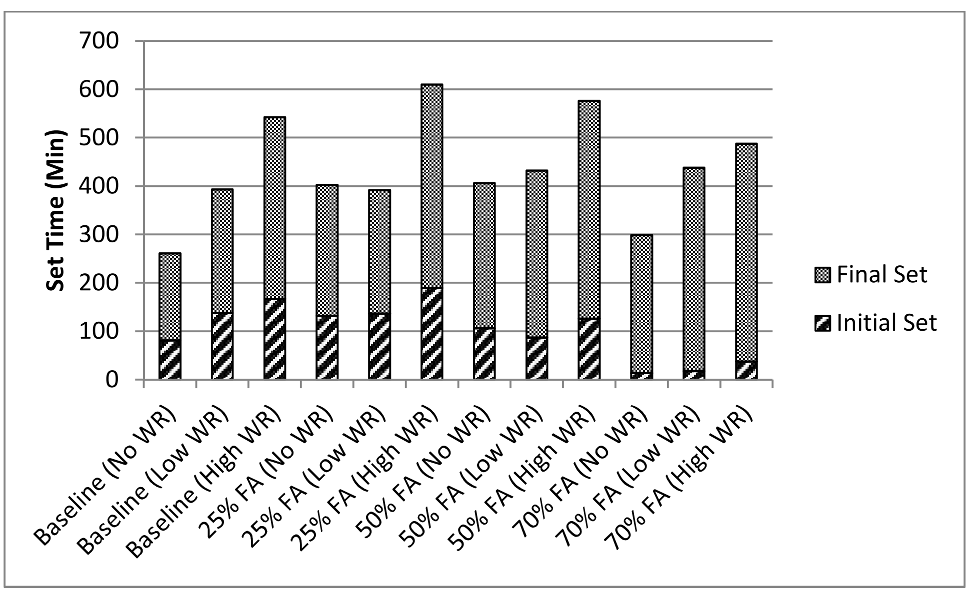

Figure 4.24. Water Reducer Effect on Combination 4-1

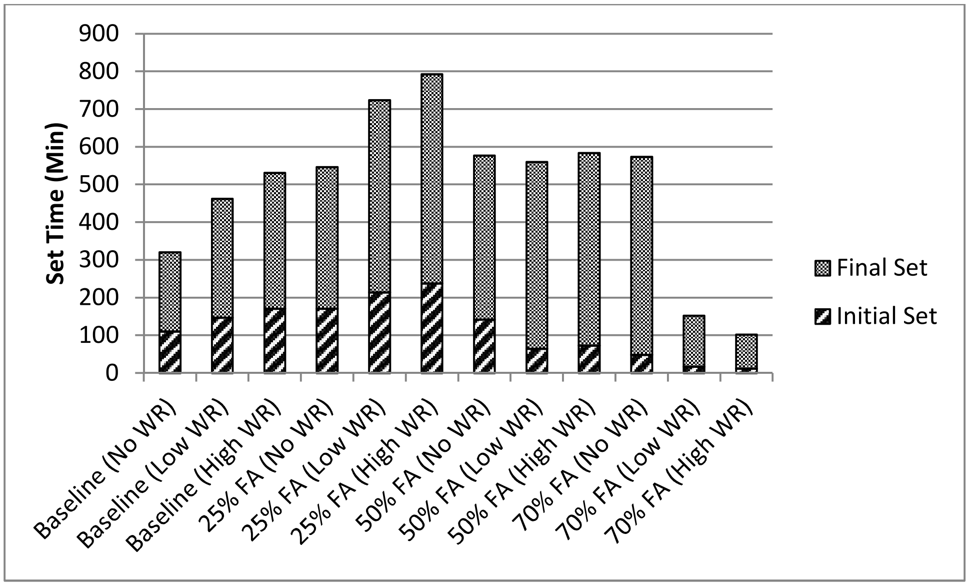

Figure 4.25. Water Reducer Effect on Combination 1-3

After a water reducer dosage of 2.75 fl oz/cwt was chosen for all mixtures in the paste study main matrix, a gypsum dosage was determined for use in the mixtures. Previous research by Bentz resulted in his selection of a 2% addition level of gypsum based upon the cement that he was using (Bentz, 2010). In this study, a 2% addition of gypsum by weight of fly ash was examined, as well as a 4% addition of gypsum by weight of fly ash. Gypsum replacement was only conducted on 50% fly ash and 70% fly ash mixtures. Figure 4.26., below, shows the effect of gypsum addition on setting time for combination 4-1. Figure 4.27 shows the effect the gypsum addition on setting time for combination 1-3. Both combinations show a similar effect on setting time, with increasing gypsum dosage resulting in an increase in set time as the increased sulfate retards the reaction of the aluminates.

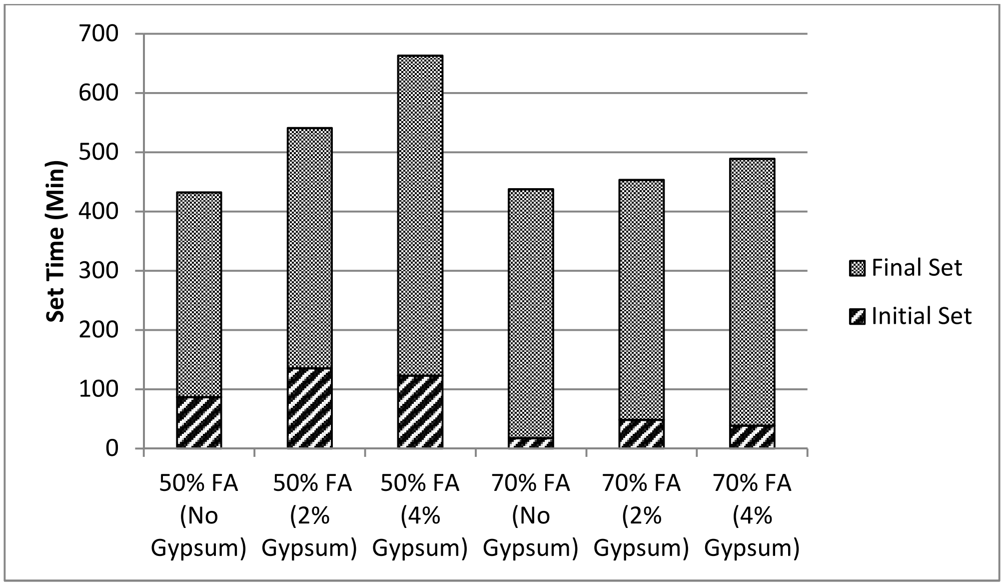

Figure 4.26. Gypsum Effect on Setting Time for Combination 4-1

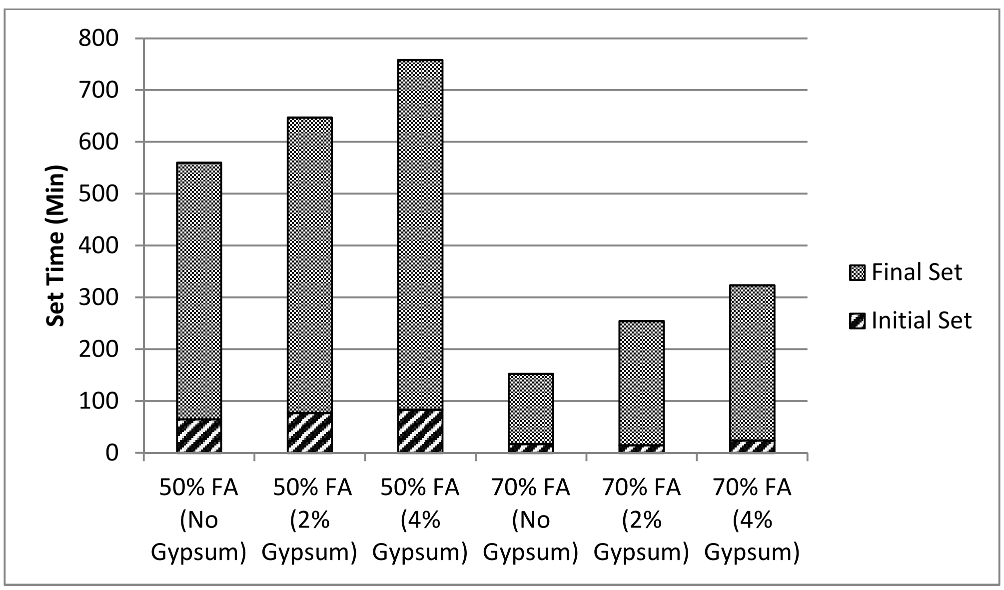

Figure 4.27. Gypsum Effect on Setting Time for Combination 1-3

Two powder activators were examined based upon research by Bentz, with dosages chosen similar to the dosages that Bentz examined. Calcium hydroxide was used at dosages of 5% replacement by weight of fly ash, as Bentz examined, as well as 10%

replacement by weight of fly ash. Rapid set cement was used at dosages of 10% replacement by weight of fly ash, as Bentz examined, as well as 20% replacement by weight of fly ash. Bentz suggested the 20% replacement level of rapid set cement, but noted concern that it might result in excessive early hydration and the mix setting too rapidly (Bentz, 2010). The results of calcium hydroxide additions are shown for combination 4-1 in Figure 4.28., and for combination 1-3 in Figure 4.29. The addition of calcium hydroxide resulted in shortened setting times for all mixtures due to the increased availability of calcium ions to fuel the silicate reactions of the paste. For the 4-1 combination, it appeared more effective at controlling the setting time of the 50% fly ash replacement, whereas at 70% fly ash replacement, no additional benefit was seen to increasing the calcium hydroxide dosage from 5% to 10%. For the 1-3 combination, all levels of fly ash replacement showed shorter setting times with increased calcium hydroxide dosages.

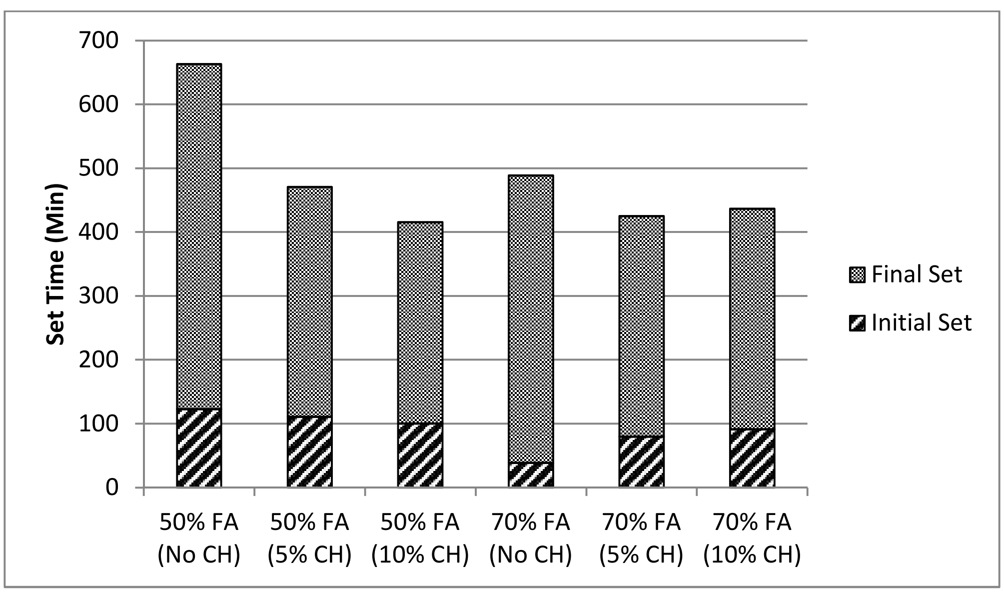

Figure 4.28. Effect of Calcium Hydroxide on Setting Time of Combination 4-1

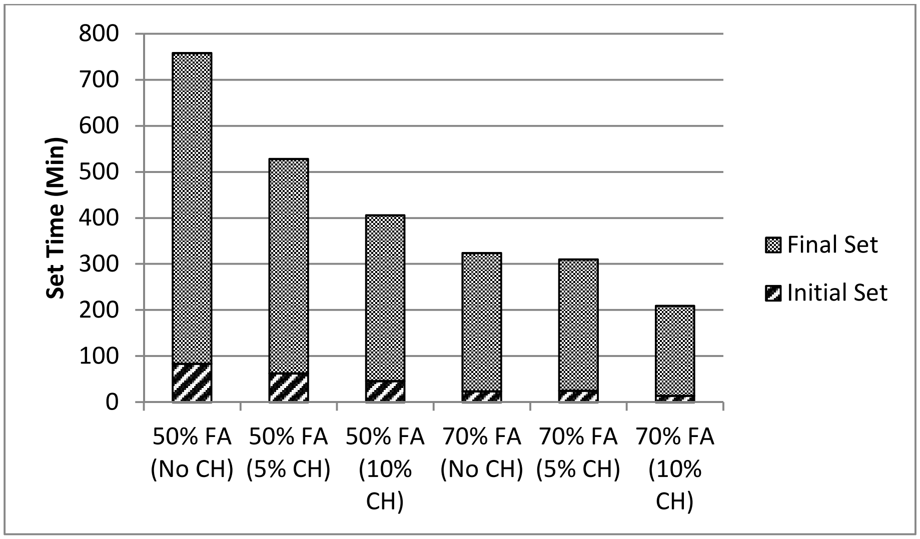

Figure 4.29. Effect of Calcium Hydroxide on Setting Time of Combination 1-3

The results of rapid set cement additions are shown below in Figure 4.30. for combination 4-1, and in Figure 4.31. for combination 1-3. Rapid set cement additions showed greatly decreased setting times for both combinations at all levels of fly ash replacement. As Bentz writes, this is due to the rapid set cement being unaffected by the retarding effects of the fly ash replacement (Bentz, 2010).

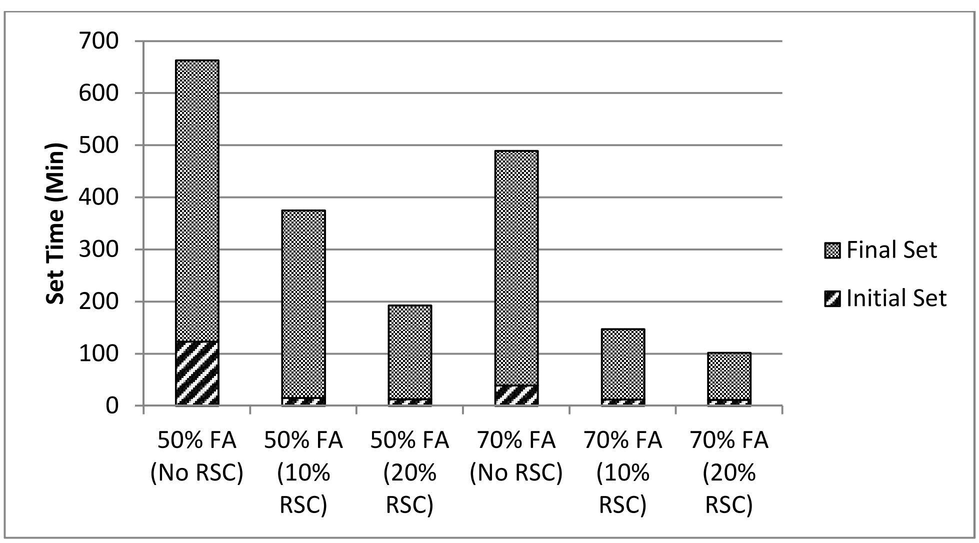

Figure 4.30. Effect of Rapid Set Cement on Setting Time of Combination 4-1

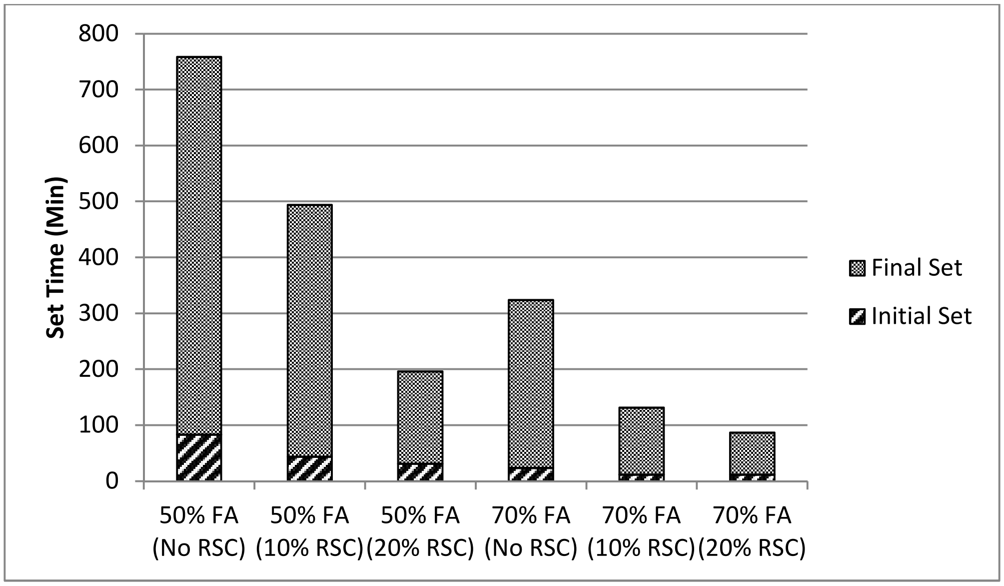

Figure 4.31. Effect of Rapid Set Cement on Setting Time of Combination 1-3

An attempt was made to draw a correlation between time of set results from ASTM C 403, and Vicat setting time results. Figure 4.32., below, presents the initial and final set results for the ten concrete mixtures by ASTM C 403 plotted against Vicat set times of cement paste mixtures. The set times are presented in Table 4.20. As can be seen, there does not appear to be a clear correlation between the two test methods. This is most likely due to the differences in water reducer dosages between the paste study and concrete study, the different batches of fly ash used in the paste study and concrete study, the presence of air entraining agent in the concrete study, and the presence of aggregate passing a #4 sieve in ASTM C 403.

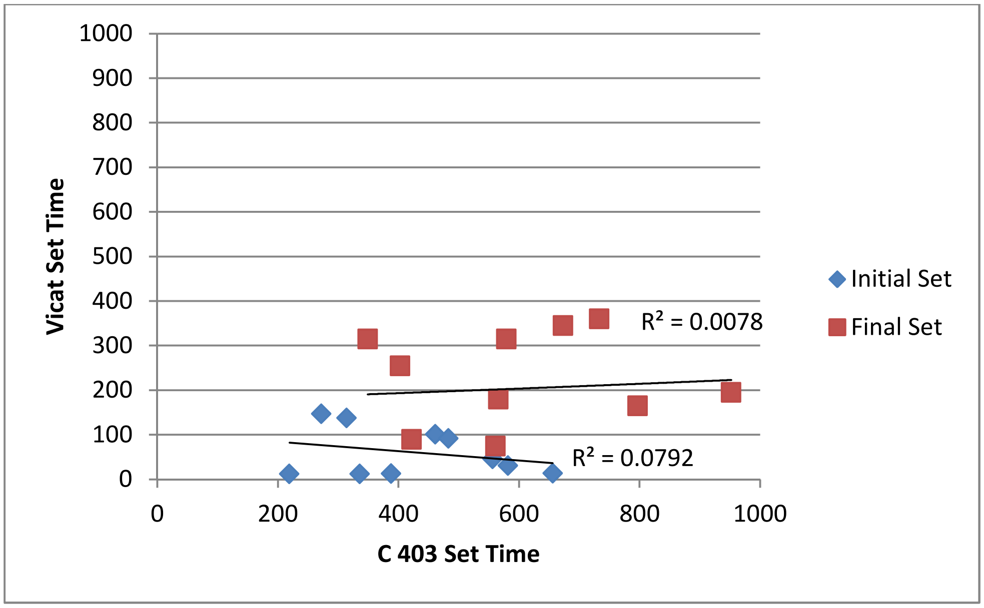

Figure 4.32. Vicat and C 403 Setting Time Comparison

Table 4.20. Vicat and C 403 Setting Times

		ASTM C 403		Vicat	
		Initial	Final	Initial	Final
4-1	Baseline	314	403	138	255
	50% w/CH	461	579	101	315
	50% w/RSC	388	566	13	180
	70% w/CH	483	673	92	345
	70% w/RSC	219	422	12	90
1-3	Baseline	272	349	147	315
	50% w/CH	556	733	46	360
	50% w/RSC	582	797	31	165
	70% w/CH	656	952	14	195
	70% w/RSC	336	561	12	75

5. SUMMARY AND CONCLUSIONS

5.1. SUMMARY

Two Missouri area cements and two Missouri area fly ashes were used in combination with gypsum, calcium hydroxide, and rapid set cement in order to test the mechanical properties of HVFA concrete mixtures utilizing powder activators and compare them to baseline mixtures containing no fly ash. The effect of fly ash and activators on required admixture dosages to attain a given slump and air content was noted, as well as the effect of fly ash and activators on the time of set. Water content was tracked using an AASHTO standard for determining microwave water content of fresh concrete. Hardened properties of the concrete fell into two areas: durability, and mechanical/strength properties. Durability properties of the hardened concrete measured included freeze-thaw resistance, scaling resistance, abrasion resistance, and rapid chloride permeability. Mechanical properties measured included compressive strength, flexural strength, splitting tensile strength, modulus of elasticity, and linear shrinkage of concrete.

5.2. CONCLUSIONS

From this study, it is clear that HVFA concrete mixtures, when tempered with the addition of powdered activators to ensure sulfate balance and restore setting characteristics, provide tangible benefits for both fresh and hardened concrete systems. The innate variability of fly ash sources, despite inclusion of ASTM classifications, however, means that cement and fly ash blends must be examined before use to ensure that they provide a viable mixture for fly ash substitution.

5.2.1. Fresh Concrete Properties. A notable benefit of using HVFA concrete mixtures is the increased workability imparted to the concrete mix by the fly ash particle size and rounded shape. Greater volumes of fly ash used in concrete mixtures means that lower water to cementitious ratios can be achieved for stronger, more durable concrete, with less addition required of expensive high range water reducers. However, the results of combination 1-3 warn that in some cases, the opposite effect may occur, with greater volumes of fly ash resulting in a stiffer mix. This should be examined before proceeding with any high volume concrete mix.

A negative effect of HVFA concrete is the greatly extended set times when high volumes of fly ash are incorporated. The incorporation of rapid set cement as an activator generally appeared to mitigate this effect more than calcium hydroxide, although the only concrete mix setting faster than the baseline mix was from combination 4-1, the 70% fly ash replacement mix using rapid set cement as an activator. This is likely due to the fact that rapid set addition was as a percentage of fly ash, and therefore a greater proportion of rapid set cement was present in this mix than was present than in the 50% fly ash mix.

5.2.2. Hardened Concrete Properties. A common and valid concern when using high volumes of fly ash in concrete is that of reaching specified compressive strength, as the fly ash is both slower to react, and depending upon the selected w/cm, possibly unlikely to reach full hydration. While even the use of powder activators still resulted in lowered 1-day strengths (on the order of 20 to 40 percent of baseline mix strength for 50% fly ash replacement, and 6 to 20 percent of baseline mix strength for 70% fly ash replacement), by 28 days of age all 50% fly ash replacement mixtures had exceeded 3000 psi, the MoDOT specification for class B concrete, and even grown stronger than 4000 psi, MoDOT's specified compressive strength for pavement concrete. Seventy percent fly ash replacement suffered in this area, typically reaching 3000 psi after 56 days of age. If a lower compressive strength is allowed or 56 day compressive strength is specified in place of 28 day compressive strength, however, 70% replacement may still remain viable.

Flexural and splitting tensile strength, while not typically specified, were affected in much the same way as compressive strength for HVFA concrete mixtures. At 50% replacement, relatively little change in flexural and splitting tensile strength was noticed, and at 70% replacement, the mixtures exhibited lowered flexural and splitting tensile strength. Again, if lowered strengths are allowed, it may be viable to use a 70% replacement fly ash concrete mix.

Modulus of elasticity saw the biggest benefit of fly ash replacement in terms of mechanical properties, with 50% fly ash resulting in a similar or noticeably stiffer end product. 70% replacement of cement with fly ash resulted in slightly lowered moduli of elasticity, though still in a reasonable range.

All HVFA concrete mixtures experienced improved durability in the areas of freeze-thaw resistance, exhibiting durability factors of 90 to 96% after 300 cycles of freezing and thawing. Despite this increased resistance to freezing and thawing, all fly ash mixtures exhibited markedly more scaling than their baseline counterparts. Rapid chloride permeability generally decreased from baseline to 50% fly ash mixtures, due to a more impermeable microstructure present in the paste. At 70% fly ash, these values increased dramatically, likely due to unhydrated fly ash present in the paste structure, leading to an increased permeability. Finally, abrasion resistance suffered in fly ash concretes, although 50% fly ash mixtures exhibited abrasion resistance closer to baseline mixtures than did 70% fly ash mixtures. Correlations indicate that this may be simply due to compressive strength rather than due to fly ash content.

Both calcium hydroxide and rapid set cement served well in creating a strong, durable mix at 28 days for 50% fly ash mixtures. Rapid set cement improved short term strengths more than did the addition of calcium hydroxide, although in most every other area, the two appeared to be almost interchangeable.

5.3. RECOMMENDATIONS

The use of powdered activators in combination with HVFA in concrete makes a good case for raising fly ash substitution limits in some cases. At 50% fly ash substitution, concrete mixtures gained adequate strength, exhibited stiffer moduli, experienced less drying shrinkage, and showed improved resistance to freezing and thawing. The areas in which HVFA concrete suffered were in abrasion resistance and scaling resistance—the latter of which may not be problematic, based upon research showing that field and laboratory scaling performance do not always correlate. The increased benefits of 50% fly ash concrete would serve well in a structural application, where wearing of the surface and ponding of chloride solution during winter deicing may not occur. It is even possible that this may be suitable for use in a pavement, if two-lift pavement construction is employed, or the HVFA concrete slab is treated with an overlay which would be subject to the wearing of traffic and scaling of deicer salts.

It is clear that even with the presence of activators, 70% fly ash concrete mixtures still perform poorly compared to their baseline counterparts, even with the addition of rapid set cement to the mixtures. While it is possible that longer term curing would impart improved properties to these mixtures, after 56 days of curing these concrete mixtures did not show great improvement over their 28 day compressive strengths.

The choice of which activator should be used appears to be based on the importance of greater early age strength imparted from rapid set cement mixtures, and the lowered setting time generally present in rapid set cement mixtures. In applications where early strength gain is not as important, it may be more suitable to select the relatively inexpensive calcium hydroxide as an activator rather than the possibly costly rapid set cement. In any application, however, the interaction of portland cement and fly ash should be tested for possible incompatibilities.

5.4. FUTURE RESEARCH

Future research recommended would include testing HVFA concrete mixtures for sulfate attack, given the large amounts of gypsum added to the mixtures in order to insure a compatible sulfate balance. This additional gypsum, if stabilized in the form of monosulfoaluminate, could react with sulfate in the soil to form ettringite in an expansive reaction, resulting in damage to the concrete.

APPENDIX

Water Content of Freshly Mixed Concrete

Using Microwave Oven Drying

AASHTO T 381-02

1-17-12

Equipment

Equipment includes a microwave oven, a turntable, and enough capacity to hold the tray and test specimen; a heat-resistant glass tray approximately 9”x9”x2”; an electronic balance with Styrofoam block to insulate it from heat, a metal scraper approximately 1” wide, a pestle with an approximately 2” porcelain grinding head; heat resistant gloves, and 14 mil fiberglass cloth with a mass of 10 oz/yd^2, cut to wrap the concrete.

Procedure

1. Obtain a 1500±100 gram test specimen from freshly mixed concrete approximately halfway through discharge of the drum. Do not let the concrete stand in order to avoid segregation.
2. Weigh the mass of the tray and cloth to the nearest 0.1 g. **(WS)**
3. Wrap the test specimen completely with the cloth.
4. Take the mass of the tray, cloth, and concrete specimen together. **(WF)**
5. Place the tray in the oven. Dry for 5±0.5 minutes at 70% power (875 W).
6. After drying, remove the assembly and quickly unwrap the test specimen. Break the coarse aggregate from the mortar with the edge of the scraper, and grind the mortar for no more than 60 seconds. Do not lose material.
7. Rewrap the test specimen, place the tray back in the oven, and dry for a further 5±0.5 minutes at 70% power (875 W).
8. Once more, remove the tray and test specimen. Unwrap the specimen. Stir the specimen with the scraper, and take the combined mass of the tray, cloth, and sample.
9. Rewrap the sample, place back in the oven, and dry for 2±0.5 at 70% power (875 W).
10. Remove the tray and determine the mass again.

   a. If the change in mass is 1 g or more, repeat the 2 minute drying period until the change in mass is less than 1 g.

11. Record the final mass of tray, cloth, and dry specimen. **(WD)**

Calculation

The water content percentage is calculated as follows:

$$WC = 100(WF - WD)/(WF - WS)$$

Total water content in lb/yd^3 can be calculated as follows:

$$WT = \frac{27(WC)(UW)}{100}$$

Where UW is the unit weight of the concrete in lb/ft^3, and WT is the total water content in lb/yd^3.

Precision

Single Operator 1s = 2.7 lb/yd^3

Single Operator d2s = 7.6 lb/yd^3

Breaking 4”x8” Cylinders

ASTM C 39, ASTM C 617

5/25/12

Equipment

Equipment includes a sulfur melting pot, a capping plate with alignment device on it, a canvas ‘jacket’, calipers, and the Forney testing machine.

Procedure (Capping)

12. Turn on the sulfur melting pot to heat the sulfur up to capping temperature 3-4 hours before capping will occur. Stir the sulfur as necessary.
13. Remove the specimens from the moist room.
14. If necessary, grind down the ends of the specimen to be perpendicular within 1/8”.
15. Dry the end of the specimen using compressed air to ensure formation of steam pockets does not occur.
16. Lightly oil the capping plate, and stir the sulfur prior to capping.
17. Pour approximately half a ladle of sulfur onto the capping plate.
18. Bring the cylinder back against the guides, and lower carefully into the sulfur.
19. Twist the cylinder to remove from the capping plate.
20. Repeat this process for the opposite end of the cylinder.
21. Return the cylinder to the moist room until the time of testing.

Procedure (Testing)

1. Remove the specimen from the moist room. Use a spray bottle to keep the outside of the specimen damp while transporting and waiting to test.
2. Take two diameter measurements at mid-height of the specimen, at 90 degrees from one another.
3. Average these readings to the nearest 0.01”.

4. Specimens shall be tested within the following tolerances:

Test Age	Tolerance
24 h	± 0.5 h
3 days	± 2 h
7 days	± 6 h
28 days	± 20 h
90 days	± 2 days

5. Place the specimen on the lower block of the Forney.
6. Center the specimen on both the lower block, and below the loading platen.
7. Zero the machine.
8. Manually advance the machine to apply a small seating load to ensure contact.
9. Once the specimen is seated, apply load at a rate of 251 pounds/sec to 628 pounds/sec until failure. The optimal loading rate is 565 pounds/sec
10. As the ultimate load is being reached, and the specimen begins to fail, make no adjustment to loading rate.
11. Record the ultimate load upon failure, and note the fracture pattern.
12. Calculate the compressive strength as load divided by area, where the area was determined in step 3.
13. Record compressive strength to the nearest 10 psi.

Calculation

$$f'c = P/A$$

Precision

Within-test precision for 4x8 cylinders has a 1s of 9.0% for two cylinders, or 10.6% for three.

Flexural Strength of Concrete

ASTM C 78

5/25/12

Equipment

Equipment includes the Test Mark beam loading apparatus, the Tinius Olsen load frame, a steel straight edge, the beam alignment jig, leather shims, a grease pencil, a grinding stone, a steel ruler, digital calipers.

Procedure (Curing)

1. Test specimens should be placed in a saturated lime-water curing tank 24 hours before flexural strength testing is to begin.

Procedure (Setup)

1. Place the steel guide on the Tinius Olsen table, securing it in place by the bolt on the back.
2. Slide the lower portion of the beam testing apparatus into place, flush against the steel guide.
3. Attach the upper portion of the beam testing apparatus to the crosshead of the Tinius Olsen.
4. Place a steel straight edge against the lower rollers.
5. Bring the crosshead down to check that the rollers are in line.
    a. If the rollers are not in line, gently tap the upper portion of the beam testing apparatus into alignment with a hammer.
6. Using the beam alignment jig, check that the spacing of the rollers is correct.
    a. If the rollers are not spaced correctly, gently tap the upper portion of the beam testing apparatus into alignment with a hammer.
7. Finally, check alignment with the steel straight edge once more to ensure it has remained in alignment.

Procedure (Testing)

1. Using a grinding stone, remove any fins on the test specimen.

2. Using a steel ruler, measure and mark the test specimens at 3”, 9”, 15”, and 21” from one end. Extend markings around the beam.
3. Place leather shims on the bottom rollers, and carefully place the beam onto the bottom rollers. The beam should be oriented so that the top as-cast will not be loaded.
4. Align the beam so that the 3” and 21” markings are centered over the bottom rollers.
5. Center the beam left to right in the machine so that it is centered over the rollers.
6. Place leather shims on top of the beam for the crosshead to bear on.
7. Begin the test in M-Test, zeroing out the load.
8. Bring the crosshead down into contact with the leather shim, applying a small seating load.
9. Press the pre-load button in M-Test, insuring that the beam is taking load.
10. Press the load button in M-Test, loading the beam at a rate of 30 lb/sec.
11. Upon failure of the test specimen, remove from the test apparatus, checking that failure has occurred in the middle third of the beam as marked.
12. Take three measurements of each face with digital calipers.
    a. The ‘b’ face is the width as loaded, and will always include the as-cast top.
    b. The ‘d’ face is the depth as loaded, and will never include the as-cast top.
13. Average the measurements of each face.
14. Calculate flexural strength.

Calculation

Modulus of Rupture is calculated by $R = \frac{PL}{bd^2}$ if the failure is in the middle third of the beam. If failure occurs outside of the middle third, but not by more than 5% of the span length, the Modulus of Rupture is calculated by $R = \frac{3Pa}{bd^2}$. Failure outside of the middle third by more than 5% indicates an invalid test.

Precision

The single operator %1s is 5.7%.

Unit Weight of Concrete

ASTM C 138

5/25/12

Equipment

Equipment includes a balance accurate to 0.1 lbs, a $^5/_8$" tamping rod, a bowl from an air meter, a strike off plate, a concrete scoop, and a rubber mallet.

Procedure

1. Obtain the weight of the measure. (**M_m**)
2. Place the concrete in the measure in three even lifts, rodding 25 times after each layer.
3. Penetrate the lower layers by 1" when rodding the second and third layers.
4. After each layer is rodded, tap the measure 10 to 15 times with the rubber mallet to close any holes.
5. Strike off the top surface and finish smoothly using the strike off plate.
    a. This is done by placing the plate over $^2/_3$ of the surface area, and withdrawing in a sawing motion to finish that $^2/_3$.
    b. Place the plate back over the finished area, this time advancing with a sawing motion to finish the remaining $^1/_3$.
    c. Incline the plate and perform final strokes with the plate to leave a smooth surface.
6. After strike off, clean the rim of the measure off with a damp sponge.
7. Obtain the weight of the combined measure and concrete. (**M_c**)
8. Calculate Unit Weight, and report to nearest 0.1 lb/ft^3.

Calculation

$$Unit\ Weight = (M_c - M_m)/V_m$$

Precision

Single Operator 1s = 0.65 lb/ft^3

Slump of Hydraulic Cement Concrete

ASTM C 143

5/25/12

Equipment

Equipment includes a slump cone, a $^{5}/_{8}$" tamping rod, a ruler, and a concrete scoop.

Procedure

1. Dampen the inside of the slump cone, and place it on a sheet of plastic on a level surface.
2. Stand on the two foot pieces.
3. Fill the mold in three lifts, each filling $^{1}/_{3}$ the volume of the cone.
    a. These lifts fill the cone to 2 $^{5}/_{8}$", 6 $^{1}/_{8}$", and 12" respectively.
4. Rod each layer 25 times, spiraling around from the outside in. For layers two and three, be sure to penetrate 1" into the previous layer.
5. For the third layer, be sure to keep excess concrete above the mold at all times.
6. After completion of rodding, strike off the concrete surface with the tamping rod, using a rolling and screeding motion.
7. Remove excess concrete from the base of the cone.
8. Carefully lift the slump cone vertically in a time of 5 ± 2 seconds.
9. Slump is measured as the distance between the top of the mold, and the original displaced center.
10. Report slump to nearest ¼".

Casting 4" x 8" Cylinders

ASTM C 192

5/25/12

Equipment

Equipment includes 4" x 8" plastic cylinder molds, a $^{3}/_{8}$" tamping rod, a rubber mallet, and a concrete scoop.

Procedure

1. Lightly oil the cylinder molds prior to casting.
2. Place the concrete in the mold using the concrete scoop, ensuring each scoop is representative of the batch. Remix the concrete in the pan if necessary.
3. The concrete should be placed in two lifts.
4. Rod each lift 25 times, uniformly distributing the strokes.
5. For the upper layer, be sure to penetrate approximately 1" into the lower layer.
6. After each layer is rodded, tap the mold 10 to 15 times lightly with a rubber mallet.
7. After the final layer, strike off the concrete and trowel finish the cylinder.
8. Cover immediately after casting with plastic sheeting.
9. Remove the specimens from the molds within 24±8 hours.
10. For concrete with prolonged setting time, remove 20±4 hours after final set.
    a. Determine final set in accordance with ASTM C 403 if necessary.
11. Mark the cylinders with a grease pencil.
12. Move cylinders to the moist cure room for the desired amount of curing time.

Casting 6" x 12" Cylinders

For Splitting Tensile and Modulus of Elasticity

ASTM C 192

5/25/12

Equipment

Equipment includes 6" x 12" plastic cylinder molds, a $^{5}/_{8}$" tamping rod, a rubber mallet, and a concrete scoop.

Procedure

1. Lightly oil the cylinder molds prior to casting.
2. Place the concrete in the mold using the concrete scoop, ensuring each scoop is representative of the batch. Remix the concrete in the pan if necessary.
3. The concrete should be placed in three lifts.
4. Rod each lift 25 times, uniformly distributing the strokes.
5. For the upper layers, be sure to penetrate approximately 1" into the lower layers.
6. After each layer is rodded, tap the mold 10 to 15 times lightly with a rubber mallet.
7. After the final layer, strike off the concrete and trowel finish the cylinder.
8. Cover immediately after casting with plastic sheeting.
9. Remove the specimens from the molds within 24±8 hours.
10. For concrete with prolonged setting time, remove 20±4 hours after final set.
    a. Determine final set in accordance with ASTM C 403 if necessary.
11. Mark the cylinders with a grease pencil.
12. Move cylinders to the moist cure room for the desired amount of curing time. This is 28 days for both Modulus of Elasticity cylinders and Splitting Tensile cylinders.

Casting Beams

ASTM C 192

5/25/12

Equipment

Equipment includes 6” x 6” x 24” beam molds, a $^{5}/_{8}$” tamping rod, a rubber mallet, a 1” wide metal scraper and a concrete scoop.

Procedure

1. Lightly oil the beam mold prior to casting.
2. Place the concrete in the mold using the concrete scoop, ensuring each scoop is representative of the batch. Remix the concrete in the pan if necessary.
3. The concrete should be placed in two lifts.
4. Rod each lift 72 times, uniformly distributing the strokes.
5. For the upper layer, be sure to penetrate approximately 1” into the lower layer.
6. After each layer is rodded, tap the mold 10 to 15 times smartly with a rubber mallet.
7. Spade around the perimeter of the beam with a 1” wide metal scraper.
8. After the final layer, strike off the concrete and trowel finish the beam.
9. Cover immediately after casting with plastic sheeting.
10. Remove the specimens from the molds within 24±8 hours.
11. For concrete with prolonged setting time, remove 20±4 hours after final set.
    a. Determine final set in accordance with ASTM C 403 if necessary.
12. Mark the beam with grease pencil.
13. Move beams to the moist cure room for the desired amount of curing time. Curing time is 28 days moist cured, with the final 24 hours before testing in a limewater tank.

Air Content by Pressure Method

ASTM C 231

5/25/12

Equipment

Equipment includes a $^{5}/_{8}$" tamping rod, a type B air meter, a strike off plate, a concrete scoop, and a rubber mallet.

Procedure

1. Place the concrete in the measure in three even lifts, rodding 25 times after each layer.
2. Penetrate the lower layers by 1" when rodding the second and third layers.
3. After each layer is rodded, tap the measure 10 to 15 times with the rubber mallet to close any holes.
4. Strike off the top surface and finish smoothly using the strike off plate.
    a. This is done by placing the plate over $^{2}/_{3}$ of the surface area, and withdrawing in a sawing motion to finish that $^{2}/_{3}$.
    b. Place the plate back over the finished area, this time advancing with a sawing motion to finish the remaining $^{1}/_{3}$.
    c. Incline the plate and perform final strokes with the plate to leave a smooth surface.
5. After strike off, clean the rim of the measure off with a damp sponge.
6. Wet the cover, including rubber rings to ensure a watertight seal.
7. Assemble the air meter.
8. Close the main air valve and open the petcocks.
9. Using a rubber syringe, inject water through one petcock until a steady stream emerges from the opposite petcock.
10. Jar the meter gently to expel air.
11. Close the air bleeder valve, and pump air into the presser chamber until the gauge hand is on the initial pressure line.
12. Allow a few seconds for the air temperature to stabilize.

13. Pump and bleed air as necessary, tapping the gauge until the gauge hand has stabilized.
14. Close both petcocks.
15. Open the main air valve.
16. Tap the sides of the bowl with the mallet. Lightly tap the pressure gauge to stabilize it.
17. Read the percentage of air on the dial gauge. (Apparent Air Content)
18. Release the main air valve.
19. Release the pressure by opening both petcocks before removing the cover.
20. Discard the sample.
21. Calculate air content, record to nearest 0.1%.

Calculation

$$Air\ Content = Apparent\ Air\ Content - Aggregate\ Correction\ Factor$$

Time of Setting of Concrete Mixtures

By Penetration Resistance

ASTM C 403-08

5/25/12

Equipment

Equipment includes a container for mortar specimens, at least 6" in least dimension, and at least 6" deep; penetration needles 1", ½", ¼", $^{1}/_{10}$", $^{1}/_{20}$", and $^{1}/_{40}$"; a loading apparatus capable of measuring penetration force with an accuracy of ±2 lbf; a tamping rod; a pipet for drawing off bleed water; a thermometer, and a No. 4 sieve.

Procedure

1. From concrete not used in slump and air content, select a portion large enough to fill the test container to a depth of 5 ½".
2. Pass the concrete over a No. 4 sieve, shaking the sieve by hand over a batch pan until no undersize materials remain on the sieve.
3. Aggregate retained on the sieve is discarded. Mortar on this aggregate should not be wiped from it before discarding.
4. Remix the mortar in the batch pan by hand methods.
5. Take the temperature of the mortar, recording it.
6. Place the mortar into the container in one lift.
7. Consolidate bytapping the sides with a tamping rod.
8. The initial test should be performed between 3 and 4 hours after contact of cement and water.
9. Penetration tests should be made at a distance from between 1" and 2" of the edge of the specimen.
10. Prior to making a penetration test, remove bleed water from the specimen with a pipet.
11. The specimen should be tilted at an angle of 10° about 2 minutes prior to help with removal of bleed water.

12. Place a needle of size depending upon the degree of setting of the mortal into the penetration resistance apparatus, and bring the tip down to meet the mortar surface.
13. Gradually and uniformly apply a downward force until the needle penetrates the mortar to a depth of $1\pm{}^{1}/_{16}$". This should take 10±2 seconds.
14. Record the force required, and the elapsed time since initial contact of cement and water.
15. Calculate penetration resistance as force divided by the bearing area of the needle.
16. Subsequent tests should be made at ½ to 1 hour intervals, and must be at least 2 needle diameters, or ½" away, whichever is more.
    a. For mixtures with accelerators, the initial test should be taken at 1 to 2 hours, and subsequent tests at ½ hour intervals.
17. At least six penetrations should be made for each test.
18. Continue to test until at least one penetration resistance reading exceeds 4000 psi.
19. Plot penetration resistance versus elapsed time.
20. Fit a power function to the plot, of the form $PR = ct^{d}$, where c and d are regression constants, PR is penetration resistance, and T is elapsed time.
21. If the correlation coefficient is less than 0.98 after removal of outliers, the following alternate must be used.
    a. Plot penetration resistance vs. elapsed time by hand on graph paper, using a scale so that 500 psi and 1 hour are each represented by a distance of ½".
    b. Hand fit a smooth curve to the data.
22. Determine initial set as the time at which penetration resistance equals 500 psi.
23. Determine final set as the time at which penetration resistance equals 4000 psi.
24. Record times to the nearest 5 minutes.

Calculation

Initial set = time at which penetration resistance equals 500 psi.

Final set = time at which penetration resistance equals 4000 psi.

Precision

Single Operator 1s for Initial set = 3.5 minutes

Single Operator 1s for Final set = 4.4 minutes

Modulus of Elasticity of Hardened Concrete

ASTM C 469

5/25/12

Equipment

Equipment includes a compressometer, the Tinius-Olsen testing machine, height blocks and metal templates for centering the specimen in the compressometer, and an LVDT.

Procedure

1. Determine ultimate compressive strength of the concrete by use of companion specimens prior to conducting the test.
2. Place the cylinder on a flat surface.
3. Place the height blocks around the cylinder at third points, and lower the compressometer onto them.
4. Using the metal templates, center the compressometer around the cylinder. Begin by centering the lower ring, then the upper ring.
5. After the cylinder is centered, tighten the screws up to ensure the compressometer is bonded well with the cylinder.
6. Place the LVDT in to measure the axial strain, making sure that it has enough stroke length to measure the deformation.
7. Place the specimen with compressometer attached in the testing machine.
8. Center the specimen.
9. Remove the metal bands connecting the top and bottom rings.
10. Bring the upper platen into contact with the test specimen, applying a small contact load.
11. Load the specimen at a rate of 35±7 psi/sec to 60% of the ultimate strength.
12. Upon reaching 60% of the ultimate strength, unload the specimen at the same rate. This is the conditioning cycle.
13. Repeat this procedure.
14. On the final loading, record load and strain when the strain is at 50 millionths, and when the load is at 40% of the ultimate strength.

15. Calculate the modulus of elasticity to the nearest 50,000 psi.

Calculation

$$E = (S_2 - S_1)/(\varepsilon_2 - 0.000050)$$

Where S_2 is the stress at 40% of ultimate load, S_1 is the stress at 50 millionths strain, and ε_2 is the strain at 40% of ultimate load.

Splitting Tensile Strength of

Cylindrical Concrete Specimens

ASTM C 496-04

5/25/12

Equipment

Equipment includes calipers, a ruler, a testing machine with large enough bearing surface to hold the specimen, and two bearing strips to be placed on the specimen.

Procedure

1. To begin, either mark diametral lines on each end of the cylinder to be tested, using a device to ensure that they are in the same axial plane, or use an aligning jig to align the concrete cylinder and bearing strips.

2. Take three diameter measurements—one near the middle, and one at each end, to the nearest 0.01 in.
3. Average these measurements to determine the diameter of the cylinder.
4. Take at least two length measurements along the marked lines to the nearest 0.1 in.
5. Average these measurements to determine the length of the cylinder.
6. To position the cylinder by diametral lines:
    a. Center one plywood bearing strip along the lower bearing block.

b. Place the specimen on the plywood bearing strip, aligning the diametral line centered along the plywood strip.

c. Place a second plywood bearing strip lengthwise on the cylinder, centered on the line.

d. Ensure that the cylinder is centered beneath the upper bearing plate.

7. To position the cylinder by aligning jig:

    a. Position the bearing strips, cylinder, and supplementary bearing bar centered beneath the center of thrust of the bearing block.

8. Load continuously in the range of 100 to 200 psi/min until failure of the specimen. For a 6" cylinder, this is 11,300 lb to 22,600 lb per minute, or 188 to 376 pounds per second.
9. Record the maximum load indicated by testing machine at failure.
10. Calculate the splitting tensile strength of the specimen.

Calculation

Splitting Tensile Strength of the specimen is calculated as:

$$T = 2P/\pi ld$$

Where P is the maximum load, l is the length of the specimen, and d is the diameter of the specimen.

Precision

Within batch %1s = 5%

Casting Specimens

for

ASTM C 666 (Freeze-thaw Resistance)

1-17-12

Equipment

Equipment includes a mold 4.5” deep, 3.5” wide by 16” long, 3/8” tamping rod, a rubber mallet, a trowel, and a concrete scoop.

Procedure

1. Coat the mold with a light coat of oil before just before casting the specimen.
2. Fill the mold in two layers, rodding 28 times each layer.
3. Tap the mold 10-15 times with a rubber mallet to close any voids after each layer.
4. Spade around the edges of the mold after tapping each layer.
5. Strike off the concrete upon completion of the consolidation, and trowel finish the specimen.
6. Cover the specimen with plastic sheeting upon finishing the surface.
7. Remove specimens from molds 24±8 hours after casting.
    a. If concrete has a prolonged setting time, remove molds 20±4 hours after final set, as determined by C 403.
8. Specimens should be stored in saturated lime water from the time of removal from molds to the time of testing.
9. Cure the specimens for 14-21 days before moving to MoDOT for testing. Total curing time is 35 days.

Casting Specimens

for

ASTM C 672 (Scaling Resistance)

5/22/12

Equipment

Equipment includes a mold at least 3” deep, 12” by 12”, 5/8” tamping rod, a rubber mallet, a trowel, a wooden strike off board, and a concrete scoop.

Procedure

1. Coat the mold with a light coat of oil before just before casting the specimen.

2. Fill the mold in one layer, rodding once for each 2 in^2 of surface area (72 roddings for 144 in^2). Add enough concrete so that after consolidation, the molds are filled approximately ½” below the lip of the mold.
3. Tap the mold 10-15 times with a rubber mallet to close any voids.
4. Spade around the edges with a flat trowel.
5. Screed off excess concrete with a sawing motion using a wooden strike-off board so that the final surface is approximately 1” below the lip of the mold.

6. Level the surface with a wooden float.
7. After a sufficient waiting period (interval between time water and cement come in contact and brushing), The waiting period will vary depending on the mixture. For concrete with ordinary portland cement, the waiting period has been approximately 3 hrs. Brush the surface with a light-to-medium bristle brush as the final finishing operation. The brush should be angled toward to direction of travel. Use one pass to create the finish.
8. Immediately after finishing, place a mortar dike 1” wide and ¾” high along the perimeter of the specimen
    a. .
    b. Use a screwdriver to make a small keyway, approximately ½” in from the edge of the specimen.

c. Mix masonry sand, cement, and water in a 3:2:1 ratio, adding water if necessary to achieve a dough-like consistency.
d. Form the mortar dike up against the scaling form. Work mortar into place with a spatula-trowel or putty knife, ensuring a good bond at the toe of the dike.

e. Upon completion of the dikes, cover the specimens with wet burlap.

9. Cover with plastic sheeting. Do not let the sheeting touch the concrete surface.
10. Remove from molds 20 to 24 h after mixing, and moist cure for 14 days.
11. Store in air for 14 days after moist cure is complete. Transport to MoDOT within 14-21 days after casting.

Casting Specimens

for

ASTM C 944 (Abrasion Resistance)

1-17-12 DR

Equipment

Equipment includes a mold 3.5” deep, 6” wide by 16” long, 5/8 ” tamping rod, a rubber mallet, an aluminum float, and a concrete scoop.

Procedure

1. Coat the mold with a light coat of oil before just before casting the specimen.
2. Fill the mold in one layer, rodding 96 times
3. Tap the mold 10-15 times with a rubber mallet to close any voids.
4. Spade around the edges of the mold.
5. Strike off the concrete upon completion of the consolidation, finish with an aluminum float (avoid using a steel trowel if simulating paving slabs). Return after bleedwater has evaporated to refinish with an aluminum float. The waiting period is typically 3 hrs after the water and cement have been in contact during mixing.
6. Cover the specimen with plastic sheeting upon finishing the surface.
7. Specimens should be removed 24±8 hours after casting.
    a. If concrete has a prolonged setting time, remove molds 20±4 hours after final set, as determined by C 403.
8. Specimens should be moved to the moist room, and cured to the appropriate age, typically 28 days for ordinary portland cement concrete and 56 days for mixes containing flyash. In comparison studies, 2 slabs are cast; one is cured 28 days while the second slab is cured 56 days.

Abrasion Resistance of Concrete

ASTM C 944

7/3/12

Equipment

Equipment includes a drill press, an abrasion head conforming to ASTM C 944, a weight applied to the drill press arm conforming to a 44 pound double load, the 32 kg Ohaus balance, digital calipers, and a stopwatch.

Procedure

1. Remove the abrasion resistance test specimen from the moist room 15 minutes before testing, drying the surface with a cloth to remove free water.
2. Secure the abrasion head into the drill press and tighten down.
3. Check that the drill press is set for 300 RPM.
4. Set the drill press table to an appropriate height so that when the abrasion head is flush with the concrete surface, the drill press arm is parallel to the ground.
5. Record the time.
6. Obtain and record the initial weight of the sample.
7. Position the test specimen in the clamp on the drill press table so that there is adequate space to conduct the test. (IE, the specimen should be placed so that the abrasion head is grinding against the concrete specimen at all times during the test.)
8. Bring the head down into contact with the specimen. Hang the weight corresponding to a 44 pound double load from the arm of the drill press.

9. Turn the drill press on, and begin timing with the stop watch.
10. Turn the drill press off after two minutes of abrasion.
11. Carefully remove the test specimen from the clamp, taking care not to damage it. Remove dust from the surface with clean air.
12. Weigh the test specimen and record.
13. Replace the test specimen in the clamp, taking care to reposition it exactly beneath the abrasion head.
14. Bring the abrasion head down manually to check position. Do this at at least two degrees of rotation to ensure positioning.
15. Repeat steps 8 through 14 twice more, so that the test specimen has been abraded in the same location three times.
16. Using the digital calipers, check the depth of wear.

   a. An average depth of wear is calculated by checking the depth of wear at eight points.
   b. The eight points correspond to the 12 o'clock, 3 o'clock, 6 o'clock, and 9 o'clock positions on the test specimen at both the innermost and outermost abraded rings on the specimen.
17. Calculate mass loss for each of the abrasion periods.
18. Sum each mass loss and record a total mass loss for that replicate.
19. This abrasion procedure is conducted three times on the specimen, for a total of three replicate tests.

		28 Day	56 Day
Replicate 1	Start Time	3:30	2:57
	Initial Weight	13192.4	13456.4
	Weight 1	13169	13431.3
	Mass Loss 1	23.4	25.1
	Weight 2	13159	13422.1
	Mass Loss 2	10	9.2
	Weight 3	13150.5	13414.8
	Mass Loss 3	8.5	7.3
	Total Mass Loss	41.9	41.6
	Depth of wear	1.91	2.49
Replicate 2	Start Time	3:39	3:08
	Initial Weight	13150.5	13414.8
	Weight 1	13122.9	13392.4
	Mass Loss 1	27.6	22.4
	Weight 2	13112.6	13382.4
	Mass Loss 2	10.3	10
	Weight 3	13104.9	13375.5
	Mass Loss 3	7.7	6.9
	Total Mass Loss	45.6	39.3
	Depth of wear	2.29	2.31
Replicate 3	Start Time	3:48	3:20
	Initial Weight	13104.9	13374.1
	Weight 1	13077.1	13349.9
	Mass Loss 1	27.8	24.2
	Weight 2	13067.1	13342.6
	Mass Loss 2	10	7.3
	Weight 3	13060.1	13335.4
	Mass Loss 3	7	7.2
	Total Mass Loss	44.8	38.7
	Depth of wear	2.35	2.0425
Average Mass Loss		44.10	39.87
Average Depth of Wear		2.18	2.28

Temperature of Fresh Concrete

ASTM C 1064

Equipment

Equipment includes a thermometer and a container with at least 3” of concrete cover in all directions around where the temperature will be taken.

Procedure

1. Submerge the thermometer at least 3” into the freshly mixed concrete.
2. Close the void by pressing the concrete around the thermometer at the surface of the concrete.
3. Leave the thermometer in for between two and five minutes.
4. Read and record the temperature to the nearest degree F.

Precision

Single operator 1s = 0.5° F

Casting Specimens

for

ASTM C1202 (Chloride Ion Penetration)

1-17-12

Equipment

Equipment includes a 4” cylinder mold, a 3/8” tamping rod, a rubber mallet, and a concrete scoop.

Procedure

1. Place fresh concrete in the cylinder molds using a concrete scoop. Remix concrete in the pan with a trowel if it is necessary to prevent segregation. The cylinder should be filled in two lifts.
2. Upon completing a layer, rod it 25 times with the 3/8” tamping rod.
3. After completing rodding, tap the cylinder 10 to 15 times with the rubber mallet to close holes left by rodding and release air bubbles.
4. After consolidation, finish the top surface by striking off with a tamping rod.
5. Cover the specimens with plastic sheeting immediately after finishing.
6. Specimens should be removed 24±8 hours after casting.
    a. If concrete has a prolonged setting time, remove molds 20±4 hours after final set, as determined by C 403.
7. Move specimens to the moist cure room. Moist cure for 14-21 days, then transport to MoDOT for testing.

Casting Shrinkage Specimens

6/14/12

Equipment

Equipment includes 4” inner diameter PVC cut to 24” lengths and scored at third points, plywood sheets, a concrete scoop, a vibrator, and an aluminum float.

Procedure

1. Attach the lengths of PVC to a level plywood base with silicone caulk at least 24 hours before casting.
2. Add concrete to the molds to fill each mold halfway.
3. Vibrate the concrete into place with one insertion of the vibrator, allowing the vibrator to penetrate the layer fully, taking care not to touch the sides of the mold. Do not allow the vibrator to touch the bottom of the mold.
4. Withdraw the vibrator slowly, taking care not to leave large air pockets behind.
5. Add concrete to the molds to slightly overfill the molds.
6. Vibrate the concrete into place with one insertion of the vibrator, allowing the vibrator to penetrate one inch into the layer below. Take care not to touch the sides of the mold.
7. Withdraw the vibrator slowly, taking care not to leave large air pockets behind.
8. Add additional concrete if necessary while removing the vibrator to maintain the final level of concrete.
9. Strike off and finish the shrinkage specimen with the aluminum float.

Testing Shrinkage Specimens

7/3/12

Equipment

Equipment includes DEMEC points, metal/concrete epoxy, and a DEMEC gauge with reference bar.

Procedure

1. 24 hours after casting, demold the specimens by use of a dremel tool with a cutting head.
2. Mark the shrinkage specimens with name and number with a black sharpie.
3. Using the DEMEC reference tool, mark the specimens with locations to place the DEMEC points, ensuring that they are placed in a vertical fashion. The first DEMEC point is placed 4 inches from the top of the specimen, and subsequent DEMEC points are placed the distance of the reference tool apart.
4. Apply a small amount of metal/concrete epoxy to the surface of the shrinkage specimen, where the DEMEC points are to be placed.
5. Press the DEMEC point into the epoxy.
6. Repeat steps 4 and 5 until all DEMEC points are applied to the specimen. For HVFA study, this is 10 DEMEC points, in lines of 5 at 180 degrees from each other.
7. Take initial readings as soon as possible after demolding and applying the DEMEC points.

Testing

1. Before taking readings, use the DEMEC gauge to take a length reading of the reference bar. Record this on the data sheet.
2. Record the temperature and relative humidity.
3. Record the time.
4. Fit the DEMEC gauge onto the points, rocking the gauge from side to side. The largest reading on the dial occurs when the gauge is perpendicular to the points, and this is the reading that should be recorded.

5. Readings should be taken on each specimen every day until 14 days of age, every 2 days until 28 days, every 4 days until 56 days, and every week thereafter.

Data

1. To obtain the shrinkage for each day, first subtract the reference bar reading from the day's length reading for each reading. These are the adjusted readings.
    a. *Example: Day 1 reading—1020. Day 2 reading—1018. Reference bar reads 800 for both days. Adjusted reading for Day 1 is 1020-800=220. Adjusted reading for Day 2 is 1018-800=218.*
2. The difference between two days (for instance, day 2 and day 1) provides the shrinkage for day 2 in dial reading increments.
    a. *Example: 220-218=2.*
3. Multiply the shrinkage in dial reading increments by the adjustment factor provided with the DEMEC gauge to convert to shrinkage in microstrain.
    a. *Example: 2*7.6 microstrain/dial reading = 15.2 microstrain.*
4. Average the microstrain for a given day.
    a. Each specimen will consist of 6 readings, averaged to determine an average strain.
5. Summing each day's strain, calculate the accumulative strain. Numbers will be negative due to calculation method.
6. Take the absolute value of these numbers to convert to a positive number, and plot accumulative strain versus age in days.

Cast Date													
3-26-12	Read Date:	3-27-12	3-28-12	3-29-12	3-30-12	3-31-12	4-01-12	4-02-12	4-03-12	4-04-12	4-05-12	4-06-12	4-07-12
	Time:	3:12	2:05	1:43	5:12	3:53	11:39	4:00	1:18	4:11	1:17	2:29	3:27
	Temp:	72	70	70	72	72	72	72	72	72	72	72	78
	Rel Humid:	55.00%	63.00%	61.00%	60.00%	60.00%	68.00%	60.00%	63.00%	70.00%	56.00%	36.00%	38.00%

Specimen	Reading	1	2	3	4	5	6	7	8	9	10	11	12
Refer Bar		806	806	807	807	807	807	806	807	807	806	807	808
Hbase 2	1--1	583	583	583	583	580	578	576	573	572	570	569	568
Hbase 2	1--2	976	975	973	970	968	965	961	958	955	954	953	948
Hbase 2	1--3	1070	1069	1065	1061	1058	1056	1052	1049	1048	1047	1042	1036
Hbase 2	2--1	470	466	463	457	456	454	451	449	448	447	444	443
Hbase 2	2--2	1268	1261	1258	1256	1251	1249	1246	1241	1238	1237	1236	1236
Hbase 2	2--3	706	697	689	682	677	675	674	671	668	668	669	663

Shrinkage Calcs:

Specimen	Reading												
Age		1	2	3	4	5	6	7	8	9	10	11	12
Hbase 2	1--1		0	-7.84	0	-23.52	-15.68	-7.84	-31.36	-7.84	-7.84	-15.68	-15.68
Hbase 2	1--2		-7.84	-23.52	-23.52	-15.68	-23.52	-23.52	-31.36	-23.52	0	-15.68	-47.04
Hbase 2	1--3		-7.84	-39.2	-31.36	-23.52	-15.68	-23.52	-31.36	-7.84	0	-47.04	-54.88
Hbase 2	2--1		-31.36	-31.36	-47.04	-7.84	-15.68	-15.68	-23.52	-7.84	0	-31.36	-15.68
Hbase 2	2--2		-54.88	-31.36	-15.68	-39.2	-15.68	-15.68	-47.04	-23.52	0	-15.68	-7.84
Hbase 2	2--3		-70.56	-70.56	-54.88	-39.2	-15.68	0	-31.36	-23.52	7.84	0	-54.88
		Average	-28.7467	-33.9733	-28.7467	-24.8267	-16.9867	-14.3733	-32.6667	-15.68	0	-20.9067	-32.6667
		Acc. Strain	-28.75	-62.72	-91.47	-116.29	-133.28	-147.65	-180.32	-196.00	-196.00	-216.91	-249.57
		Plot	28.74667	62.72	91.46667	116.2933	133.28	147.6533	180.32	196	196	216.9067	249.5733

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VITA

Drew Alexander Davis was born in North Kansas City, Missouri to Terry and Cynthia Davis. He has one brother, Evan Davis, and one sister, Chloe Davis. Drew was raised in Raytown, Missouri, and attended Raytown South High School, where he graduated in 2006. Drew attended the Missouri University of Science and Technology, graduating in 2010 with a Bachelors of Science in Civil Engineering. In December of 2012, he earned his Masters of Science degree in Civil Engineering from the Missouri University of Science and Technology.

While attending the Missouri University of Science and Technology, Drew was a member of Chi Epsilon, the national civil engineering honor society. He worked as a graduate teaching assistant for an introductory construction materials course for three semesters, as well as working as a research assistant during his graduate studies. He is currently residing in Kansas City, Missouri, as a structural engineer working in the power generation and transmission field.