DEVELOPMENT OF CONCRETE SHRINKAGE PERFORMANCE SPECIFICATIONS

by

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ABSTRACT

During its service life, concrete experiences volume changes. One of the types of deformation experienced by concrete is shrinkage. The four main types of shrinkage associated with concrete are plastic, autogeneous, carbonation and drying shrinkage. The volume changes in concrete due to shrinkage can lead to the cracking of the concrete. In the case of reinforced concrete, the cracking may produce a direct path for chloride ions to reach the reinforcing steel. Once chloride ions reach the steel surface, the steel will corrode, which itself can cause cracking, spalling, and delamination of the concrete.

The development of concrete shrinkage performance specifications that limit the amount of drying shrinkage for concrete mixtures typically used by the Virginia Department of Transportation (VDOT) were assessed. Five existing shrinkage prediction models were also assessed to determine the accuracy and precision of each model as it pertains to the VDOT mixtures used in this study. The five models assessed were the ACI 209 Code Model, Bazant B3 Model, CEB90 Code Model, Gardner/Lockman Model, and the Sakata Model.

The percentage length change limits for the portland cement concrete mixtures were 0.0300 at 28 days, and 0.0400 at 90 days. For the supplemental cementitious material mixtures, the percentage length change limits were 0.0400 at 28 days, and 0.0500 at 90 days. The CEB90 Code model performed best for the portland cement concrete mixtures, while the Gardner/Lockman Model performed best for the supplemental cementitious material mixtures

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CHAPTER 1. INTRODUCTION

One of the causes that result in the early deterioration of reinforced concrete involves volume changes in concrete due to autogenous shrinkage and moisture loss. As concrete cures and dries, tensile stresses are created due to hydration and loss of moisture. The tensile stresses cause the concrete to shrink. Drying shrinkage is defined as the decrease in concrete volume with time due to moisture loss, whereas, autogenous shrinkage is defined as the reduction in volume of the concrete due to hydration of the cement. Drying shrinkage cracking is related not only to the amount of shrinkage, but also the modulus of elasticity, creep, and tensile strength of the concrete (Mehta, 1993).

In the case of reinforced concrete, the cracking of the concrete due to the combination of drying and autogenous shrinkage may lead to corrosion of the reinforcing steel. Chloride ions, which are present in seawater and deicer salts, reach the concrete-steel surface either by diffusion through the concrete pore water or through cracks in the concrete. Once chloride ions reach the steel surface, the steel will corrode; the iron oxide produced can cause cracking, spalling, and delamination of the concrete. In the case of prestress concrete systems, drying shrinkage is an important factor. The strain produced in the concrete from drying shrinkage leads to a reduction of strain in the prestressed steel. This in turn contribute to prestress losses in the system.

Much of the current research stresses the development of a low permeable concrete to reduce the effects of corrosion and other deterioration mechanisms. However, little research has been directed towards the reduction of cracking in concrete. The development of a low permeable concrete with a reduced propensity for cracking will help to reduce the deterioration of reinforced concrete from the ingress of aggressive ions through cracks.

CHAPTER 2: BACKGROUND

2.1 Introduction

Concrete experiences volume changes throughout its service life. The total in-service volume change is the resultant of applied loads and shrinkage. When loaded, concrete experiences and instantaneous recoverable elastic deformation and a slow inelastic deformation called creep. Creep of concrete is composed of two components, basic creep or deformation under constant load without moisture loss or gain, and drying creep. Drying creep is the time-dependent deformation of a drying specimen under constant load minus the sum of the drying shrinkage and basic creep. Deformation of concrete in the absence of applied loads is often called shrinkage. There are four main types of shrinkage; plastic, drying, autogeneous, and carbonation shrinkage. The shrinkage mechanisms in concrete hall be addressed. This shall include a theoretical and empirical background, a theory on the moisture diffusion in concrete, as well as, the influence of concrete composition on shrinkage. The discussion shall also include prediction models used to predict the amount of shrinkage in concrete, as well as, different test methods used to measure shrinkage in concrete.

2.2 Shrinkage Mechanism

There are four main types of shrinkage in concrete; plastic, autogeneous, carbonation, and drying shrinkage. Plastic shrinkage is due to moisture loss from the concrete before the concrete sets. Autogeneous shrinkage is associated with the loss of water from the capillary pores due to the hydration of the cement (Holt, 1998). This type of shrinkage tends to increase at higher temperatures and at higher cement contents. In general, it is relatively small and is not distinguished from shrinkage caused by drying of concrete. Carbonation shrinkage is caused by the chemical reaction of various cement hydration products with carbon dioxide present in the air. This type of shrinkage is usually limited to the surface of the concrete (Dilger, 1997). Drying shrinkage can be defined as the volumetric change due to drying of the concrete.

2.2.1 Theoretical

Numerous papers have discussed the mechanisms that affect drying shrinkage in concrete. Capillary depression, variations in surface tension, and variations in surface tension are all associated with the movement and loss of water from concrete during drying (Hau, 1995, Hansen, 1987). The variation of capillary depression is deduced from the Laplace and Kelvin laws:

$$p_v - p_c = \frac{2\sigma}{r}\cos\theta \qquad \text{(Laplace)}$$

$$p_c - p_v = \frac{RT}{Mv}\ln(H) \qquad \text{(Kelvin)}$$

Where: σ = surface tension of water/water vapor interface

θ = moistening angle

p_c = pressure in water

p_v = pressure in water vapor

r = radius of pore where there is a meniscus

v = specific volume of water

M = molar mass of water

R = ideal gas constant

T = temperature

H = relative humidity

Hau et. al. (Hau, 1995) discussed that in a given unsaturated state, there exists an access radius, r. All capillaries with a radius less than the access radius are filled with water, and all capillaries with a radius greater than the access radius are empty. This introduces a corresponding tension in the liquid phase, thus, the solid skeleton undergoes compression.

The mechanism of surface tension deals with the attractive forces of atoms or molecules at the surface. This mechanism operates at relatively low humidities. Above a certain relative humidity, the entire surface is covered by adsorbed water molecules, thus, the variation in relative hunidity can no longer vary the surface tension.

The mechanism of disjoining pressure concerns the interaction between two solid surfaces. As the thickness of the adsorbed water molecule layer increases, it can no longer develop freely. As the relative humidity increases, the adsorption of water tends to separate the two solid surfaces. Thus, the two surfaces undergo a pressure called “disjoining pressure.” The maximum disjoining pressure occurs at the saturated state. When the system goes from a saturated to unsaturated state, shrinkage occurs because of decreased disjoining pressure.

2.2.2 Emperical

Neville discussed the loss of water in concrete associated with drying shrinkage. The change in volume of the concrete is not equal to the volume of the water lost. The loss of free water occurs first, this causes little to no shrinkage. As the drying of the concrete continues, the adsorbed water is removed. This adsorbed water is held by hydrostatic tension in small capillaries (< 50 nm). The loss of this water produces tensile stresses which cause the concrete to shrink. The shrinkage due to this water loss is significantly greater than that associated with the loss of free water (Neville, 1998).

DeLarrard et al (DeLarrard, 1994) discussed some of the factors that affect the magnitude of drying shrinkage in concrete. These factors include the aggregate used, the water/cement ratio (w/c), the relative humidity, and the member size (DeLarrard, 1994). The aggregate used in the concrete mixture acts to restrain the shrinkage of the cement paste. Concrete with a higher aggregate content has less shrinkage than those with a lower aggregate content. Aggregates with a higher modulus of elasticity or a rougher surface are more resistant to shrinkage. In general, a higher water-to-cement (w/c) ratio will produce greater drying shrinkage (Hansen, 1987). With a higher w/c ratio, the strength and stiffness of the paste is decreased, which can lead to increased shrinkage. As with creep, there is a lower shrinkage at higher relative humidities. Member size also plays a role in drying shrinkage, the greater the volume of the member, the less the drying shrinkage.

Reversible drying shrinkage is the part of the drying shrinkage of the concrete that is reproducible during wetting and drying cycles (Mehta, 1993). Irreversible drying shrinkage is the part of the total drying shrinkage during the first drying cycle that cannot be reproduced during subsequent wetting and drying cycles. Mehta states that the irreversible shrinkage is probably due to the development of chemicals within the calcium silicate hydrate structure as a consequence of drying of the concrete.

Drying shrinkage can cause cracking in concrete. The cracking is due to tensile stresses caused by the restraint conditions. Thus, drying shrinkage is related to not only the amount of shrinkage, but also the modulus of elasticity, creep, and tensile strength of the concrete (Suzuki, 1993). All of these properties vary with time, so it is difficult to determine the cracking tendency of the concrete based solely on shrinkage. Therefore, the modeling of creep and shrinkage of concrete has to take into account many different variables.

2.3 Moisture Diffusion in Concrete

Moisture diffusion and distribution in concrete are important factors that are needed to determine the drying shrinkage and creep. Two types of moisture diffusion were discussed, macrodiffusion and microdiffusion (Bazant, 1993). Macrodiffusion is characterized by the movement of water through the path of least resistance. This movement occurs in larger pores and has no measurable effect on the concrete deformation. Microdiffusion is the movement of water between capillary pores and gel pores. These are the smaller pores in the concrete and thus the movement of water in these pores has an effect on the concrete deformation. The movement of water in the gel pores, also known as micropores, allows for the breakage of bonds that are the source of creep. Therefore, the movement of water in the gel pores intensifies creep.

Three of the components of moisture mass transport in concrete are hardened cement paste pores, aggregate pores, and aggregate/cement paste interface pores (Chaube, 1993). The hardened cement paste pores consist of capillary and gel pores. The aggregate is dispersed in the cement paste matrix in a manner that does not provide for a continuos porous path for moisture to travel. The pores are arranged as a buffer zone, which can either store or release moisture to the surrounding cement paste matrix. At the aggregate/cement paste interface, channels may be present. These channels can be the result of insufficient compaction, bleeding, or aggregate to aggregate contact. This situation can lead to rapid bulk movement of moisture.

Many papers have been written on moisture diffusion as it relates to the drying of concrete. Bazant and Najjar discussed the drying of concrete as a nonlinear diffusion problem (Bazant, 1971). Ficks 2nd Law was used to express the loss of water from cement paste and concrete.

$$\frac{\partial w}{\partial t} = div(Cgradw) \qquad (1)$$

Where: w = specific water content

t = time

C = diffusion constant

The drying of concrete can also be described in terms of pore humidity.

$$\frac{\partial H}{\partial t} = kdiv(cgradH) \qquad (2)$$

Where: H = pore humidity

t = time

k = function of H = dH = kdw

c = diffusion coefficient = C/k

The diffusion coefficient, c, represents the permeability and is equal to the mass flux due to a unit gradient H. Thus, equation (2) simplifies to:

$$\frac{\partial H}{\partial t} = div(CgradH) \qquad (3)$$

These equations allow the determination of the diffusion coefficient as a function of pore humidity and water content.

2.4 Influence of Concrete Composition on Shrinkage

Factors which contribute to the dimensional changes in concrete may be categorized as mixture composition, curing conditions, ambient exposure conditions, and element geometry. In addition to the above factors, this section shall address shrinkage performance specifications for bridge decks and other Portland cement concrete structures. With respect to mixture composition, the influence of aggregate type, cement type and fineness, cement and water content, and mineral and chemical admixtures shall be addressed.

2.4.1 Effect of Aggregate

Smaller aggregates experience more uniform shrinkage. The type of aggregate, rather than the aggregate size, has an enhanced effect on the concrete shrinkage. Aggregate that shrinks considerably has a low rigidity compared to the compressive stresses developed by the shrinkage of the cement paste. These types of aggregate may also have a large water absorption value which will result in a concrete with higher shrinkage (Troxell, 1996).

Han and Walraven (Han, 1994) examined the effect of aggregate in high strength concrete on creep and shrinkage. The shrinkage testing was conducted on 100 x 100 x 400 mm specimens cured at 20 +/- 3 ^{o}C and 65 % relative humidity. The different concrete mixtures included three types of aggregate; crushed gravel, granite, and limestone. The high strength concrete with the limestone aggregate had less shrinkage than the mixtures containing crushed gravel or granite. The rate of shrinkage of the limestone mixture was less than that of the mixtures containing the other aggregate types. It was determined that the limestone mixture had the highest early elastic modulus which explains the reduced shrinkage behavior.

The influence of aggregate on the shrinkage of concrete has two primary effects. The water demand of the aggregate, and the stiffness of the aggregate relative to the cement paste. The cement paste is the primary source of shrinkage. Aggregate with lower water demands will therefore produce concretes with lower shrinkage characteristics. It has also been determined that higher elastic modulus concrete produces lower creep and shrinkage values. Thus, aggregate affects concrete deformation through water demand, aggregate stiffness and volumetric concentration, and paste/aggregate interaction.

Almudaiheem and Hansen (Almudaiheem, 1987) studied the effect of specimen size compared to drying shrinkage. Within their results they found that shrinkage decreases with increasing aggregate content (Almudaiheem, 1987). All of the mixtures had w/c ratios of 0.40. The maximum aggregate size was 9.5 mm and the specimens were cured in lime saturated water for 28 days. The mixtures consisted of either 50% or 60% aggregate content. The aggregate content had a more profound influence on shrinkage than did the specimen size.

Differences between expansive and ordinary cements and the role of aggregate with respect to shrinkage were examined by Saito (Saito, 1991). River expanded shale was used as the fine aggregate with crushed stone and expanded shale being used as the coarse aggregate. Aggregate used in the mixture were in the saturated surface dry state. All of the mixtures had a constant w/c ratio of 0.50. Shrinkage tests were conducted on 100 x 100 x 300 mm prism specimens. The specimens were placed in a controlled environment of 20 ^{o}C and 85 % relative humidity for 24 hours. The specimens were then cured in water at the same temperature as above for 13 days. The specimens were then exposed to 20 ^{o}C and 60 % relative humidity for 490 to 533 days. A strain gage was placed inside an aggregate particle to examine the stress exerted on the aggregate by the cement paste.

Shrinkage strains of river sand mortars and crushed stone concrete made with Portland cement and expansive cements are similar to shrinkage strains calculated from equations derived by Pickett. Light-weight aggregate mortars and concrete have less shrinkage than the Pickett calculations due to the large amount of water retained in the pores of the aggregate particles.

Shrinkage in expansive cement concretes is slightly less than those of general Portland cement concretes. The presence of coarse aggregate particles diminishes the effectiveness of the expansive cement for reducing shrinkage.

The elastic properties of the aggregate have a predominate effect on shrinkage. The lower the value of the Young's modulus of the aggregate, the lower the restraining effect of the aggregate on shrinkage. Light-weight aggregate in tests would be expected to show more shrinkage than a normal or heavy-weight aggregate. However, that was not the case, due to using the aggregate at a saturated surface dry condition, the water in the pores of the aggregate had an influence on the drying shrinkage data. The light-weight aggregate used in this experiment showed that the shrinkage of light-weight concrete is more sensitive to change in aggregate content than that of concrete made with normal weight aggregate.

Tazawa and Miyazawa (Tazawa, 1997) investigated the influence of cementitious materials on autogenous shrinkage. The cement paste specimens were 20 x 20 x 160 mm, 40 x 40 x 160 mm, and 100 x 100 x 400 mm prisms. Mortar specimens were fabricated with dimensions of 40 x 40 x 160 mm. Concrete specimens were 100 x 100 x 1200 mm prisms. Specimens were either sealed with aluminum tape, subjected to drying, or submerged in water. Length change was measured at 20 ^{o}C. The decrease in aggregate volume fraction was found to increase the sealed specimen shrinkage. The effect of the aggregate can be explained by both the reduction in cement paste content and the elastic deformations of the aggregate particles.

2.4.2 Influence of Cement Type and Fineness

In the previously mentioned examination of expansive cement by Saito, it was determined that expansive cement as a mortar shows a large amount of shrinkage reduction. Expansive cement used in concrete had a more negligible effect on shrinkage. The aggregate plays a role in allowing the cement paste to change. Strain was measured within the aggregate particle. It was found that at the beginning of shrinkage, some cracks had already existed around the coarse aggregate particles embedded in the unreinforced and reinforced expansive cement concretes. The formation of cracks were found to lead to a partial loss of restraint of coarse aggregate particles against drying shrinkage.

Tazawa and Miyazawa found that cement composition has a greater influence on autogenous shrinkage than drying shrinkage. Compared to normal Portland cement, larger autogenous shrinkage was observed for high early strength cement at an early age, and blast furnace slag cement at later ages. Less autogenous shrinkage was observed for moderate heat cement paste, and low heat Portland cement with a high C_2S content. Autogenous shrinkage depends on the hydration of C_3A and C_4AF and it increases with an increase in these compounds.

2.4.3 Influence of Cement and Water Content

The water content has a large influence on the drying shrinkage of cement paste and concrete. For a given w/c ratio, concretes of wet consistencies with a high paste content, have a greater amount of shrinkage than a stiffer mixture (Troxell, 1996). For given proportions of cement and aggregate, concretes of wet consistencies have a higher w/c ratio, thus they have a greater amount of shrinkage than a stiffer mixture.

2.4.4 Influence of Mineral Admixtures

The use of mineral admixtures has become popular in industry, especially for high strength and low permeable concretes. The most common types of mineral admixtures are silica fume and fly ash. In general, some of these admixtures increase the water requirements for a concrete mixture. In theory, the increased water demand should increase the shrinkage of the concrete, however, some studies have shown that the use of mineral admixtures with an increased water demand do not always increase the amount of shrinkage.

2.4.4.1 Silica Fume

Silica fume is an industrial by-product with a particle size about 100 times finer than Portland cement (Mehta, 1986). This material, which is highly pozzolanic also creates a greater water demand or the use of a high range water reducer.

In Weigrink, Marrikunte, and Shah's (Weigrink, 1996) investigation of concrete shrinkage, they found that higher silica fume contents produced a concrete with higher early drying shrinkage. Tazawa and Yonekura examined shrinkage and creep of mortar and concrete. Drying shrinkage of concrete was tested using 100 x 100 x 400 mm prism specimens. The specimens were in a controlled environment of 20 ^{o}C, 50 % relative humidity. The drying shrinkage of the concrete mixtures with the silica fume was lower than that of the same type mixtures without the silica fume.

Bloom and Bentur tested concrete based on a graded aggregate with a maximum nominal aggregate size of 7 mm. This was due to the small cross section resulting in a need for smaller aggregate sizes to gain a representative sample. Shrinkage tests were conducted on 40 x 40 x 1000 mm prism specimens. The specimens were exposed to either 40 ^{o}C, 45 % relative humidity, or they were sealed.

Silica fume considerably increased the free plastic shrinkage of the concrete compared to the reference Portland cement concrete with the same water to binder ratio (Bloom, 1995). Concrete with a low water to binder ratio of 0.33 cracked due to plastic shrinkage regardless of silica fume in the mixture. Concrete with a higher water to binder ratio of 0.50 did not have cracking, and the mixtures with a water to binder ratio of 0.40 cracked with silica fume added, but no cracking was observed in the non-silica fume mixtures. The shrinkage of the sealed specimens was found to be neglible.

Haque (Haque, 1996) measured the drying shrinkage on 85 x 85 x 285 mm prism specimens. The addition of both 5 and 10 % silica fume (by weight) in concrete mixtures resulted in substantial reduction of drying shrinkage. Further addition of 20 % fly ash or slag increased the shrinkage of these concretes.

Tazawa and Miyazawa (Tazawa, 1991) found that autogenous shrinkage of concrete during the first 24 hours after placement increases with decreasing water to binder ratio. When the water to binder ratio was reduced to 0.17 with superplasticizers and silica fume, the greater part of the shrinkage in the dried condition was attributed to autogenous shrinkage.

Whiting et al (Whiting, 2000) found that the tendency of concrete with silica fume to crack is influenced by the curing of the concrete not the addition of silica fume. When the concrete is cured for 7 days in a continually moist condition, there was no statistically significant effect on the tendency of the concrete to crack. However, it was found that at early ages, the silica fume concrete mixtures did show somewhat higher shrinkage than those mixtures not containing silica fume. It was recommended from this research that specifications for silica fume concrete mixtures used in bridge deck construction include a provision for a 7 day continuous moist curing of exposed surfaces.

2.4.4.2 Fly Ash

The particle size distribution, morphology, and surface characteristics of fly ash used as a mineral admixture has a considerable influence the water requirement, workability, and rate of strength development of concrete (Mehta, 1986). Particle sizes range from less than 1 micron to 100 microns in diameter, with more than 50 % under 20 microns. The Class C high calcium fly ash is more chemically active than the low calcium Class F fly ash.

Tests were conducted on 15 x 40 x 160 mm prism specimens to measure length change by Tangtermsirikul (Tangtermsirikul, 1995). The drying shrinkage tests were conducted in a controlled environment of 25 ^{o}C and 60 % relative humidity. Three types of Class C fly ash and one type of Class F fly ash were used in the experiment. The class C fly ash had a smaller drying shrinkage than the ordinary cement paste mixtures. The application of the fly ash reduced the water requirement of the mixtures, thus reducing the shrinkage. The Class C fly ash also reduced the autogenous shrinkage due to chemical expansion of the concrete mixture.

Gebler and Klieger (Gebler, 1950) tested prism specimens of 75 x 75 x 285 mm according to ASTM C157. The specimens were cured in a controlled environment of both 23 ^{o}C and 4.4 ^{o}C, 100% relative humidity. Concrete containing fly ash and cured at 23 ^{o}C was not significantly different in shrinkage from the mixtures not containing fly ash.

2.4.5 Influence of Chemical Admixtures

Chemical admixtures such as shrinkage reducing admixtures (SRA) are presently being used on a limited basis. The use of high range water reducers (HRWR) are common in use today. SRA lowers the surface tension of the pore water solution in the cement paste, thus decreasing the shrinkage stresses and reducing the cracking due to shrinkage. Concretes with a low w/c ratio and HRWR admixtures produce a more workable concrete mixture. In general, HRWR admixtures do not affect the shrinkage deformation of concrete.

Balogh (Balogh, 1996) conducted tests on concrete with SRA according to ASTM C 157-93. Lower w/c ratio produces concrete with a greater percentage of shrinkage reduction. A w/c ratio of less than 0.60 reduces the 28 day shrinkage by 80 % or more, and the 56 day shrinkage was reduced by about 70 %. The admixture dosage rate was 1.5 % by weight of cement. A w/c ratio of 0.68 reduced the 28 and 56 day shrinkage by 37 % and 36 % respectively.

The SRA was tested with different cements, one with fly ash, one with fly ash and slag cement. The long term shrinkage reductions without curing the concrete ranged from 25 % to 38 % depending on the mixture.

Berke et al (Berke, 1997) conducted tests on concrete mixtures cured from one to 14 days. The specimens were stored at 23 ^{o}C, 50 % relative humidity. The specimens containing 2 % by weight of cement of SRA showed a minimal shrinkage at early ages after controlled drying. Drying shrinkage increased as the w/c ratio increases with all the mixtures having the same cement content. The drying shrinkage was greatly reduced with the introduction of the SRA. Drying shrinkage was significantly reduced with increased curing time. Longer curing periods reduced the sensitivity to changes in the w/c ratio with respect to shrinkage reduction.

Folliard and Berke (Folliard, 1997) used silica fume slurry and superplasticizer along with an SRA to produce a high strength concrete. The concrete was kept at a slump of 150 to 200 mm. Concrete prisms of 75 x 75 x 285 mm were cast to measure free drying shrinkage. The use of a SRA reduced the drying shrinkage of the high strength concretes both with and without silica fume.

The ring test was used to determine the restrained shrinkage. The steel ring used had an inner diameter of 250 mm and an outer diameter of 300 mm. The concrete was placed 50 mm thick and 150 mm high around the steel ring. The restrained shrinkage was significantly reduced when the SRA was used. The shrinkage reduction was more significant with the silica fume mixtures.

Shah, Karaguler, and Sarigaphuti (Shah, 1992) used the ring test to determine restrained shrinkage. The steel ring had an inner diameter of 305 mm and an outer diameter of 375 mm. The specimens were placed in a controlled environment of 20 ^{o}C, 40 % relative humidity. Three different SRAs were used. Tests were also conducted on 100 x 100 x 285 mm prism specimens.

The SRAs may decrease the compressive strength of the concrete. The addition of the SRA did reduce the amount of shrinkage. As the amount of SRA added increases, the shrinkage further decreases. The addition of SRA reduced the restrained shrinkage crack width.

Shah et al (Shah, 1992) used ring specimens to test for restrained shrinkage. The inner diameter of the ring was 305 mm and the outer diameter was 375 mm. Free shrinkage was also measured on 100 x 100 x 400 mm prism specimens. The addition of SRA greatly improved the reduction of free shrinkage. An equal amount of water was removed when the SRA was added. The addition of the SRA caused a delay in the restrained shrinkage cracking. Typical specimens cracked at 48 days or more.

Tazawa and Miyazawa (Tazawa, 1991) found that surface tension reducing agents, water repellant-treated powders, and expansive admixtures were effective in reducing autogenous shrinkage. Alsayed (Alsayed, 1998) examined the drying shrinkage of 12 high strength concrete prisms, the dimensions of the prism specimens were 76 x 76 x 286 mm. These specimens were monitored over a three year time period. All of the mixtures were identical except for the admixture content. Three mixtures were compared; the first had a superplastisizer as the admixture, the second had a superplasticizer and 10 % silica fume by weight, and the third mixture had a regular plastisizer and 10 % silica fume by weight. The specimens were submerged in water for seven days. Six specimens were then put in a laboratory controlled environment, while the other six specimens were exposed to field conditions. By adding 10 % silica fume, the shrinkage was reduced over time. The mixture with the superplasticizer and silica fume showed a reduction in shrinkage. Specimens with the normal plasticizer showed larger drying shrinkage than those with the superplasticizer. The combined superplasticizer and silica fume mixtures showed a reduced rate of the first months drying shrinkage. The addition of the silica fume helped to reduce the sensitivity of the concrete to curing conditions. After the first 90 days of exposure, 75 % to 80 % of the drying shrinkage occurred depending on the curing conditions.

2.4.6 Influence of Curing

The longer the curing time, the less shrinkage will occur. Alsayed and Amjad (Alsayed, 1994) tested twelve 1000 mm x 1000 mm x 200 mm concrete slabs and twelve 150 mm x 300 mm cylinders. The specimens were placed to examine the effects of curing conditions on shrinkage. Shrinkage measurements began on the eighth day after specimen fabrication. Watering twice a day, burlap, polyethylene, and air curing were all found to result in high shrinkage rates. Other methods were recommended to reduce the shrinkage rate. Sealing the concrete with resin modified wax or watering the concrete four to five times a day may decrease the shrinkage rate of the concrete.

2.4.7 Influence of Ambient Conditions

Torrenti et al (Torrenti, 1999) examined a non-reinforced concrete beam of 0.3 x 1 x 3 m for ambient effects on shrinkage. The shrinkage of the beam was proportional to its self weight. The thermal expansion coefficient of the concrete had a direct relation to the shrinkage values, but temperature had very little effect on the variations of the thermal expansion coefficient. The variations in the relative humidity had a greater influence on the thermal expansion coefficient.

Almusallam et al (Almusallam, 1999) exposed 450 x 450 x 20 mm specimens to different temperature, relative humidity, and wind velocity conditions. The increased relative humidity caused a decrease in water evaporation when there was no wind. Relative humidity became insignificant to evaporation of water under windy conditions. The increase in wind increased the rate of water evaporation, crack length and area, and early cracking as compared to non-windy conditions. The increase in temperature increased the rate of water evaporation and the crack length and area. It was concluded that water evaporation should be minimized to reduce the intensity of plastic shrinkage cracking.

2.4.8 Influence of Specimen Size

The size and shape of a concrete specimen definitely influence the rate of loss or gain of moisture under a given storage condition, and this can affect the rate of volume change as well as total expansion or contraction.

Almudaiheem and Hansen (Almudaiheen, 1987) observed the shrinkage of various specimen size over a one year period. The shrinkage decreased with increasing specimen size. The ultimate shrinkage of paste, mortar, and concrete was found to be independent of specimen size and shape according to the dynamic shrinkage/weight loss curves. They concluded that the ultimate drying shrinkage may be estimated from shrinkage vs. drying time curves for small laboratory specimens of 25 x 25 x 279 mm with the same mixture proportions as the larger structural members.

2.5 Performance Specifications

Ramey, Wolff, and Wright discussed the design actions that may reduce bridge deck cracking. Plastic and drying shrinkage are two of the main causes of cracking. Plastic shrinkage in bridge decks is most commonly found in reinforced concrete slabs due either to rapid early drying or to insufficient cover depth. The amount of plastic shrinkage may be minimized by improving early curing. Long term drying shrinkage is most common in thin slabs. By reducing the w/c ratio, and improving curing, long term drying shrinkage may be reduced.

Babaei et al (Babaei, 1995) conducted a field investigation of bridge deck cracking due to shrinkage. Cracking occurs in the concrete deck when the restraining stress exceeds the tensile stress of the concrete. By limiting the thermal shrinkage to 150 microstrain and the 4 month test specimen drying shrinkage to under 700 microstrain, shrinkage cracking may be reduced. Thermal shrinkage requirements may be satisfied by maintaining the concrete to a deck differential temperature of under 22 ^{o}F for at least 24 hours after placement of the concrete.

2.6 Prediction Models

There are many models associated with predicting creep and shrinkage of concrete. A review of the literature for these types of prediction models shows that the most widely discussed and used models are Comite Euro-International Du Beton (CEB Model Code 1990), Bazant and Panula (BP-KX and Model B3), and American Concrete Institute (ACI 209). There are many other models and proposed models that are in use; however, it appears that all of these models are compared to at least one of the three models mentioned above. There are many parameters to be considered in the modeling of creep and shrinkage. The following is a discussion of the various parameters associated with the different prediction models and various comparisons between models. Chapter four presents the equations used in various models to predict shrinkage.

Ojdrovic and Zarghamee (Ojdrovic, 1996) presented a method for predicting the ultimate creep and shrinkage from the results of short-term creep and shrinkage tests. The ACI-209 and Bazant-Panula (BP-KX) models were used to predict the ultimate creep and shrinkage from these short-term test results. The predicted values were compared to the results of long-term creep and shrinkage tests. These results showed that by adjusting the models based on short-term test results, the accuracy of long-term tests was significantly increased. They discussed the two different approaches to predict creep and shrinkage, empirical and analytical. The empirical approach uses time functions determined from a number of tests by curve fitting; the analytical approach uses time functions obtained by solving differential equations of postulated processes governing creep and shrinkage behavior. The ACI-209 model is an empirical model based on creep and shrinkage tests. The formulas represent mean behavior of many test results. The BP-KX model is an analytically derived time function with empirically determined parameters. The results found that the BP-KX model produced a better fit.

McDonald and Roper (McDonald, 1993) discussed a comparison between seven shrinkage prediction models. The models included the ACI-209, Bazant-Panula, CEB90, CEB-FIP, and three Australian code models. The paper (McDonald, 1993) lists the parameters used for creep and shrinkage by the various models. All of the models used humidity, size, and age at loading as parameters. The Bazant-Panula model used fourteen parameters, ACI-209 used nine, and CEB90 used five. Of these three models, the results showed that the CEB90 model performed best. The Bazant-Panula model performed well early but began to deviate at later times. The Australian models are considered to be relatively simple as compared to the other models. The authors concluded that the more complex models were not necessarily more accurate than the simple models when used for the Australian concretes used in the investigation. They found that the simple Australian Code AS1481 model performed better than the other models for predicting shrinkage.

Bahl and Jain (Bahl, 1995) presented a paper on the effect of age at the time of loading on creep of concrete. In this paper they discussed some of the parameters used by the CEB90 model in predicting creep. The parameters include relative humidity, temperature, size of specimen, elastic modulus, and age at loading. The results were that age at loading has a significant effect on the creep of concrete.

Bahl and Mittal (Bahl, 1996) discussed the parameters used by the ACI-209 model in predicting creep and shrinkage. For predicting creep, the model uses the following parameters, relative humidity, age at loading, concrete composition, average thickness of member, fine aggregate/total aggregate ratio, and air content. The model uses the following parameters for predicting shrinkage, relative humidity, concrete composition, average thickness of member, fine aggregate/total aggregate ratio, air content, cement content, and age of concrete.

Mehta (Mehta, 1986) discussed some of the parameters used in predicting creep and shrinkage by the CEB90 and ACI-209 models. For predicting shrinkage, the CEB90 model uses coefficients to account for the effects of mix proportions, drying time, and specimen geometry. The drying shrinkage of the ACI-209 model can be determined as a function of time of drying and ultimate drying shrinkage at 40 percent relative humidity. The creep coefficient of the CEB90 model takes into account the effects of mix proportioning, cement composition, time under load, relative humidity, and specimen geometry. The creep coefficient of the ACI-290 model is estimated taking into account time under load, and the value of the ultimate creep coefficient.

Gardner and Zhao (Gardner, 1993) proposed a model for predicting creep and shrinkage, this proposed model was compared to the CEB90 and ACI-209 models. They also discussed the different equation parameters used by the CEB90 and ACI-209 models to represent concrete deformation. The ACI-209 uses the following:

Total strain = shrinkage strain + stress/E_{cmto}*[1+creep coefficient]

The CEB90 model uses the following:
Total strain = shrinkage strain + stress/E_{cmto} + stress/E_{cm28}*creep coefficient

Where
E_{cmto} = mean modulus of elasticity at loading
E_{cm28} = mean modulus of elasticity at 28 days

Experimental data were reduced to develop expressions for creep and shrinkage. The concrete strengths were calculated using reported E_c values at age of loading and 28 days; these strengths were then averaged with the measured compressive strengths. Expressions were developed using these average strengths to develop the shrinkage strain. These shrinkage strains were then compared to reported shrinkage strains. The elastic moduli were calculated using the reported measured strengths at age of loading and averaged with the measured elastic modulus. And finally, residual creep strain was calculated by subtracting the calculated elastic strain from the measured load-induced strain. Gardner developed models for predicting creep and shrinkage. The equation developed for shrinkage allowed correction factors for age of loading, strength of concrete, duration of loading, and member size and relative humidity. For the developed creep model, the drying creep coefficient included the effects of relative humidity, member size, developed concrete strength, and 28 day compressive strength. The proposed expressions, which are presented at the end of this discussion, could be used to calculate the shrinkage and total strains within a spread of 20 percent with a confidence level of 65 percent. It was also found that ACI-209 overestimated shrinkage at early ages, and underestimated shrinkage at later ages. The CEB underestimated shrinkage, and both models underestimated creep.

CHAPTER 3. PURPOSE AND SCOPE

The objective of this study is two-fold. The first objective is to develop a concrete shrinkage performance specifications and an associated test procedure. The test procedure shall be used to determine limits for the amount of drying shrinkage in concrete mixtures purchased by the Virginia Department of Transportation (VDOT).

The second objective is to assess the accuracy of existing unrestrained shrinkage prediction models for a range of typical Virginia Department of Transportation mixtures.

The proposed study will be limited to A3 – General Paving (3000 psi at 28 days), A4 – General Bridge Deck (4000 psi at 28 days), and A5 – General Prestress (5000 psi at 28 days) concrete mixtures approved by the Virginia Department of Transportation. Some of these mixtures will include slag cement, and some will include pozzolans such as fly ash and microsilica. In addition, three types of normal weight coarse aggregate, limestone, gravel, and diabase, and their associated fine aggregate shall be included as variables. Chemical admixtures such as air entrainers, retarders, and high-range water reducers, shall also be included in the mixtures. However, the chemical admixtures will not be a study variable, only one type and manufacturer of each admixture shall be used.

CHAPTER 4. METHODS AND MATERIALS

4.1 Restrained Shrinkage Testing

The restrained shrinkage testing was conducted in accordance with AASHTO PP34-98, Standard Practice for Estimating the Cracking Tendency of Concrete. The test method involves casting a concrete ring around a steel ring. Sonotube was used as a form for casting the concrete around the steel ring. Figure 4.1 in presents the specimen configuration. Strain gages were mounted on the inside of the steel ring to monitor the strain in the steel ring caused by the shrinkage of the concrete. Figure 4.2 presents the strain gage configuration.

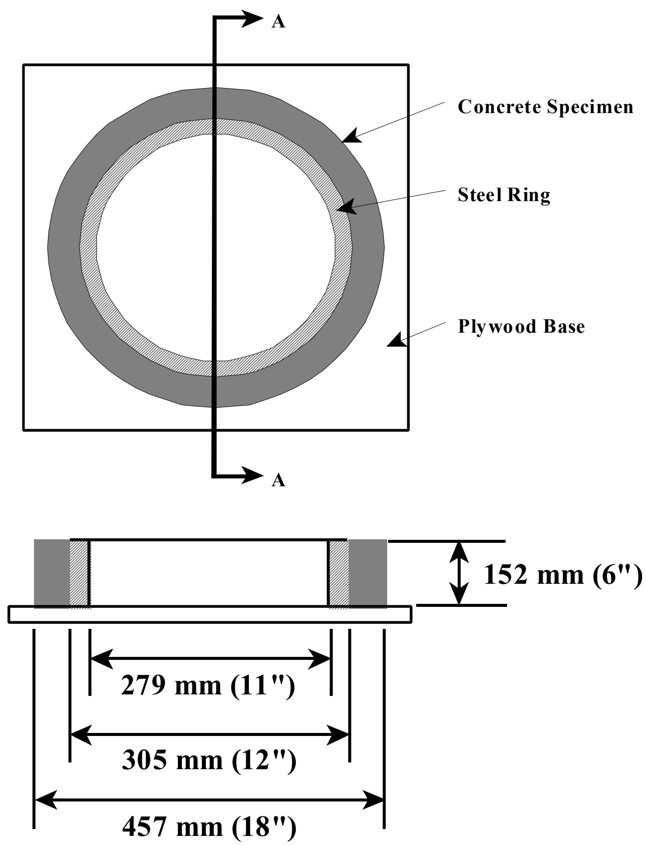

Figure 4.1 Restrained Shrinkage Specimen Configuration

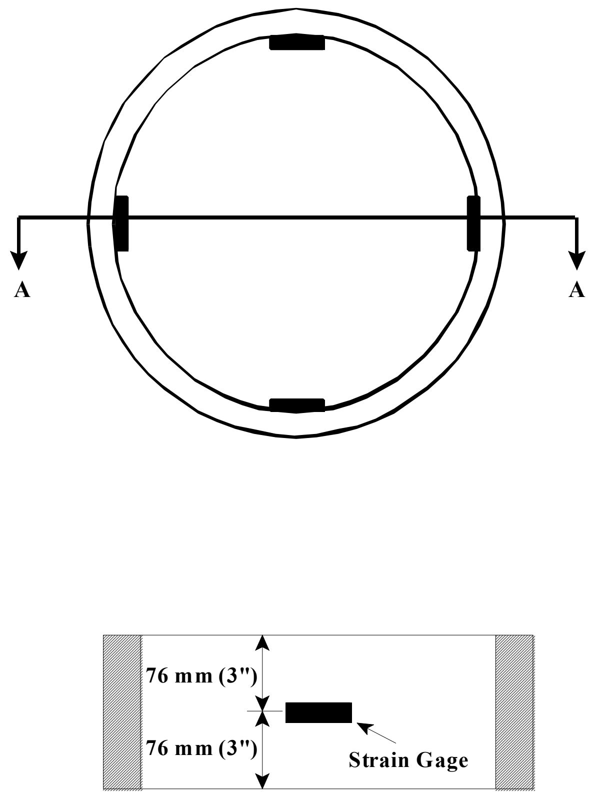

Figure 4.2 Restrained Shrinkage Specimen Strain Gage Configuration

As the concrete shrinks, a compressive stress is produced in the steel ring, which is balanced by a tensile stress in the concrete. When cracking occurs in the concrete, the stress and thus the strain in the steel ring is released.

The specimens were cured and measured in the following manner. Immediately after the specimens were fabricated, an initial strain measurement was conducted. Each strain gage was measured using a strain indicator. The specimens were then placed in a controlled environment of 23 °C ± 2 °C and 50% ± 4% relative humidity. The specimens were then covered with wet burlap and a 6 mil polyethylene sheet and allowed to cure for 24 hours. After 24 hours, the sonotube molding was removed. A 6 mil polyethylene sheet was then adhered to the top surface of the concrete ring. This was done to limit the drying of the concrete from only the annular exposed face. Strain measurements were then taken on each strain gage. Strain readings were taken again at seven days, then every seven days until 90 days. Subsequent readings were taken at 120, 150, and 180 days.

The specimens were visually monitored on a daily basis for cracking. Cracking became visible when the crack width was approximately 2 mm (0.08 in.). Strain readings were also monitored to detect cracking. When cracking occurred, strain readings were taken on all strain gages on a daily basis for 14 days. The crack width and length were also measured on a daily basis for the 14 days after cracking occurred. The crack width was measured at three locations along the crack length, and an average was calculated.

4.2 Unrestrained Shrinkage Testing

Unrestrained shrinkage testing was conducted in accordance with ASTM C157-98, Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete. The test method involves measuring the length change of 75mm x 75mm x 279mm concrete prisms.

Specimens were fabricated in steel molds according to ASTM C 192-98, Practice for Making and Curing Concrete Test Specimens in the Laboratory. The specimens were then covered with wet burlap and a 6 mil polyethylene sheet for 24 hours. After 24 hours of wet curing, the specimens were removed from the steel molds. Initial measurements using a comparator were then taken on each specimen in accordance with ASTM C 490-98, Practice for Use of Apparatus for the Determination of Length Change of Hardened Cement Paste, Mortar, and Concrete. After initial readings were taken, the specimens were placed in lime saturated water at 23 °C ± 1°C. The specimens were kept in the lime-saturated water for a period of six days, with length change measurements being conducted each day. After six days in lime-saturated water, the specimens were removed and placed in a controlled environment of 23 °C ± 2 °C and 50% ± 4% relative humidity. Subsequent length change measurements were conducted every seven days up to 90 days, and then at 120, 150, and 180 days.

4.3 Compressive Strength Testing

Compressive strength specimens were fabricated for each concrete mixture in accordance with ASTM C 192-98. Cylindrical specimens were fabricated for testing at seven, 28, 56, and 90 days. The specimen dimensions were 102 mm x 203 mm (4 in x 8 in). Specimens were tested in accordance with ASTM C 39-98, Test Method for Compressive Strength of Cylindrical Concrete Specimens.

4.4 Modulus of Elasticity Testing

Modulus of elasticity specimens were fabricated for each concrete mixture in accordance with ASTM C 192-98. Cylindrical specimens were fabricated for testing at seven, 28, 56, and 90 days. The specimen dimensions were 152 mm x 305 mm (6 in x 12 in). Specimens were tested in accordance with ASTM C 469-98, Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression.

4.5 Aggregate Properties

Three types of number 57 coarse aggregate were used for this study, limestone, gravel, and diabase. Coarse and the associated fine aggregate were obtained from various locations in the Commonwealth of Virginia. Samples were taken from each aggregate source in accordance with ASTM D 75-98, Practice for Sampling Aggregates. A sieve analysis was performed on each aggregate sample in accordance with ASTM C 136-98, Method for Sieve Analysis of Fine and Coarse Aggregates. All of the aggregate met VDOT Road and Bridge 1997 specifications. Specific gravity and absorption tests were conducted in accordance with ASTM C 127-98, Test Method for Specific Gravity and Absorption of Coarse Aggregate, and ASTM C 128-98, Test Method for Specific Gravity and Absorption of Fine Aggregate. The aggregate properties are presented in Table A1 in Appendix A.

4.6 Cement Properties

The portland cement used in this study was a Type I/II that met ASTM C-150-98, Specification for Portland Cement. Type I is classified as normal cement, while Type II is classified as moderate sulfate resistance. For this study a blended Type I/II portland cement and 40 % (by weight) ground granulated blast furnace slag (GGBFS) was also used for select mixtures. The GGBFS was a grade 120 and met ASTM C 989-98, Specification for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars. Table 4.1 presents the cement properties.

Table 4.1 Cement Properties

Chemical Analysis	**Percent by Weight**		**ASTM C 150-98**
Analyte	**Sample 1**	**Sample 2**	**Type II**
SiO_2	21.25	21.17	20.0 min
Al_2O_3	4.49	4.49	6.0 max
Fe_2O_3	3.04	3.03	6.0 max
CaO	63.51	63.41	--
MgO	2.48	2.50	6.0 max
SO_3	2.47	2.46	3.0 max
Na_2O	0.17	0.17	--
K_2O	0.82	0.81	--
TiO_2	0.21	0.22	--
P_2O_5	0.11	0.11	--
Mn_2O_3	0.06	0.06	--
SrO	0.14	0.14	--
L.O.I (950 C)	1.06	1.07	3.0 max
Total	99.83	99.65	--
Alkalis as Na_2O	0.72	0.71	*0.6 max

Compounds

Calculated			**Mass Estimated**	**ASTM C 150-98**
ASTM C 150-97	**Sample 1**	**Sample 2**	**By QXRD**	**Type II**
C3S	55	56	65	--
C2S	19	19	16	--
C3A	7	7	4.2	8.0 max
C4AF	9	9	10	--

* Low alkali cement requirement

4.7 Pozzolans

The pozzolans used in this study were a Class F fly ash, and microsilica which is a relatively pure amorphous silica dioxide that is 100 times finer than portland cement. Both pozzolans were tested according to ASTM C 311-97. The fly ash met ASTM C 618-97 specifications and the microsilica met ASTM C 1240-97 specifications.

4.8 Mixture Test Series

Mixtures for this study consisted of A3, A4, and A5 mixtures using portland cement as the binder. Mixtures also consisting of portland cement and various supplemental cementitious materials as the binder. Tables 4.2 through 4.4 present the mixture proportions for A3, A4, and A5 mixtures using portland cement as the binder. Table 4.5 presents the mixture proportions for mixtures using supplemental cementitious materials as the binder. The tables also present the chemical admixture dosages, air-entrainment (AEA), retarder, and high range water reducer (HRWR), used in the various mixtures.

Table 4.2: A3 Portland Cement Concrete Mixtures

	Limestone		Gravel		Diabase	
Ingredient	Kg/m^3	Lbs/yd^3	Kg/m^3	Lbs/yd^3	Kg/m^3	Lbs/yd^3
Cement	349	588	335	564	349	588
Fine Aggregate	810	1365	685	1154	716	1207
Coarse Aggregate	1029	1734	1098	1850	1138	1918
Water	171	289	154	259	166	279
Total	2359	3976	2271	3827	2368	3992
AEA, mL	131		125		131	
HRWR, mL	1740		1669		1740	
w/c	0.49		0.46		0.47	

Table 4.3: A4 Portland Cement Concrete Mixtures

	Limestone		Gravel		Diabase	
Ingredient	Kg/m^3	Lbs/yd^3	Kg/m^3	Lbs/yd^3	Kg/m^3	Lbs/yd^3
Cement	377	635	377	636	377	636
Fine Aggregate	763	1286	584	984	667	1125
Coarse Aggregate	1029	1734	1098	1850	1138	1918
Water	170	286	158	267	163	275
Total	2338	3941	2217	3737	2346	3954
AEA, mL	141		141		141	
HRWR, mL	1880		1880		1880	
Retarder, mL	564		564		564	
w/c	0.45		0.42		0.43	

Table 4.4: A5 Portland Cement Concrete Mixtures

	Limestone		Gravel		Diabase	
Ingredient	Kg/m^3	Lbs/yd^3	Kg/m^3	Lbs/yd^3	Kg/m^3	Lbs/yd^3
Cement	415	700	418	705	419	706
Fine Aggregate	781	1316	640	1078	670	1130
Coarse Aggregate	1043	1758	1098	1850	1138	1918
Water	138	233	148	250	164	276
Total	2377	4007	2304	3883	2391	4030
AEA, mL	155		157		157	
HRWR, mL	2072		2087		2090	
w/c	0.33		0.35		0.39	

Table 4.5: Supplemental Cementitious Materials Mixtures

	A4-Fly Ash		A4-Microsilica		A4-Slag Cement		A5-Slag Cement	
Ingredient	Kg/m^3	Lbs/yd^3	Kg/m^3	Lbs/yd^3	Kg/m^3	Lbs/yd^3	Kg/m^3	Lbs/yd^3
Cement	321	541	351	591	227	382	252	424
SCM	75	127	27	45	151	254	167	282
FA	641	1081	669	1128	667	1125	670	1130
CA(Diabase)	1138	1918	1138	1918	1138	1918	1138	1918
Water	163	275	163	275	163	275	164	276
Total	2339	3942	2348	3957	2346	3954	2391	4030
AEA, mL	148		141		141		157	
HRWR, mL	1977		1883		1883		2090	
Retarder, mL	692		659		659		0	
w/c + p	0.43		0.43		0.43		0.39	

Specimens were fabricated and tested in three series. The first series consisted of A3, A4, and A5 mixtures for all three coarse aggregates, using portland cement as the binder. Table 4.6 presents the specimens fabricated for test series 1. The second series consisted of four A4 mixtures using diabase as the coarse aggregate. The three A4 mixtures included either fly ash, microsilica, or slag cement with portland cement as the binder. The A5 mixture included slag cement and portland cement as the binder. The pozzolans and slag cement were proportioned on a weight basis in the mixtures according to VDOT approved mixtures as follows:

Fly Ash: remove 15% portland cement, replace with 20% fly ash

Microsilica: replace portland cement with 7% microsilica

Slag cement: replace portland cement with 40% slag cement

Table 4.7 presents the specimens fabricated for test series 2. The third series consisted of A3, A4, and A5 mixtures for all three coarse aggregates, using portland cement as the binder. Table 4.8 presents the specimens fabricated for test series 3. The batch quantities for all of the mixtures performed in this study are presented in Tables A3 through A18 in Appendix A.

Table 4.6: Test Series 1 Specimen Fabrication Per Batch

Mixture	Batches	Rings	Prisms	4x8 Cylinders	6x12 Cylinders
A3-Limestone	1	2	2	8	1
A4-Limestone	1	2	2	8	1
A5-Limestone	1	2	2	8	1
A3-Gravel	1	2	2	8	1
A4-Gravel	1	2	2	8	1
A5-Gravel	1	2	2	8	1
A3-Diabase	1	2	2	8	1
A4-Diabase	1	2	2	8	1
A5-Diabase	1	2	2	8	1

Table 4.7: Test Series 2 Specimen Fabrication Per Batch

Mixture	Batches	Rings	Prisms	4x8 Cylinders	6x12 Cylinders
A4-D/Fly Ash	3	2	6	8	1
A4-D/Microsilica	3	2	6	8	1
A4-D/Slag Cement	3	2	6	8	1
A5-D/Slag Cement	3	2	6	8	1

Table 4.8: Test Series 3 Specimen Fabrication Per Batch

Mixture	Batches	Rings	Prisms	4x8 Cylinders	6x12 Cylinders
A3-Limestone	3	0	3	8	1
A4-Limestone	3	0	3	8	1
A5-Limestone	3	0	3	8	1
A3-Gravel	3	0	3	8	1
A4-Gravel	3	0	3	8	1
A5-Gravel	3	0	3	8	1
A3-Diabase	3	0	3	8	1
A4-Diabase	3	0	3	8	1
A5-Diabase	3	0	3	8	1

4.9 Existing Prediction Models

Five existing shrinkage prediction models were used to compare the actual shrinkage measurements obtained in this study to the predicted values of each model. The following presents the equations for the five existing prediction models:

4.9.1 American Concrete Institute – ACI 209 Code Model

(Bhal, 1995, Bhal, 1996, Mehta, 1986)

$$\varepsilon_{sh}(t, t_{sh,o}) = \frac{(t - t_{sh,o})}{35 + (t - t_{sh,o})} \varepsilon_{sh\infty} \; (moist / cure)$$

$$\varepsilon_{sh}(t, t_{sh,o}) = \frac{(t - t_{sh,o})}{55 + (t - t_{sh,o})} \varepsilon_{sh\infty} \; (steam / cure)$$

where: $\varepsilon_{sh}(t,t_{sh,o})$ = shrinkage strain (in./in.)
t = time (days)
$t_{sh,o}$ = time at start of drying (days)
$\varepsilon_{sh\infty}$ = ultimate shrinkage strain (in./in.)

4.9.2 Bazant B3 Model

(Bazant, 1995)

$$\varepsilon_{sh}(t, t_o) = -\varepsilon_{sh\infty} K_h S(t)$$

$$\varepsilon_{sh\infty} = -\alpha_1 \alpha_2 \left(26 (w)^{2.1} (f_c^{'})^{-0.28} + 270 \right) * 10^{-6}$$

$$K_h = 1 - h^3$$

$$S(t) = \tanh \sqrt{\frac{t - t_o}{T_{sh}}}$$

Where: $\varepsilon_{sh}(t,t_o)$ = shrinkage strain (in./in.)

$\varepsilon_{sh\infty}$ = ultimate shrinkage strain (in./in.)

α_1 and α_2 = 1.0

w = water content of concrete (lb/ft^3)

K_h = cross-section shape factor

h = relative humidity (%)

t = age of concrete (days)

t_o = age of concrete at beginning of shrinkage

S(t) = time function for shrinkage

4.9.3 Euro-International Concrete Committee – CEB 90 Code Model

(Bhal, 1995, Bhal, 1996, Mehta, 1986)

$$\varepsilon_{cso} = \varepsilon_s(f_{cm})(\beta_{RH})$$

$$\varepsilon_s(f_{cm}) = (160 + 10\beta_{sc}(9 - f_{cm} / 1450)) * 10^{-6}$$

$$\beta_{RH} = -1.55\beta_{ARH}$$

$$\beta_{ARH} = 1 - (RH / 100)^3$$

where: ε_{cso} = drying shrinkage of portland cement concrete (in./in.)

ε_s = drying shrinkage obtained from RH-shrinkage chart

β_{sc} = coefficient depending on type of cement

β_{RH} = coefficient for relative humidity

f_{cm} = mean 28-day compressive strength (psi)

4.9.4 Gardner/Lockman Model

(Gardner, 1998)

$$\varepsilon_{sh} = \varepsilon_{shu}\beta(h)\beta(t)$$

$$\varepsilon_{shu} = 1000 * K * \left(\frac{4350}{f'_{cm28}}\right)^{1/2} * 10^{-6}$$

$$\beta(h) = 1 - 1.18h^4$$

$$\beta(t) = \left(\frac{(t - t_c)}{t - t_c + 97(V / S)^{1/2}}\right) * 10^{-6}$$

where: ε_{sh} = shrinkage strain (in./in.)

ε_{shu} = ultimate shrinkage strain (in./in.)

$\beta(h)$ = correction term for effect of humidity on shrinkage

$\beta(t)$ = correction term for effect of time on shrinkage

h = humidity

t_c = age drying commenced (days)

t = age of concrete (days)

K = correction term for effect of cement type

4.9.5 Sakata Model

(Sakata, 1993)

$$\varepsilon_{sh}(t, t_o) = \varepsilon_{sh\infty}\left[1 - \exp\{-0.108(t - t_o)^{0.56}\right]$$

$$\varepsilon_{sh\infty} = -50 + 78(1 - \exp(RH / 100) + 38(\ln(w)) - 5(\ln(V / S) / 10)^2 * 10^{-5}$$

where: ε_{sh} (t, t_o)= predicted shrinkage strain (in./in.)

$\varepsilon_{sh\infty}$ = ultimate shrinkage strain (in./in.)

w = water content of the concrete (kg/m^3)

RH = relative humidity (%)

V/S = volume-to-surface area ratio

t = time (days)

t_o = time drying started (days)

CHAPTER 5: RESULTS

5.1 Introduction

This chapter presents the results of the standard compressive strength, modulus of elasticity, restrained shrinkage, and unrestrained shrinkage tests. Also presented are the residuals for the five shrinkage prediction models. As previously stated the compressive strength, modulus of elasticity, and unrestrained shrinkage test results are for the first and third test series of A3, A4, and A5 portland cement concrete mixtures. The second test series is the supplemental cementitious material mixtures. Restrained shrinkage test specimens were fabricated for test series one and two only. The compressive strengths, modulus of elasticity, and unrestrained shrinkage test results for test series one and three were not significantly different. Therefore, the test results were combined to form an A3 test group, A4 test group, and an A5 test group.

5.2 Compressive Strength

5.2.1 A3 Portland Cement Concrete Mixtures

Figure 5.1 presents the compressive strengths of the A3 portland cement concrete mixtures at seven, 28, and 90 days. Two 102 mm x 204 mm (4 in. x 8 in.) cylinders were tested at seven, 28, and 90 days. The average seven day compressive strengths were 33 MPa, 37 MPa, and 36 MPa (4840 psi, 5380 psi, and 5250 psi) for the limestone, gravel and diabase mixtures, respectively. The average 28 day compressive strengths were 40 MPa, 41 MPa, and 41 MPa (5750 psi, 5980 psi, and 5880 psi) for the limestone, gravel and diabase mixtures, respectively. The average 90 day compressive strengths were 46 MPa, 48 MPa, and 46 MPa (6620 psi, 6890 psi, and 6730 psi) for the limestone, gravel and diabase mixtures, respectively.

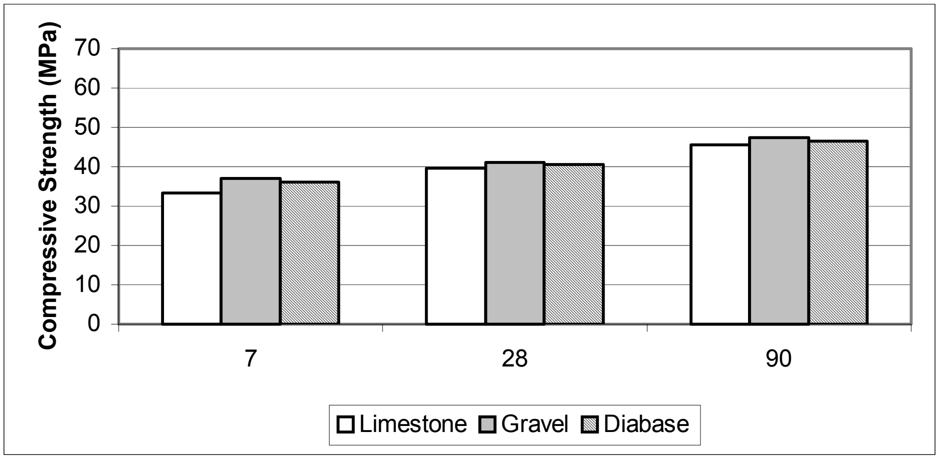

Figure 5.1 Compressive Strengths for A3 Mixtures.

5.2.2 A4 Portland Cement Concrete Mixtures

Figure 5.2 presents the compressive strengths of the A4 portland cement concrete mixtures at seven, 28, and 90 days. Two 102 mm x 203 mm (4 in x 8 in) cylinders were tested at seven, 28, and 90 days. The average seven day compressive strengths were 36 MPa, 38 MPa, and 36 MPa (5220 psi, 5500 psi, and 5220 psi) for the limestone, gravel and diabase mixtures, respectively. The average 28 day compressive strengths were 43 MPa, 44 MPa, and 43 MPa (6220 psi, 6410 psi, and 6210 psi) for the limestone, gravel and diabase mixtures, respectively. The average 90 day compressive strengths were 48 MPa, 50 MPa, and 48 MPa (6920 psi, 7310 psi, and 6950 psi) for the limestone, gravel and diabase mixtures, respectively.

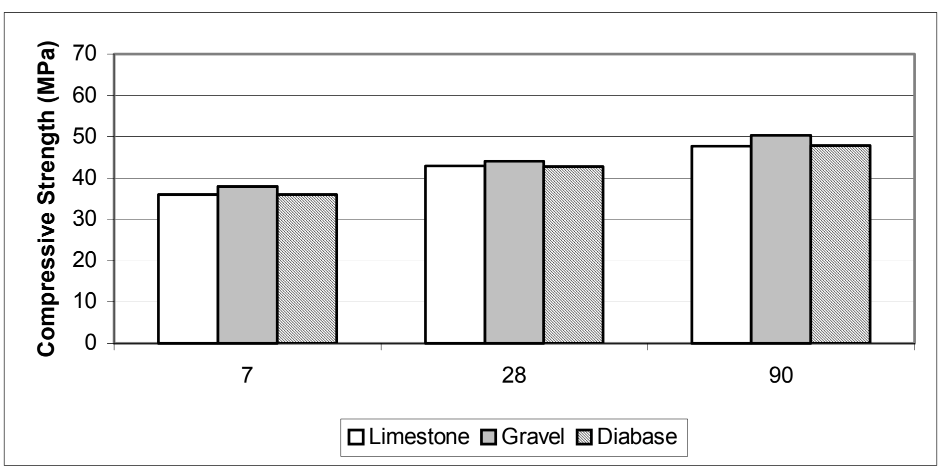

Figure 5.2 Compressive Strengths for A4 Mixtures.

5.2.3 A5 Portland Cement Concrete Mixtures

Figure 5.3 presents the compressive strengths of the A5 portland cement concrete mixtures at seven, 28, and 90 days. Two 102 mm x 203 mm (4 in x 8 in) cylinders were tested at seven, 28, and 90 days. The average seven day compressive strengths were 50 MPa, 44 MPa, and 42 MPa (7220 psi, 6380 psi, and 6120 psi) for the limestone, gravel and diabase mixtures, respectively. The average 28 day compressive strengths were 53 MPa, 49 MPa, and 48 MPa (7740 psi, 7150 psi, and 6920 psi) for the limestone, gravel and diabase mixtures, respectively. The average 90 day compressive strengths were 58 MPa, 56 MPa, and 53 MPa (8430 psi, 8060 psi, and 7660 psi) for the limestone, gravel and diabase mixtures, respectively.

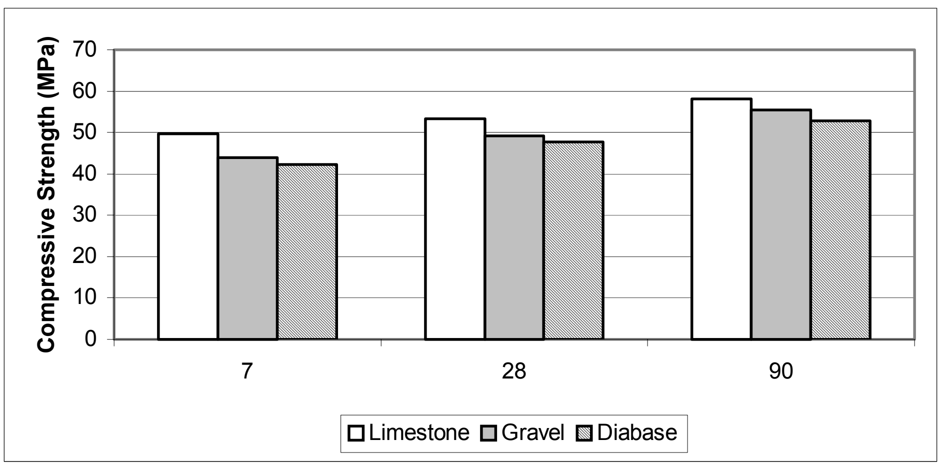

Figure 5.3 Compressive Strengths for A5 Mixtures.

5.2.4 Supplemental Cementitious Material Mixtures

Figure 5.4 presents the compressive strengths of the supplemental cementitious material mixtures in test series 2 at seven, 28, and 90 days. Two 102 mm x 203 mm (4 in x 8 in) cylinders were tested at seven, 28, and 90 days. The average seven day compressive strengths were 48 MPa, 47 MPa, 50 MPa, and 51 MPa (6950 psi, 6870 psi, 7280 psi, and 7450 psi) for the A4-Diabase/Fly Ash, A4-Diabase/Microsilica, A4-Diabase/Slag cement, and A5-Diabase/Slag cement, respectively. The average 28 day compressive strengths were 53 MPa, 53 MPa, 54 MPa, and 55 MPa (7740 psi, 7650 psi, 7880 psi, and 8020 psi) for the A4-Diabase/Fly Ash, A4-

Diabase/Microsilica, A4-Diabase/Slag cement, and A5-Diabase/Slag cement, respectively. The average 90 day compressive strengths were 58 MPa, 60 MPa, 61 MPa, and 62 MPa (8430 psi, 8720 psi, 8850 psi, and 9030 psi) for the A4-Diabase/Fly Ash, A4-Diabase/Microsilica, A4-Diabase/Slag cement, and A5-Diabase/Slag cement, respectively.

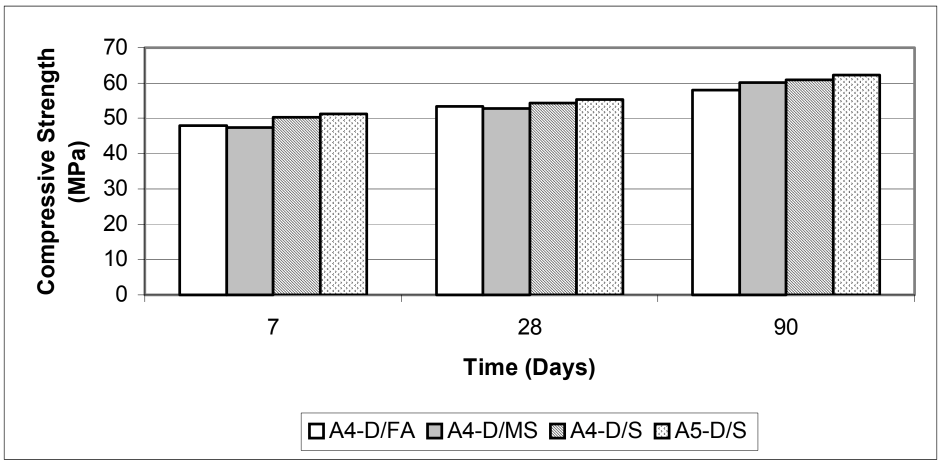

Figure 5.4 Compressive Strengths for Supplemental Cementitious Material Mixtures.

5.3 Modulus of Elasticity

5.3.1 A3 Portland Cement Concrete Mixtures

Figure 5.5 presents the modulus of elasticity for the A3 portland cement concrete mixtures at seven, 28, and 90 days. The modulus of elasticity at 7 days was 27 GPa, 28 GPa, and 28 GPa (3.96 x10^6 psi, 4.07 x10^6 psi, and 4.02 x10^6 psi) for the limestone, gravel and diabase mixtures, respectively. The modulus of elasticity at 28 days was 29 GPa, 30 GPa, and 29 GPa (4.19 x10^6 psi, 4.28 x10^6 psi, and 4.23 x10^6 psi) for the limestone, gravel and diabase mixtures, respectively. The modulus of elasticity at 90 days was 31 GPa, 32 GPa, and 31 GPa (4.54 x10^6 psi, 4.62 x10^6 psi, and 4.52 x10^6 psi) for the limestone, gravel and diabase mixtures, respectively.

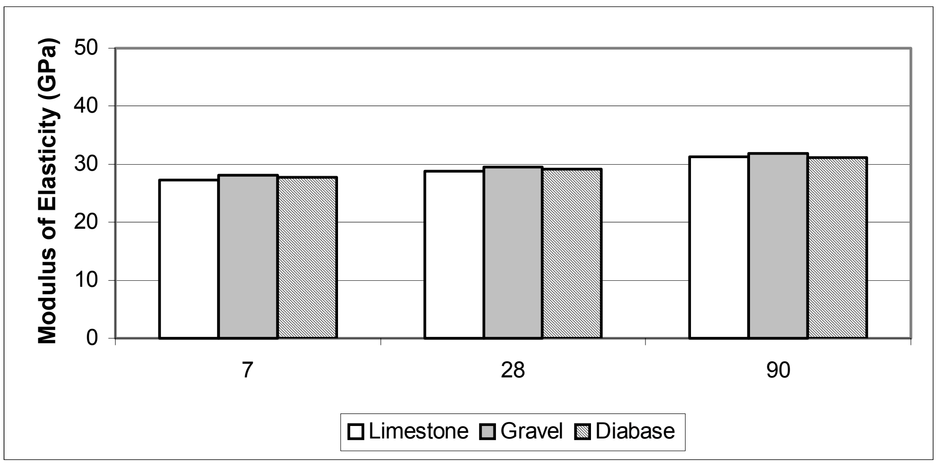

Figure 5.5 Modulus of Elasticity for A3 Mixtures.

5.3.2 A4 Portland Cement Concrete Mixtures

Figure 5.6 presents the modulus of elasticity for the A4 portland cement concrete mixtures at seven, 28, and 90 days. The modulus of elasticity at 7 days was 28 GPa, 29 GPa, and 27 GPa (4.00 x10^6 psi, 4.17 x10^6 psi, and 3.90 x10^6 psi) for the limestone, gravel and diabase mixtures, respectively. The modulus of elasticity at 28 days was 29 GPa, 30 GPa, and 29 GPa (4.27 x10^6 psi, 4.40 x10^6 psi, and 4.25 x10^6 psi) for the limestone, gravel and diabase mixtures, respectively. The modulus of elasticity at 90 days was 34 GPa, 35 GPa, and 34 GPa (4.87 x10^6 psi, 5.07 x10^6 psi, and 4.91 x10^6 psi) for the limestone, gravel and diabase mixtures, respectively.

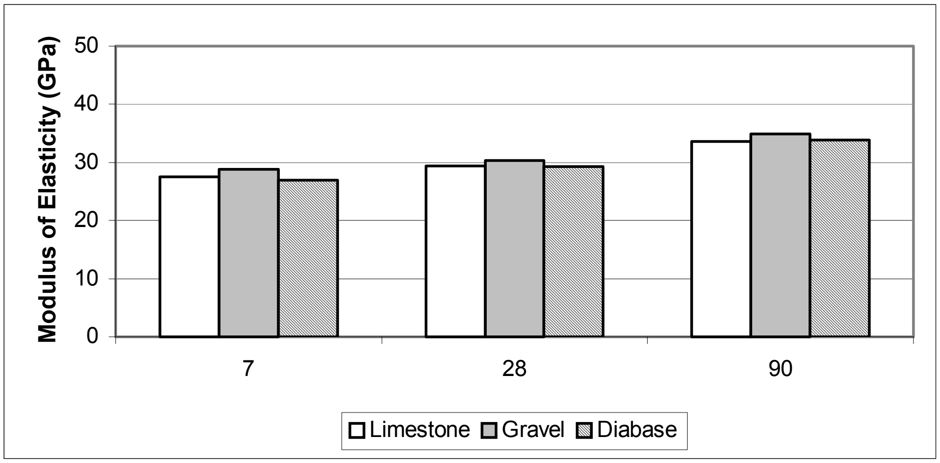

Figure 5.6 Modulus of Elasticity for A4 Mixtures.

5.3.3 A5 Portland Cement Concrete Mixtures

Figure 5.7 presents the modulus of elasticity for the A5 portland cement concrete mixtures at seven, 28, and 90 days. The modulus of elasticity at 7 days was 33 GPa, 32 GPa, and 31 GPa (4.83 x10^6 psi, 4.63 x10^6 psi, and 4.48 x10^6 psi) for the limestone, gravel and diabase mixtures, respectively. The modulus of elasticity at 28 days was 35 GPa, 34 GPa, and 33 GPa (5.11 x10^6 psi, 4.96 x10^6 psi, and 4.77 x10^6 psi) for the limestone, gravel and diabase mixtures, respectively. The modulus of elasticity at 90 days was 39 GPa, 37 GPa, and 36 GPa (5.67 x10^6 psi, 5.32 x10^6 psi, and 5.17 x10^6 psi) for the limestone, gravel and diabase mixtures, respectively.

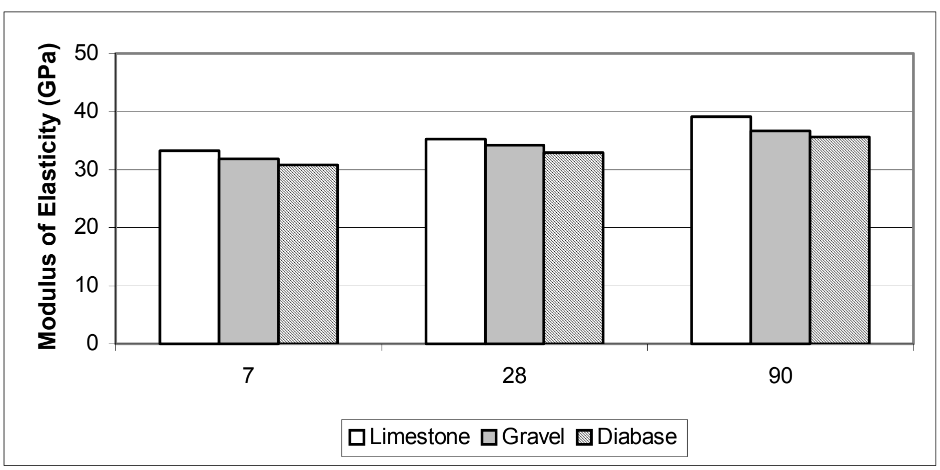

Figure 5.7 Modulus of Elasticity for A5 Mixtures.

5.3.4 Supplemental Cementitious Material Mixtures

Figure 5.8 presents the modulus of elasticity for the supplemental cementitious material mixtures in test series 2 at seven, 28, and 90 days. The modulus of elasticity at 7 days was 31 GPa, 30 GPa, 33 GPa, and 33 GPa (4.52 x10^6 psi, 4.41 x10^6 psi, 4.83 x10^6 psi , and 4.81 x10^6 psi) for the A4-Diabase/Fly Ash, A4-Diabase/Microsilica, A4-Diabase/Slag cement, and A5-Diabase/Slag cement mixtures, respectively. The modulus of elasticity at 28 days was 35 GPa, 36 GPa, 37 GPa, and 38 GPa (5.12 x10^6 psi, 5.15 x10^6 psi, 5.37 x10^6 psi , and 5.52 x10^6 psi) for the A4-Diabase/Fly Ash, A4-Diabase/Microsilica, A4-Diabase/Slag cement, and A5-Diabase/Slag cement mixtures, respectively. The modulus of elasticity at 90 days was 41 GPa, 42 GPa, 42 GPa, and 45 GPa (5.91 x10^6 psi, 6.11 x10^6 psi, 6.14 x10^6 psi , and 6.47 x10^6 psi) for the A4-Diabase/Fly Ash, A4-Diabase/Microsilica, A4-Diabase/Slag cement, and A5-Diabase/Slag cement mixtures, respectively.

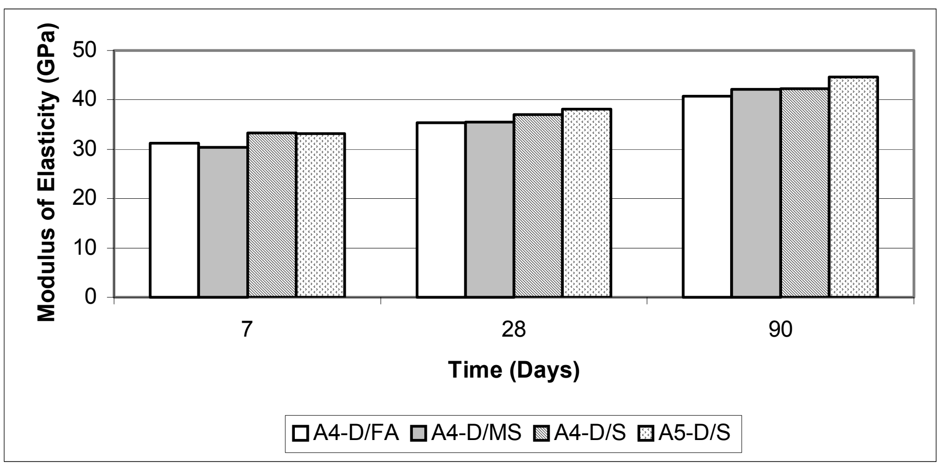

Figure 5.8 Modulus of Elasticity for Supplemental Cementitous Material Mixtures.

5.4 Unrestrained Shrinkage

5.4.1 A3 Portland Cement Concrete Mixtures

Figures 5.9 through 5.11 present the average and 95% confidence limits for the unrestrained shrinkage of the A3 limestone, gravel, and diabase portland cement concrete mixtures. A total of nine prism specimens were tested for each aggregate type. The diabase mixture exhibited the largest percent shrinkage, while the gravel mixture exhibited the lowest percent shrinkage for the test series. Figure 5.12 presents a comparison of the average percent shrinkage for the A3 mixtures. As shown, the diabase mixtures exhibited a greater average percent shrinkage beyond 90 days. Whereas, the limestone and gravel mixtures are the same.

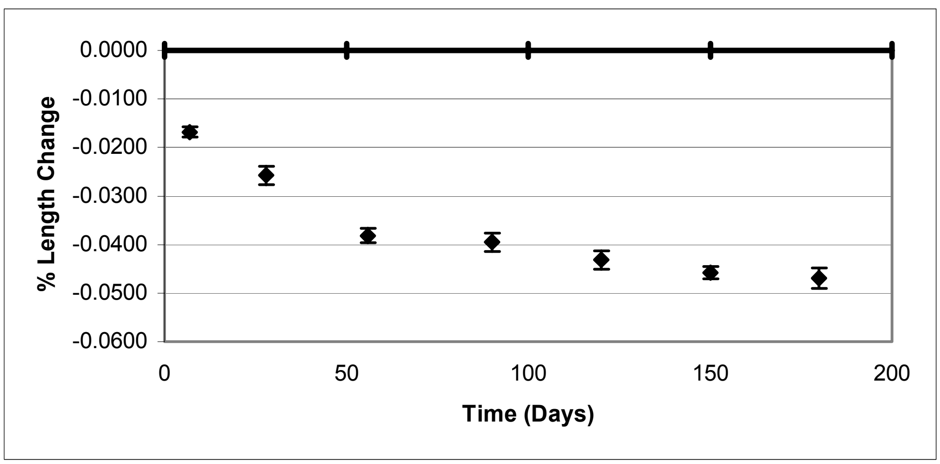

Figure 5.9 Unrestrained Shrinkage for A3 Limestone Mixtures.

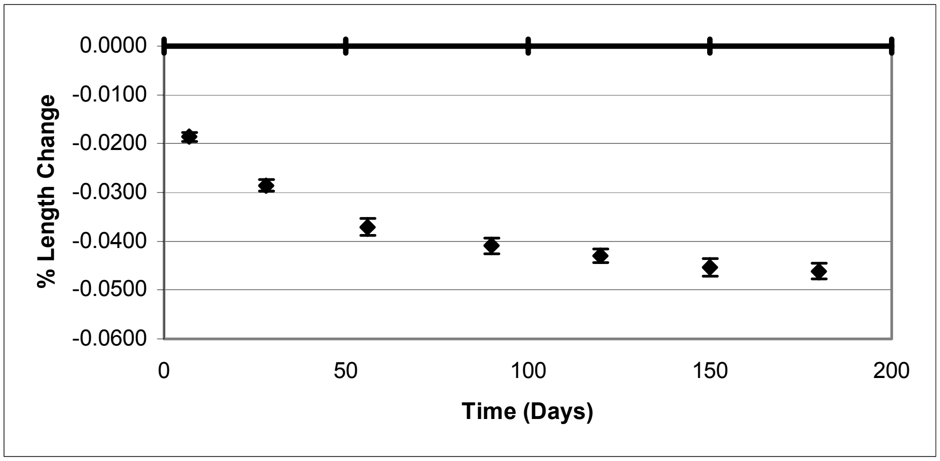

Figure 5.10 Unrestrained Shrinkage for A3 Gravel Mixtures.

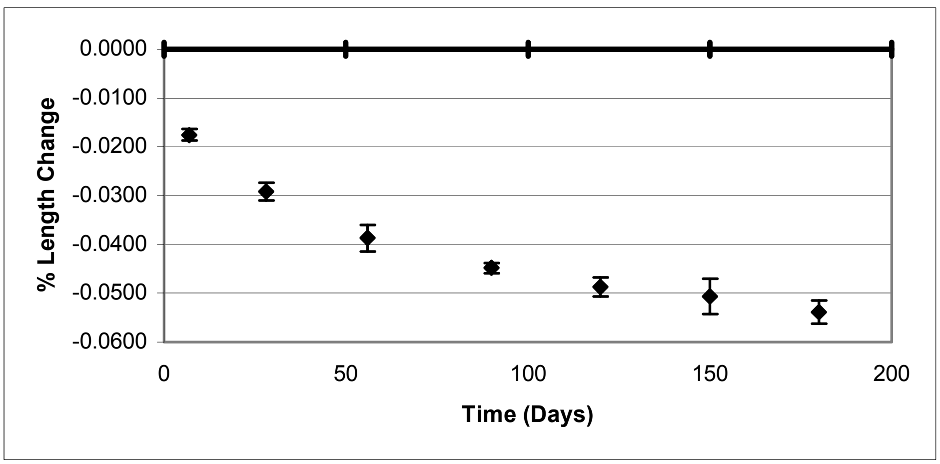

Figure 5.11 Unrestrained Shrinkage for A3 Diabase Mixtures.

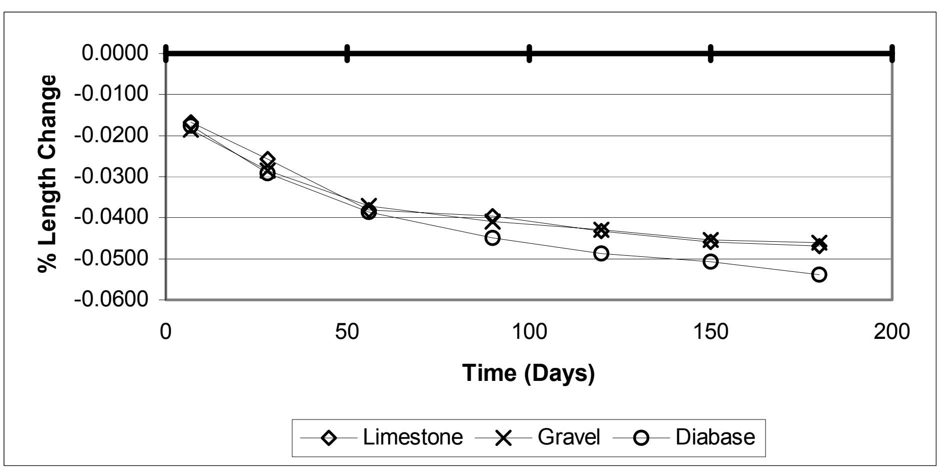

Figure 5.12 Unrestrained Shrinkage for A3 Mixtures.

5.4.2 A4 Portland Cement Concrete Mixtures

Figures 5.13 through 5.15 present the average and 95% confidence limits for the unrestrained shrinkage of the A4 limestone, gravel, and diabase portland cement concrete mixtures. A total of nine prism specimens were tested for each aggregate type. Figure 5.16 presents a comparison of the A4 mixtures. The diabase mixture exhibited the greatest percent shrinkage, while the gravel mixture exhibited the lowest percent shrinkage values for the test series.

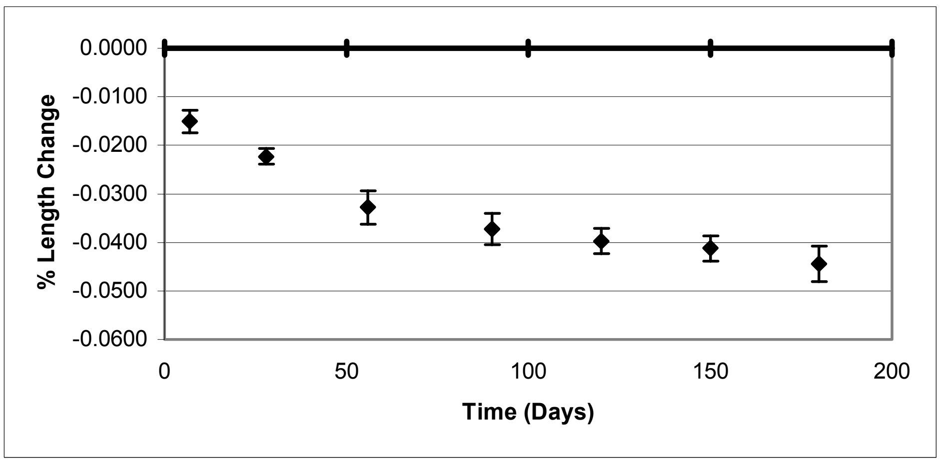

Figure 5.13 Unrestrained Shrinkage for A4 Limestone Mixtures.

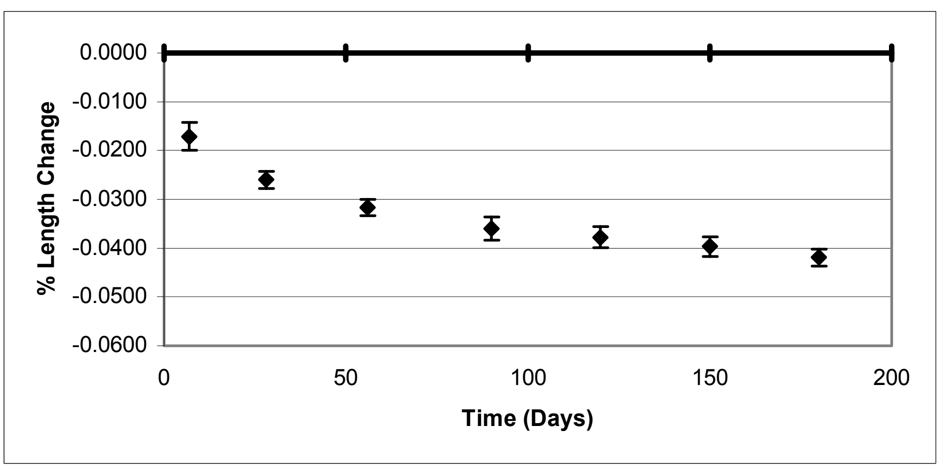

Figure 5.14 Unrestrained Shrinkage for A4 Gravel Mixtures.

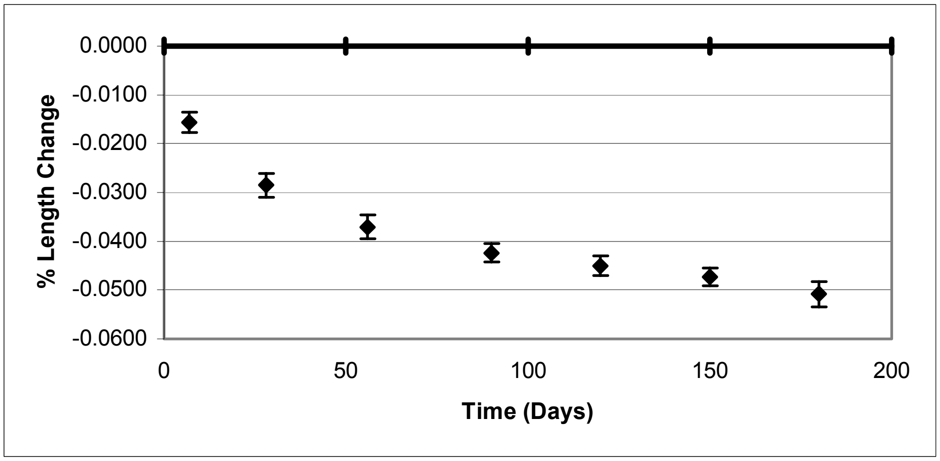

Figure 5.15 Unrestrained Shrinkage for A4 Diabase Mixtures.

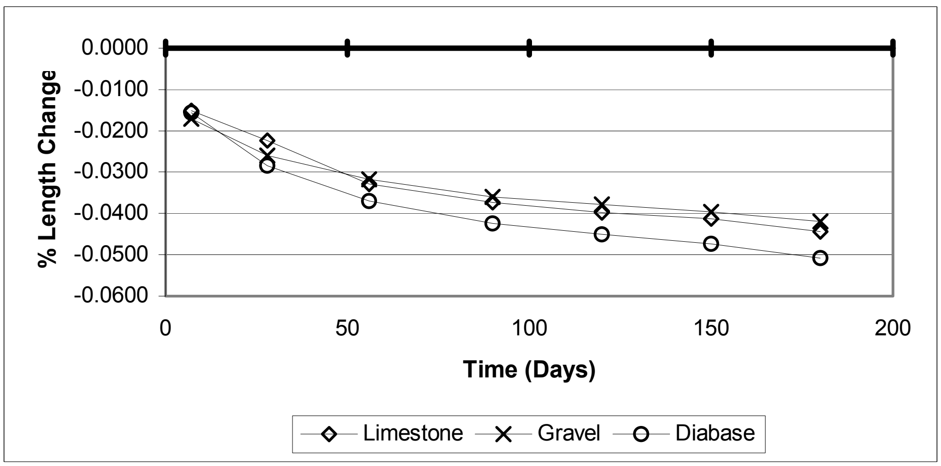

Figure 5.16 Unrestrained Shrinkage for A4 Mixtures.

5.4.3 A5 Portland Cement Concrete Mixtures

Figures 5.17 through 5.19 present the average and 95% confidence limits for the unrestrained shrinkage of the A5 limestone, gravel, and diabase portland cement concrete mixtures. A total of nine prism specimens were tested for each aggregate type. Figure 5.20 presents a comparison of the A5 mixtures. The diabase mixture exhibited the greatest percent shrinkage, while the limestone mixture exhibited the lowest percent shrinkage for the test series.

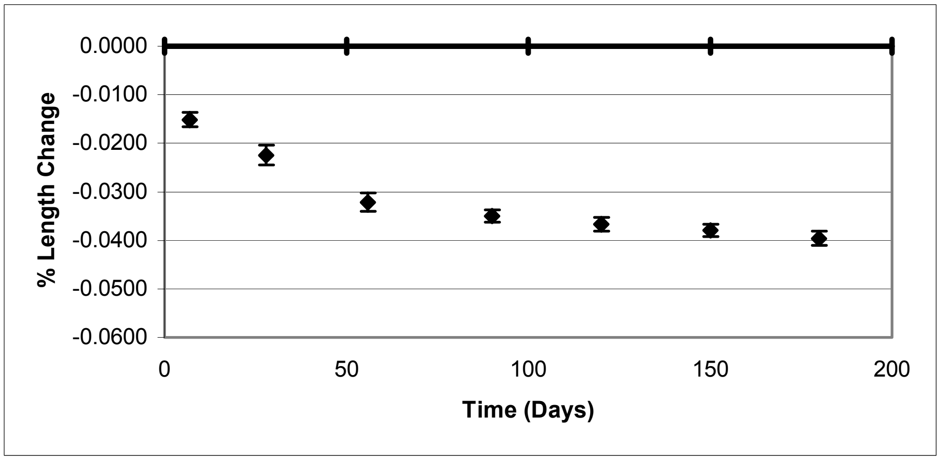

Figure 5.17 Unrestrained Shrinkage for A5 Limestone Mixtures.

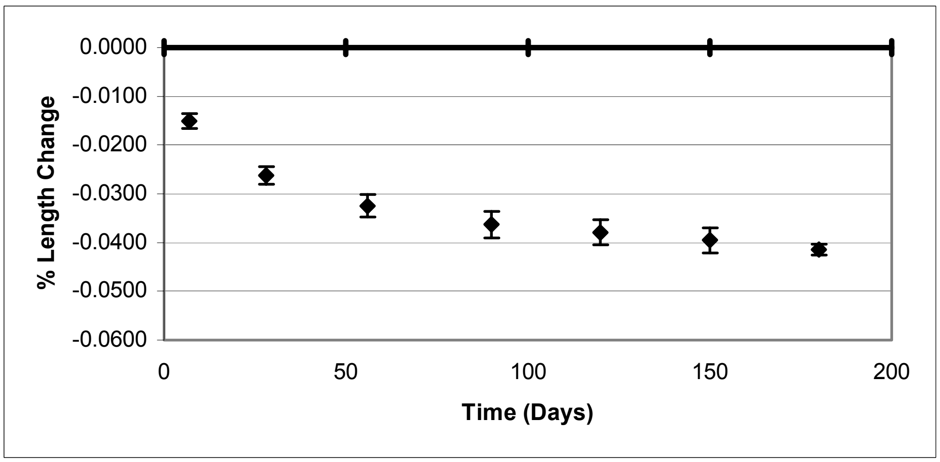

Figure 5.18 Unrestrained Shrinkage for A5 Gravel Mixtures.

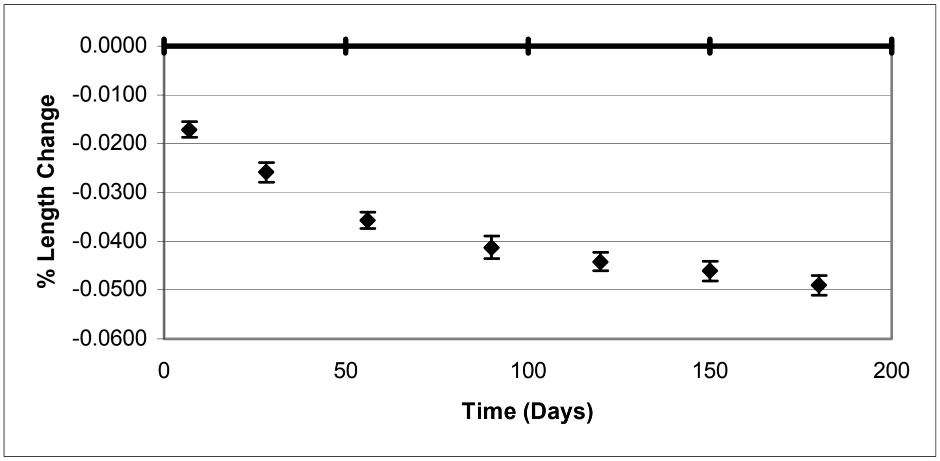

Figure 5.19 Unrestrained Shrinkage for A5 Diabase Mixtures.

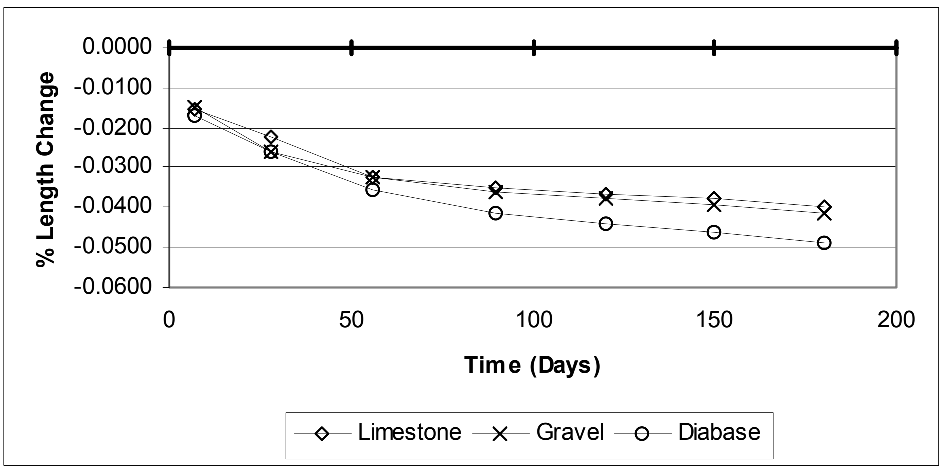

Figure 5.20 Unrestrained Shrinkage for A5 Mixtures.

5.4.4 Supplemental Cementitious Material Mixtures

Figures 5.21 through 5.24 present the average and 95% confidence limits for the unrestrained shrinkage of the A4-Diabase/Fly ash, A4-Diabase/Microsilica, A4-Diabase/Slag cement, and A5-Diabase/Slag cement mixtures. A total of 18 prism specimens were tested for each mixture. Figure 5.25 presents a comparison of the unrestrained shrinkage for the mixtures in test series two. The A4-Diabase/Fly ash mixtures exhibited the greatest percent shrinkage, while the A5-Diabase/Slag cement mixtures exhibited the lowest percent shrinkage for the test series. The mixtures containing slag cement and microsilica all had similar shrinkage values which were significantly lower than the fly ash mixture. Figure 5.25 presents a comparison of the shrinkage values for the mixtures performed in test series two.

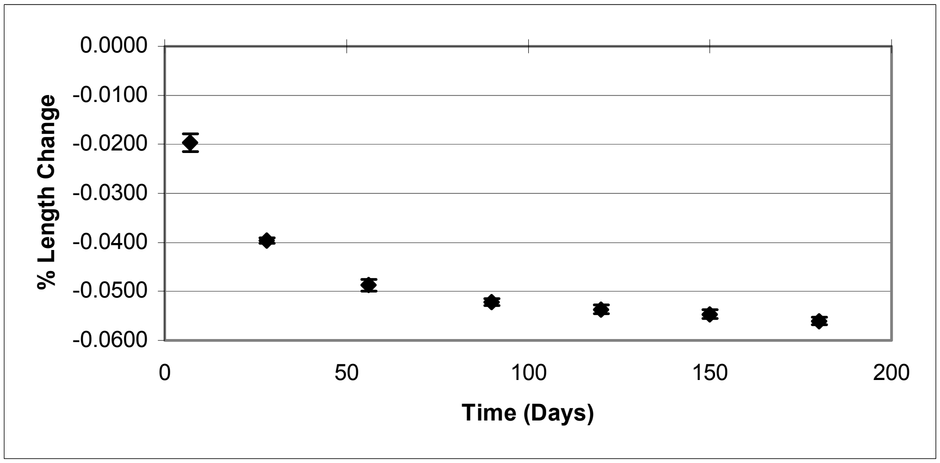

Figure 5.21 Unrestrained Shrinkage for A4-Diabase/Fly Ash Mixtures.

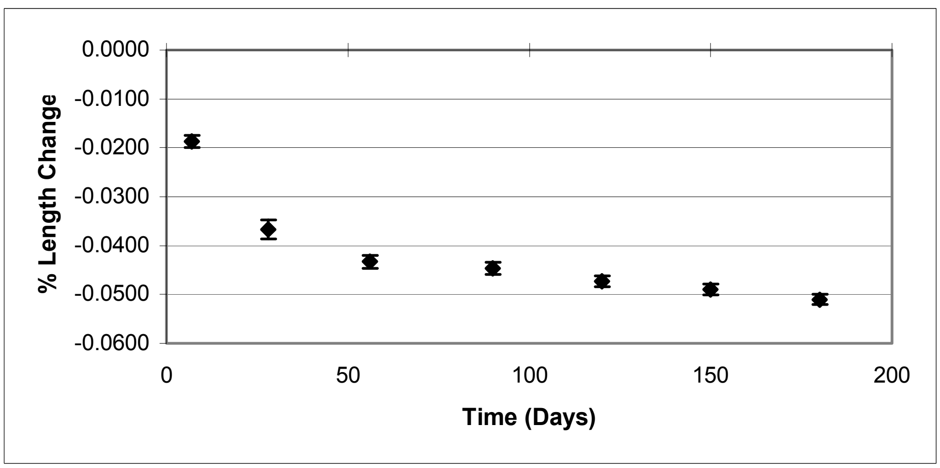

Figure 5.22 Unrestrained Shrinkage for A4-Diabase/Microsilica Mixtures.

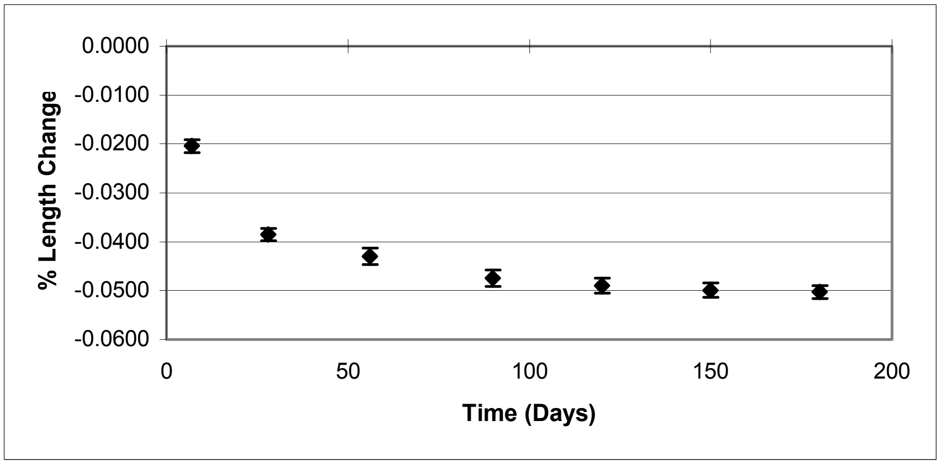

Figure 5.23 Unrestrained Shrinkage for A4-Diabase/Slag Cement Mixtures.

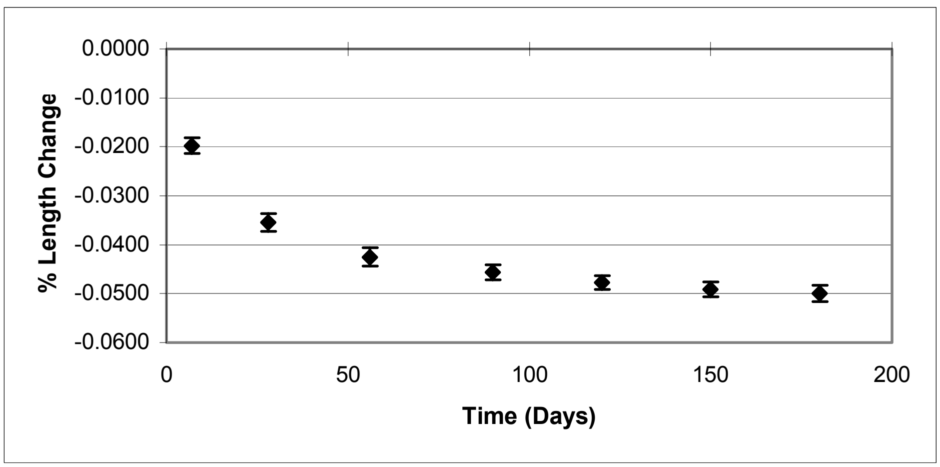

Figure 5.24 Unrestrained Shrinkage for A5-Diabase/Slag Cement Mixtures.

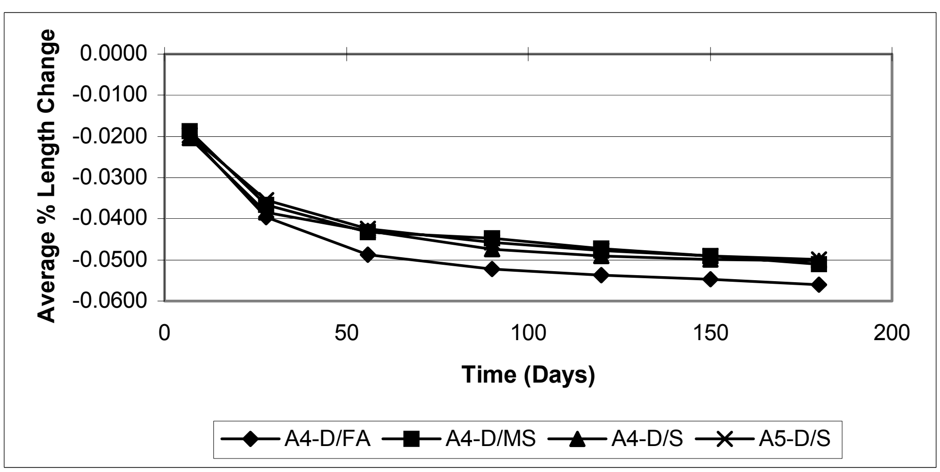

Figure 5.25 Unrestrained Shrinkage for Supplemental Cementitious Material Mixtures.

5.5 Restrained Shrinkage

5.5.1 A3 Portland Cement Concrete Mixtures

Figures 5.26 through 5.28 present the average and 95% confidence limits for restrained shrinkage of the A3 limestone, gravel, and diabase portland cement concrete mixtures. Figure 5.29 presents a comparison of the average microstrain shrinkage of the A3 mixtures. The gravel mixture cracked at 117 days, and the limestone mixture cracked at 125 days. The diabase mixture had not cracked as of 180 days. Figure 5.29 presents a comparison of the A3 mixtures.

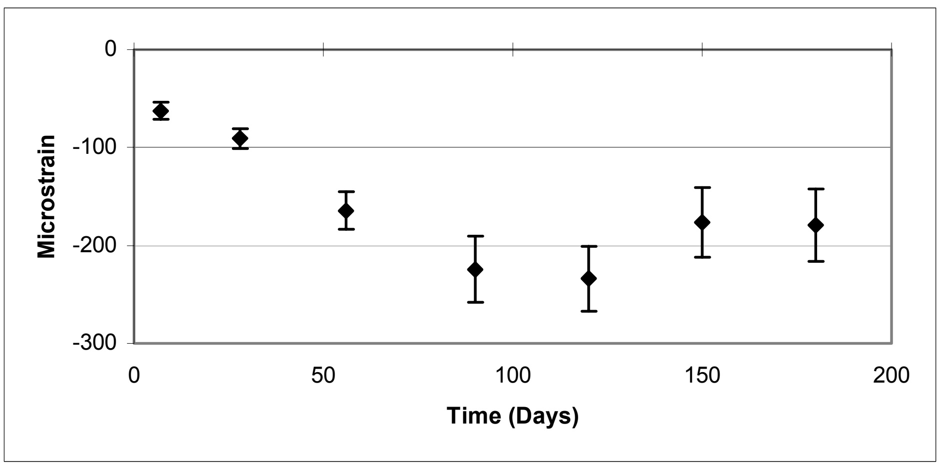

Figure 5.26 Restrained Shrinkage for A3 Limestone Mixture.

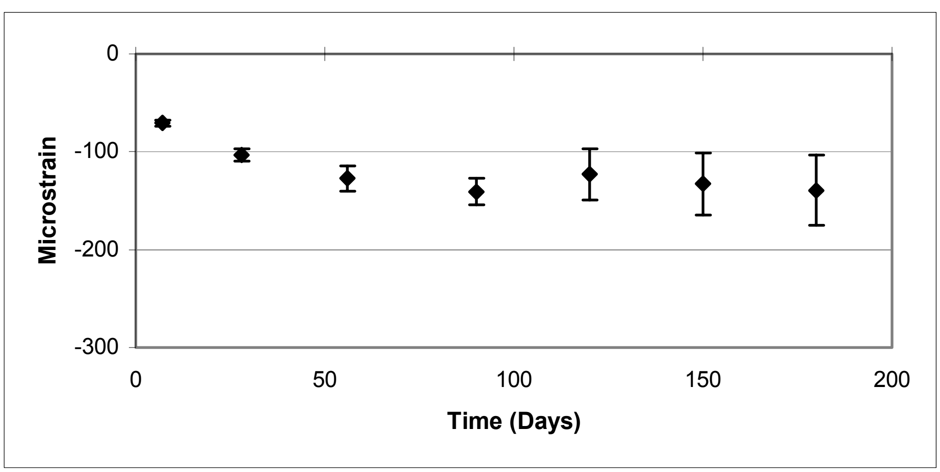

Figure 5.27 Restrained Shrinkage for A3 Gravel Mixture.

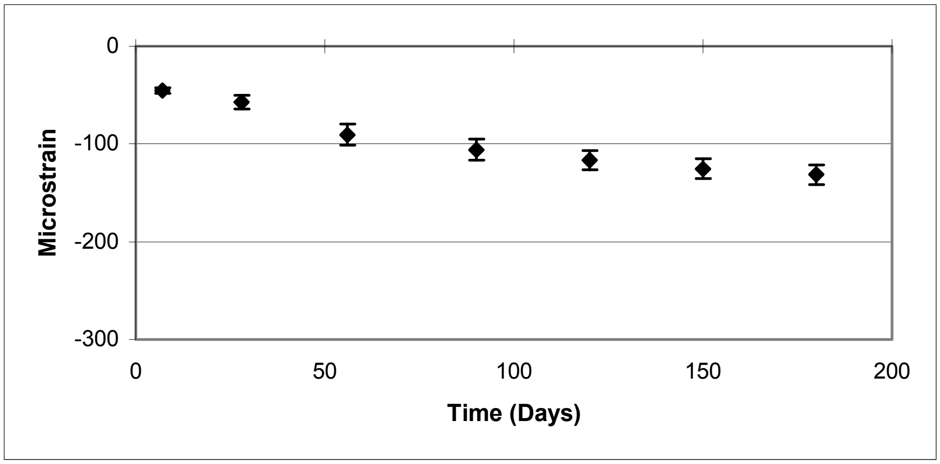

Figure 5.28 Restrained Shrinkage for A3 Diabase Mixture.

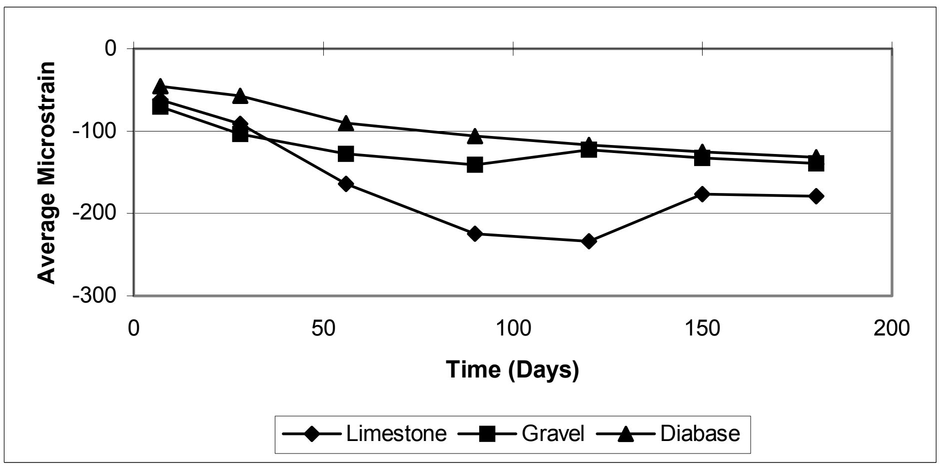

Figure 5.29 Restrained Shrinkage for A3 Portland Cement Concrete Mixtures.

5.5.2 A4 Portland Cement Concrete Mixtures

Figures 5.30 through 5.32 present the average and 95% confidence limits for the restrained shrinkage of the A4 limestone, gravel, and diabase portland cement concrete mixtures. Figure 5.33 presents a comparison of the average microstrain shrinkage for the A4 mixtures. As of 180 days, none of the A4 specimens had cracked.

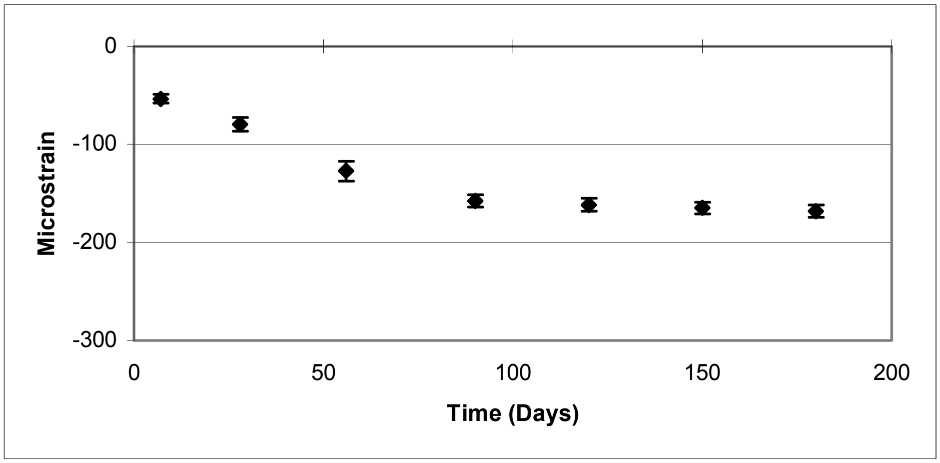

Figure 5.30 Restrained Shrinkage for A4 Limestone Mixture.

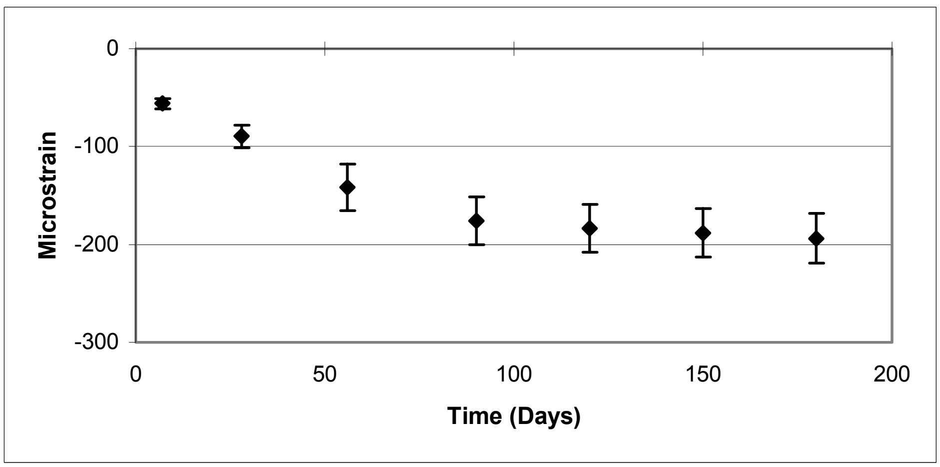

Figure 5.31 Restrained Shrinkage for A4 Gravel Mixture.

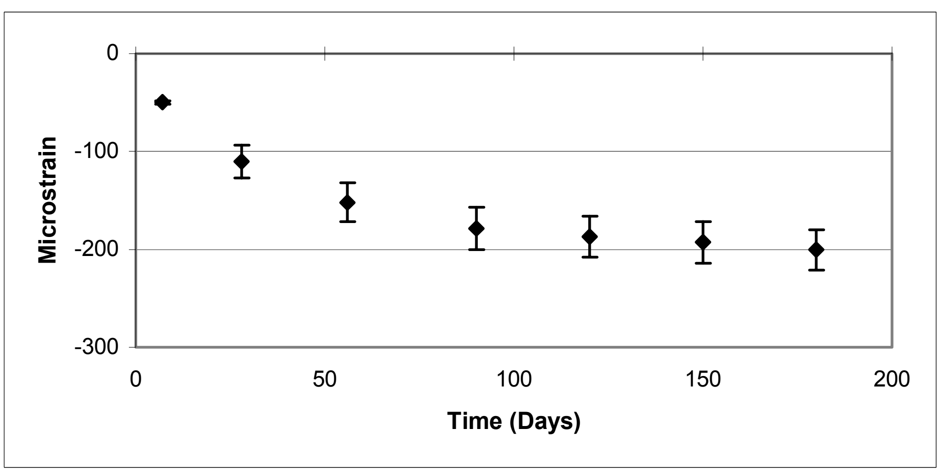

Figure 5.32 Restrained Shrinkage for A4 Diabase Mixture.

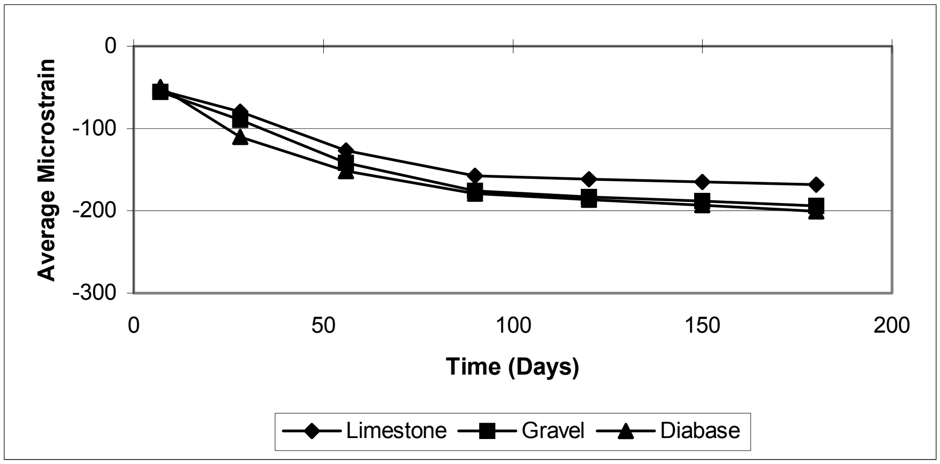

Figure 5.33 Restrained Shrinkage for A4 Portland Cement Concrete Mixtures.

5.5.3 A5 Portland Cement Concrete Mixtures

Figures 5.34 through 5.36 present the average and 95% confidence limits for the restrained shrinkage of the A5 limestone, gravel, and diabase portland cement concrete mixtures. Figure 5.37 presents a comparison of the average microstrain shrinkage of the A5 mixtures. The diabase mixture cracked at 165 days, while the gravel mixture cracked at 172 days. The limestone mixture specimens had not cracked as of 180 days.

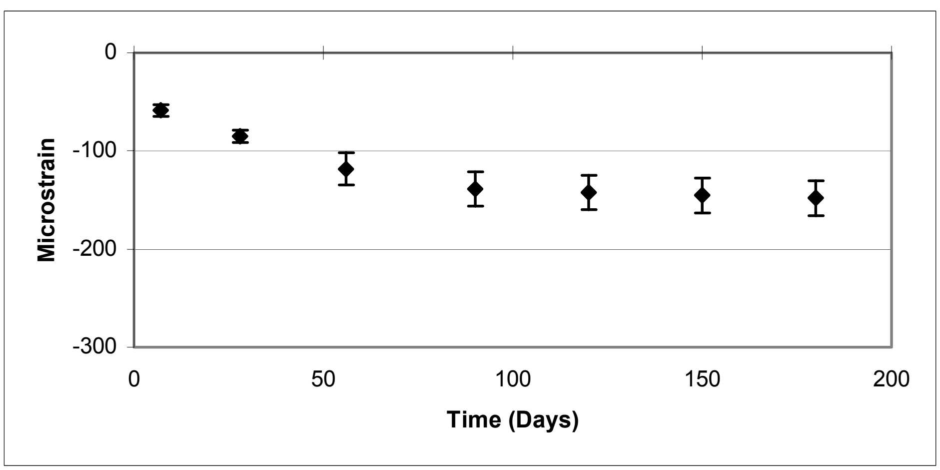

Figure 5.34 Restrained Shrinkage for A5 Limestone Mixture.

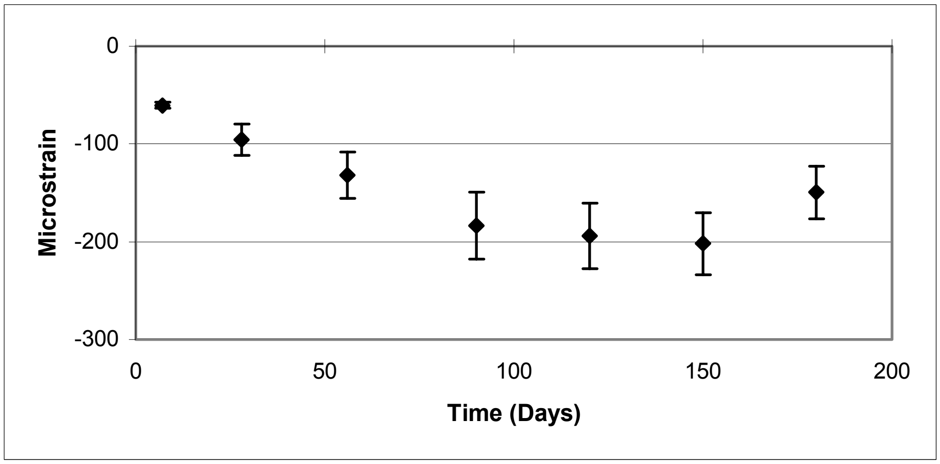

Figure 5.35 Restrained Shrinkage for A5 Gravel Mixture.

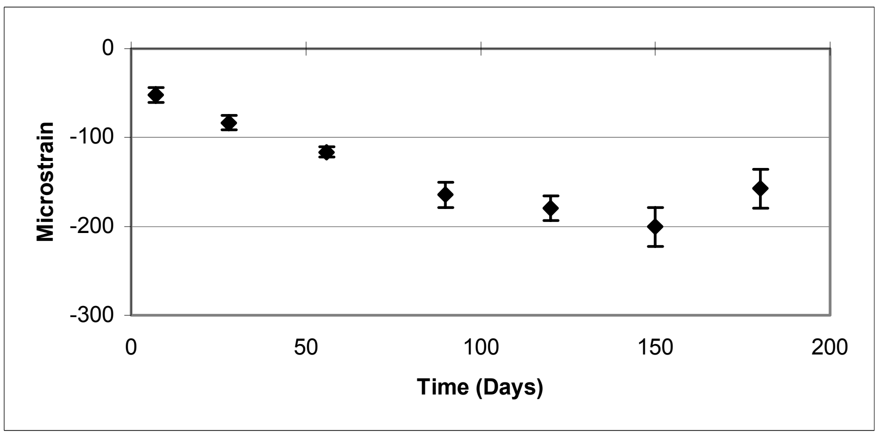

Figure 5.36 Restrained Shrinkage for A5 Diabase Mixture.

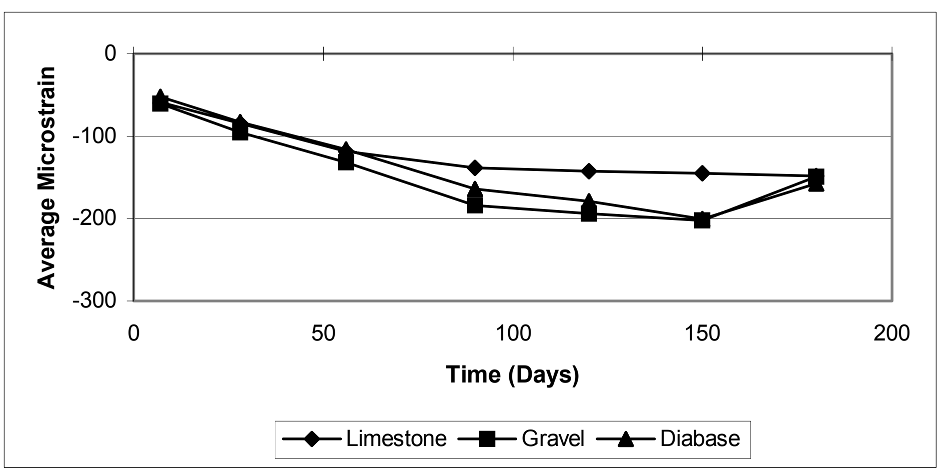

Figure 5.37 Restrained Shrinkage for A5 Portland Cement Concrete Mixtures.

5.5.4 Supplemental Cementitious Material Mixtures

Figures 5.38 through 5.41 present the average and 95% confidence limits for the restrained shrinkage of the A4-Diabase/Fly ash, A4-Diabase/Microsilica, A4-Diabase/Slag cement, and A5-Diabase/Slag cement mixtures. Figure 5.42 presents a comparison of the supplemental cementitious material mixtures. As of 180 days, none of the specimens had cracked. The fly ash mixture exhibited the greatest percent shrinkage strain, while the slag cement and microsilica mixtures all had similar strain values which were less than the strain in the fly ash mixtures.

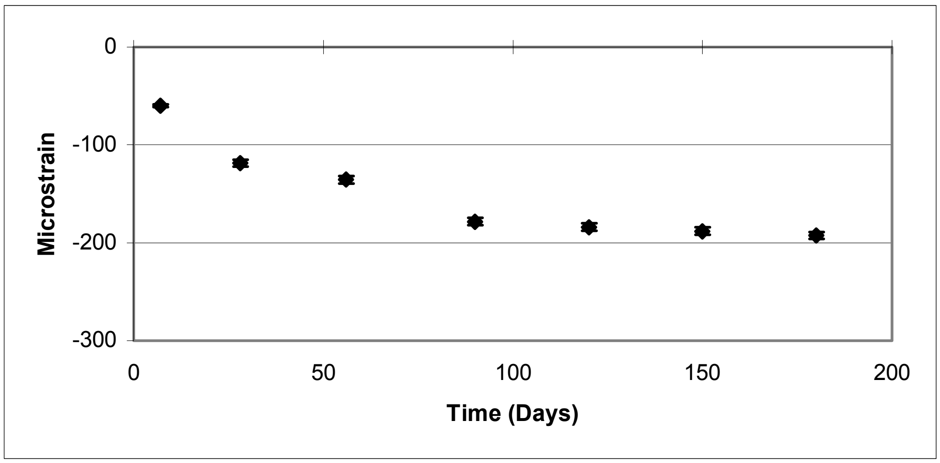

Figure 5.38 Restrained Shrinkage for A4-Diabase/Fly Ash Mixtures.

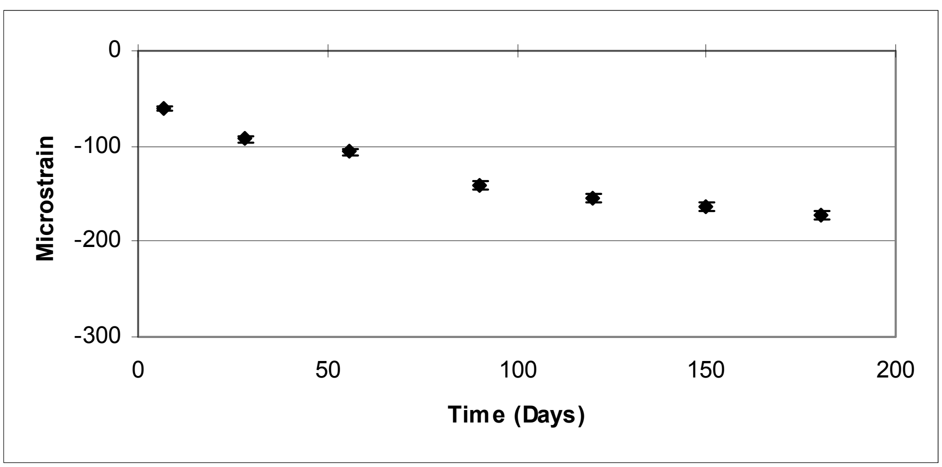

Figure 5.39 Restrained Shrinkage for A4-Diabase/Microsilica Mixtures.

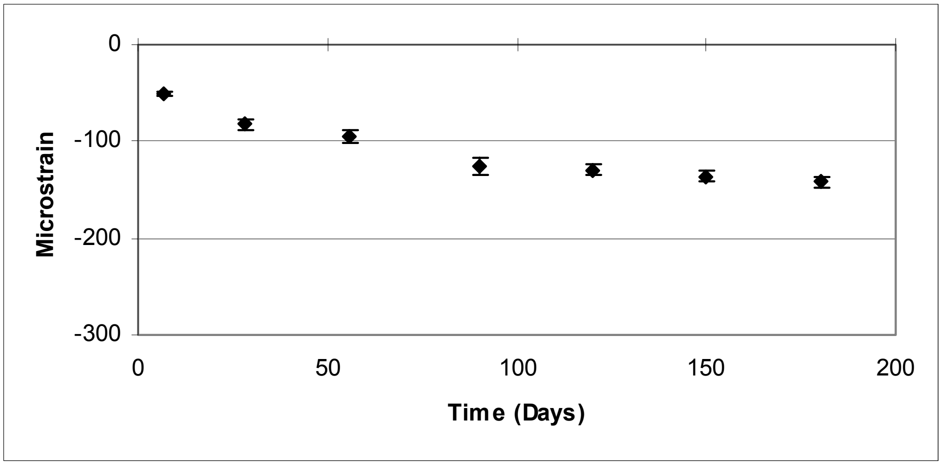

Figure 5.40 Restrained Shrinkage for A4-Diabase/Slag Cement Mixtures.

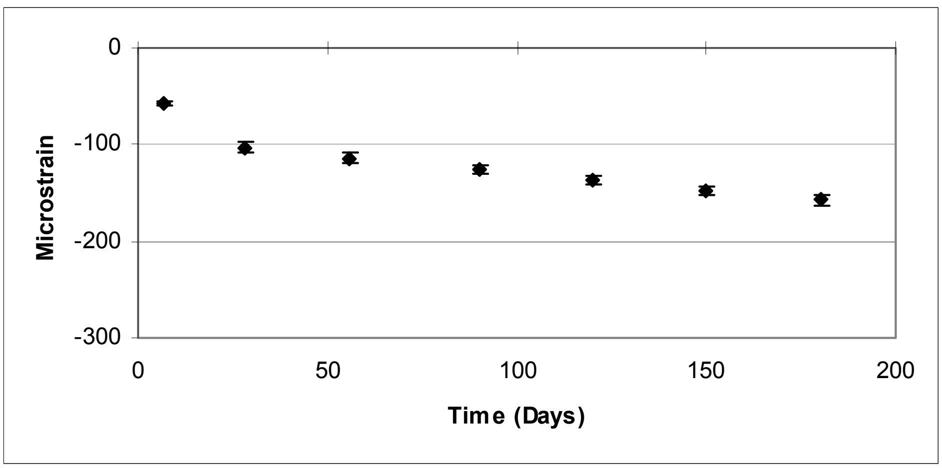

Figure 5.41 Restrained Shrinkage for A5-Diabase/Slag Cement Mixtures.

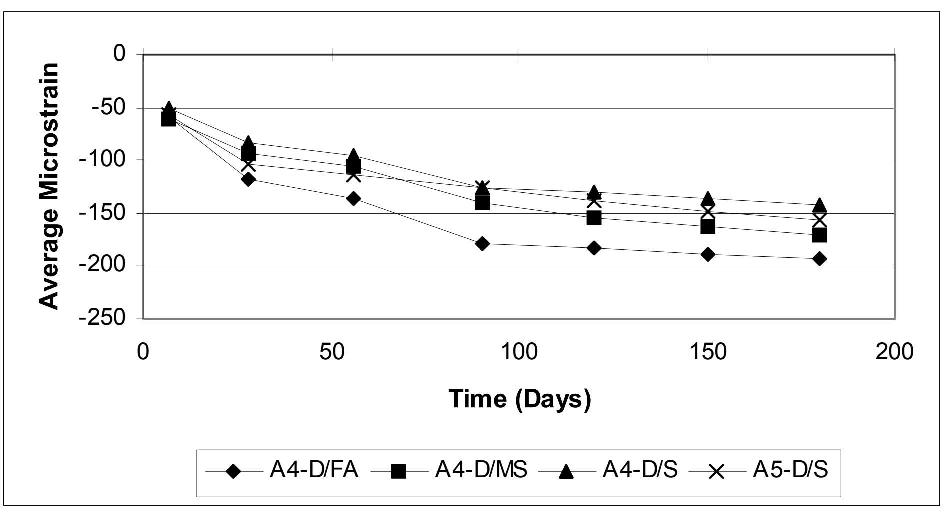

Figure 5.42 Restrained Shrinkage for Supplemental Cementitious Material Mixtures.

Table 5.1 presents a summary of the restrained shrinkage specimens. As shown, those specimens which have cracked within 180 days had an estimated microstrain of greater than 200 microstrain, and those that have not cracked were 200 microstrain and less.

Table 5.1 Summary of Shrinkage(microstrain) and Age at Cracking.

		Microstrain		Cracking	
Mixtures	28 Days	90 Days	180 Days	Days	Estimated με
A3/PCC					
Limestone	-91	-224	---	125	-240
Gravel	-103	-141	---	117	-210
Diabase	-57	-106	-132	*	*
A4/PCC					
Limestone	-80	-157	-168	*	*
Gravel	-90	-176	-194	*	*
Diabase	-110	-179	-200	*	*
A5/PCC					
Limestone	-85	-139	-148	*	*
Gravel	-96	-184	---	172	-220
Diabase	-83	-164	---	165	-210
A4/SCM					
Fly ash	-119	-178	-193	*	*
Microsilica	-93	-141	-172	*	*
Slag cement	-53	-122	-142	*	*
A5/SCM					
Slag cement	-103	-125	-157	*	*

* Specimens which have not cracked as of 180 days.

5.6 Prediction Models

5.6.1 Introduction

The percent shrinkage was calculated for each of the five models at seven, 28, 56, 90, 120, 150, and 180 days after shrinkage had commenced. A residual value for each measured unrestrained shrinkage specimen was calculated as follows:

$$\text{Residual Value} = \text{Predicted Value} - \text{Measured (Experimental) Value} \quad \text{(Eq. 1)}$$

Thus, if the residual value was positive, it indicated that the model over estimated the shrinkage. If the residual value was negative, it indicated that the model underestimated the shrinkage. The ACI 209 and Sakata models are applicable for only Type I General and Type III High Early Strength cements. Therefore, residuals were not calculated for the A4-Diabase/Fly ash, A4-Diabase/Slag cement, and A5-Diabase/Slag cement mixtures for the ACI 209 and Sakata models, because these cementing materials hydrate at a slower rate than a Type I or Type III cement. They are closer to a Type II Low Heat cement.

5.6.2 Limestone Mixtures

Figures 5.43 through 5.47 present the calculated residuals for the five models for the A3, A4, and A5 portland cement limestone mixtures. As shown, the ACI 209 and Sakata model residuals are much larger than the Bazant, CEB90, and Gardner/Lockman models. This is also generally true for the remaining portland cement mixtures, where applicable.

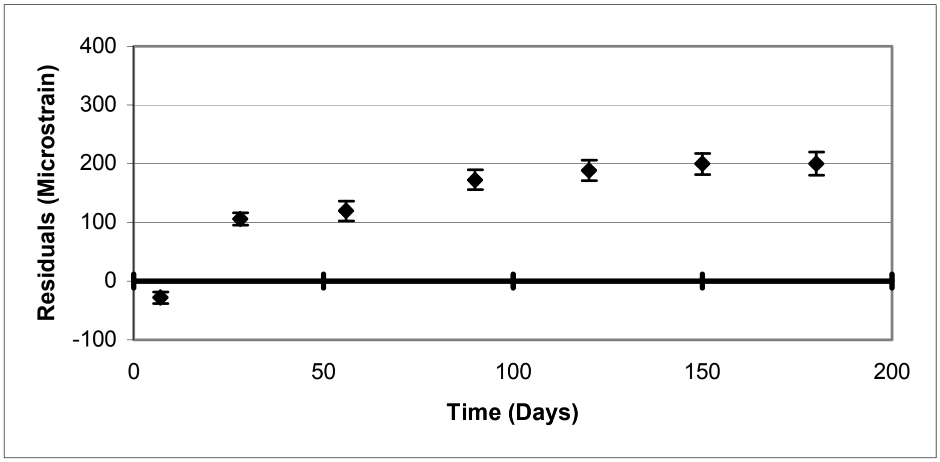

Figure 5.43 ACI 209 Residuals for Limestone Mixtures.

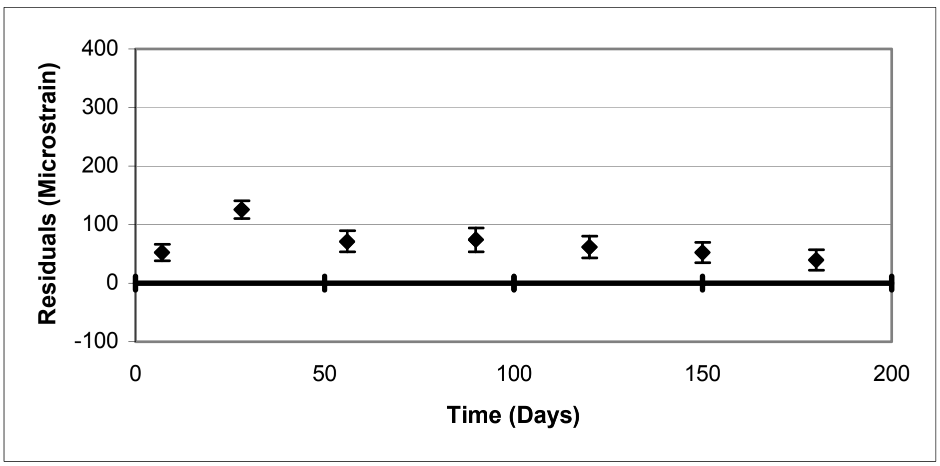

Figure 5.44 Bazant B3 Residuals for Limestone Mixtures.

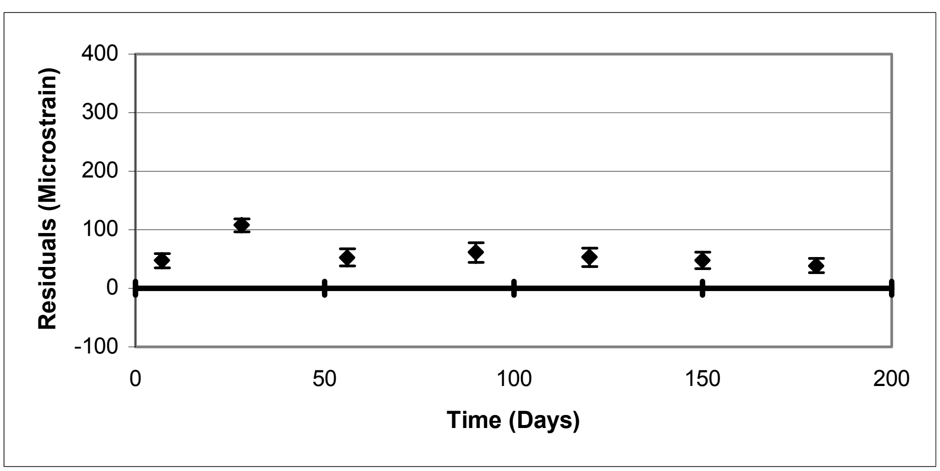

Figure 5.45 CEB90 Residuals for Limestone Mixtures.

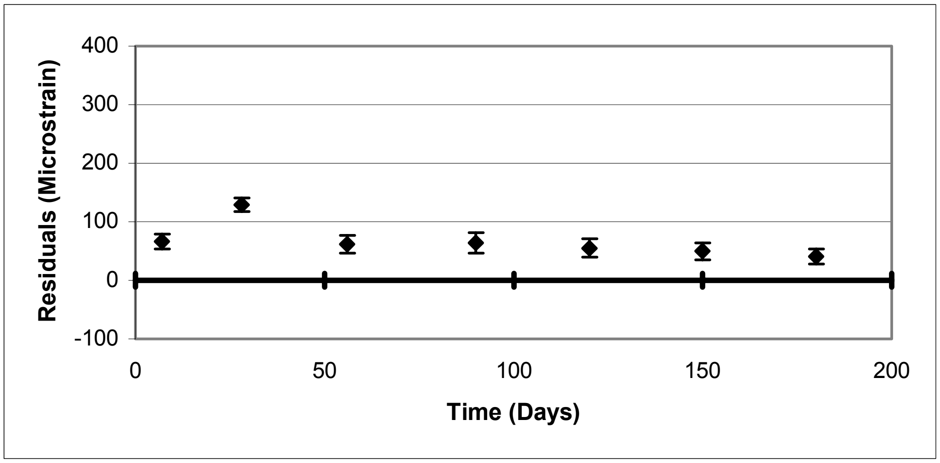

Figure 5.46 Gardner/Lockman Residuals for Limestone Mixtures.

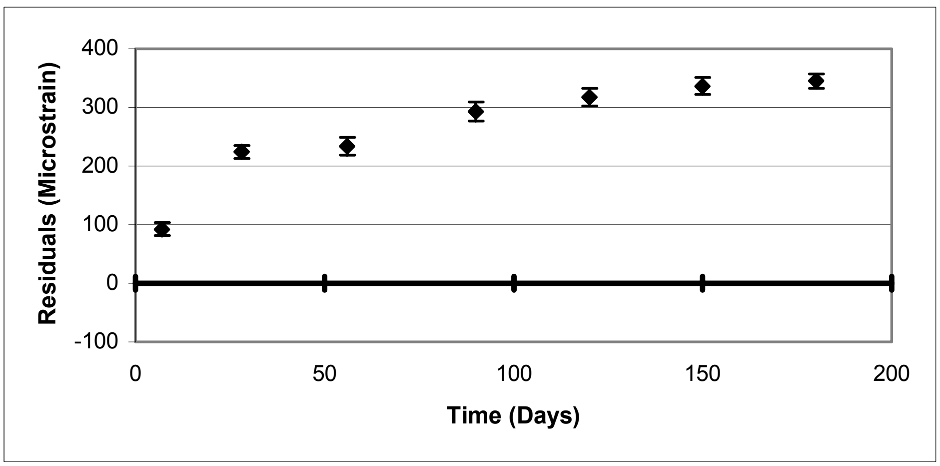

Figure 5.47 Sakata Residuals for Limestone Mixtures.

5.6.3 Gravel Mixtures

Figures 5.48 through 5.52 present the residuals for the five models for the A3, A4, and A5 portland cement gravel mixtures.

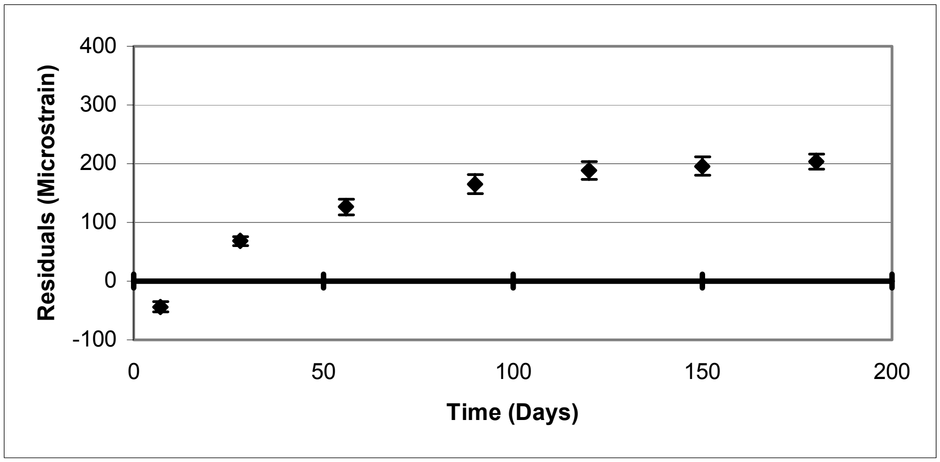

Figure 5.48 ACI 209 Residuals for Gravel Mixtures.

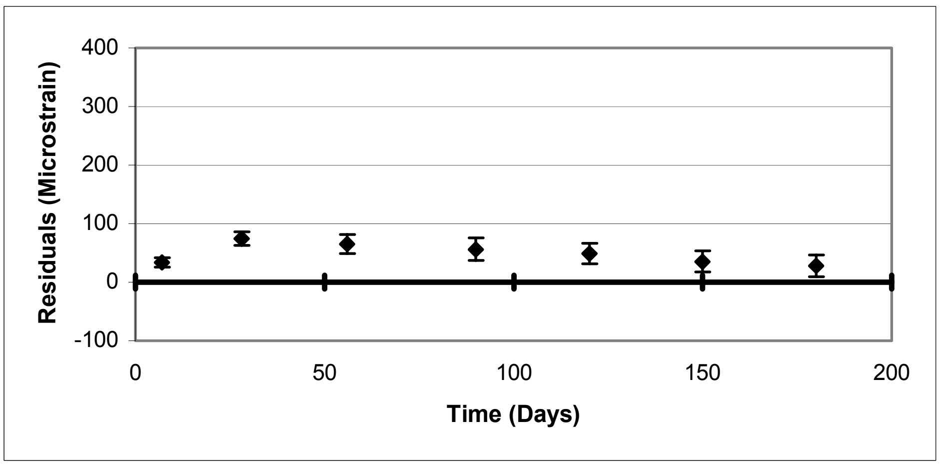

Figure 5.49 Bazant B3 Residuals for Gravel Mixtures.

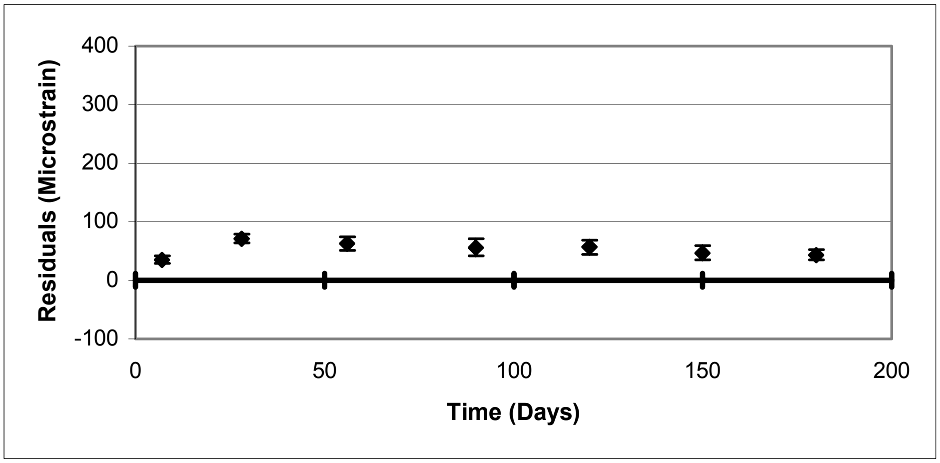

Figure 5.50 CEB90 Residuals for Gravel Mixtures.

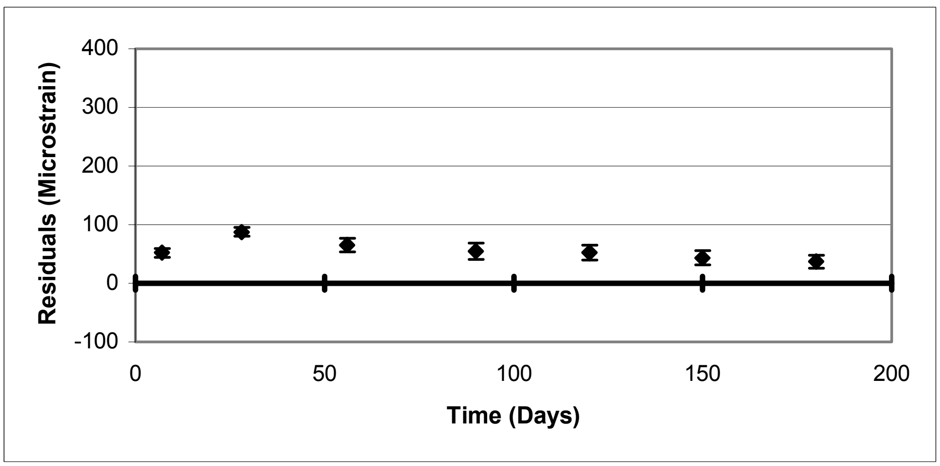

Figure 5.51 Gardner/Lockman Residuals for Gravel Mixtures.

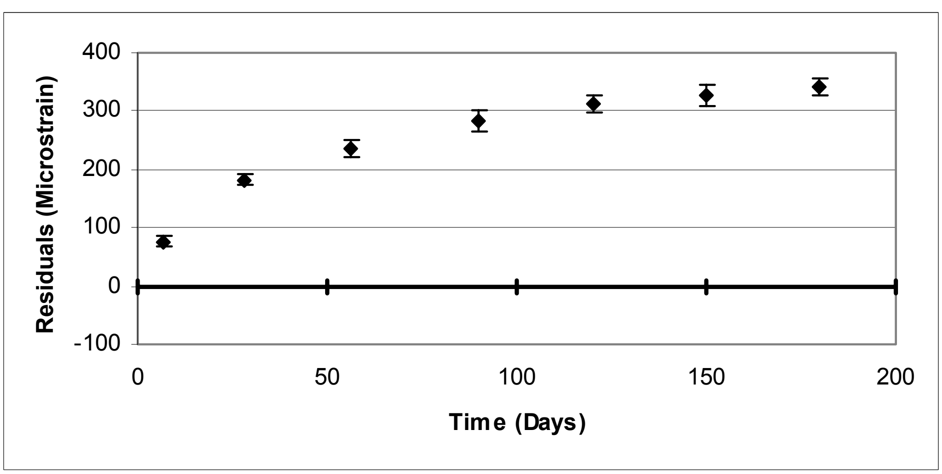

Figure 5.52 Sakata Residuals for Gravel Mixtures.

5.6.4 Diabase Portland Cement Concrete Mixtures

Figures 5.53 through 5.57 present the calculated residuals for the five models for the A3, A4, and A5 portland cement diabase mixtures.

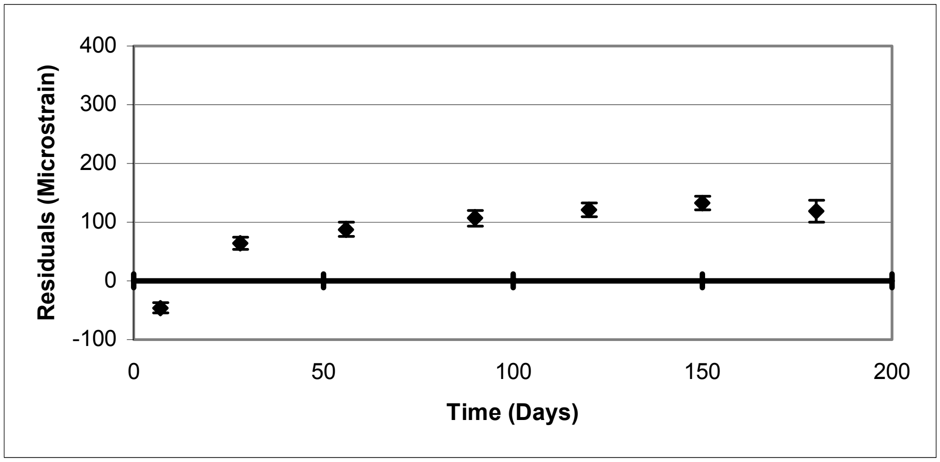

Figure 5.53 ACI 209 Residual for Diabase Mixtures

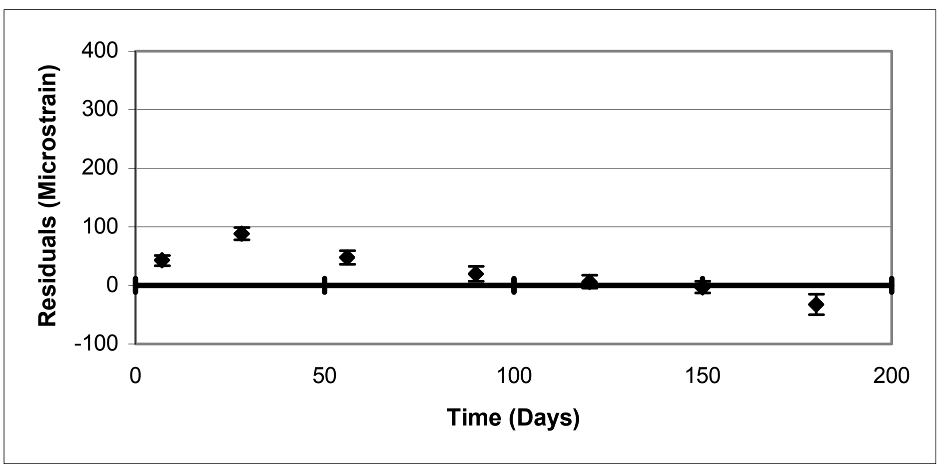

Figure 5.54 Bazant B3 Residuals for Diabase Mixtures

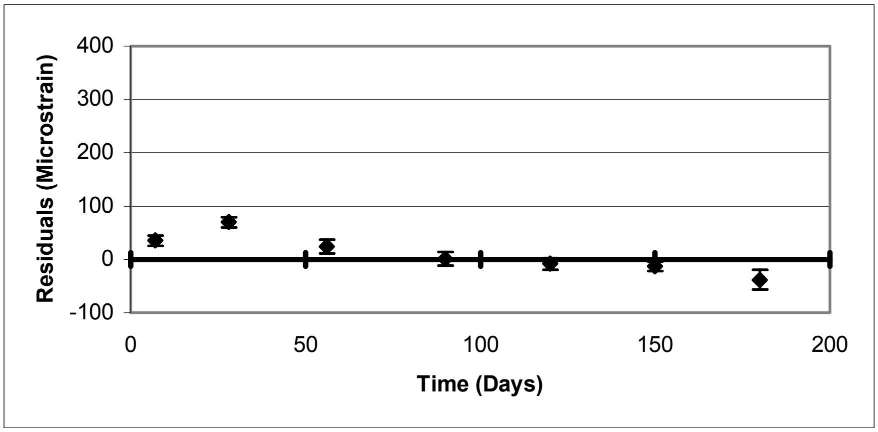

Figure 5.55 CEB90 Residuals for Diabase Mixtures.

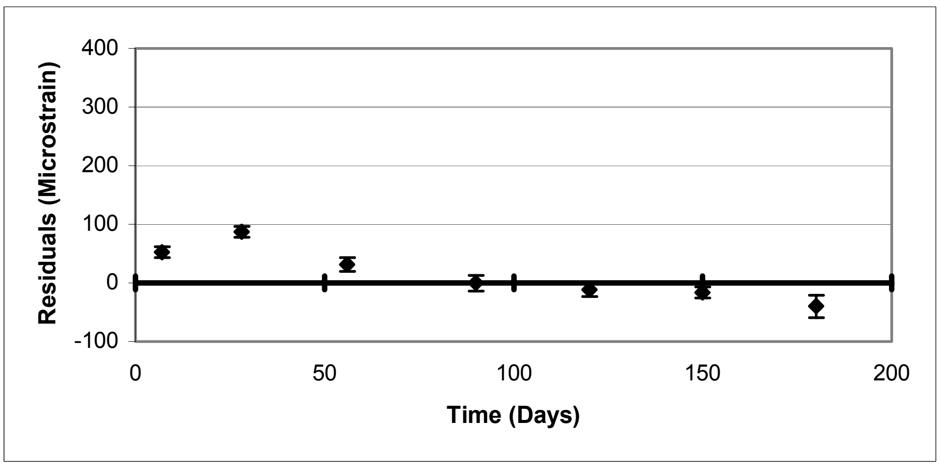

Figure 5.56 Gardner/Lockman Residuals for Diabase Mixtures.

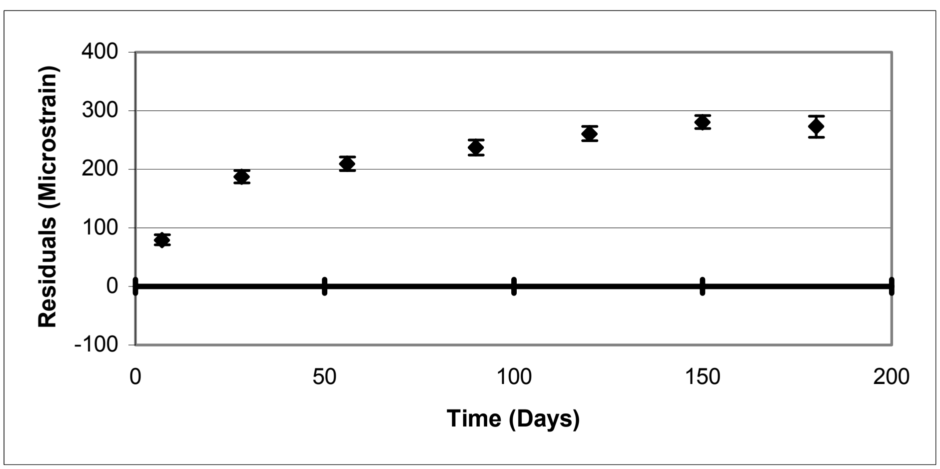

Figure 5.57 Sakata Residuals for Diabase Mixtures.

5.6.5 A4-Diabase/Fly Ash Mixtures

Figures 5.58 through 5.60 present the calculated residuals for Bazant B3, CEB90, and the Gardner/Lockman models for the A4-diabase/fly ash mixtures. As shown, all three models underpredicted the shrinkage at all ages.

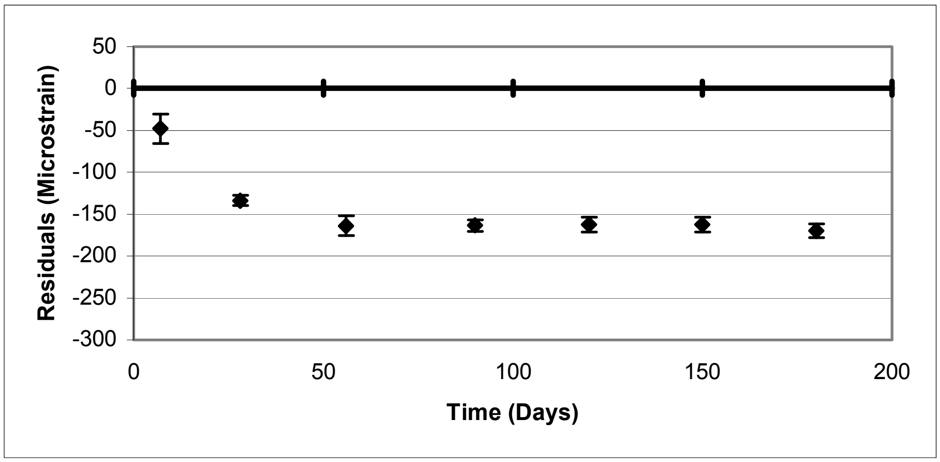

Figure 5.58 Bazant B3 Residuals for A4-Diabase/Fly Ash Mixtures.

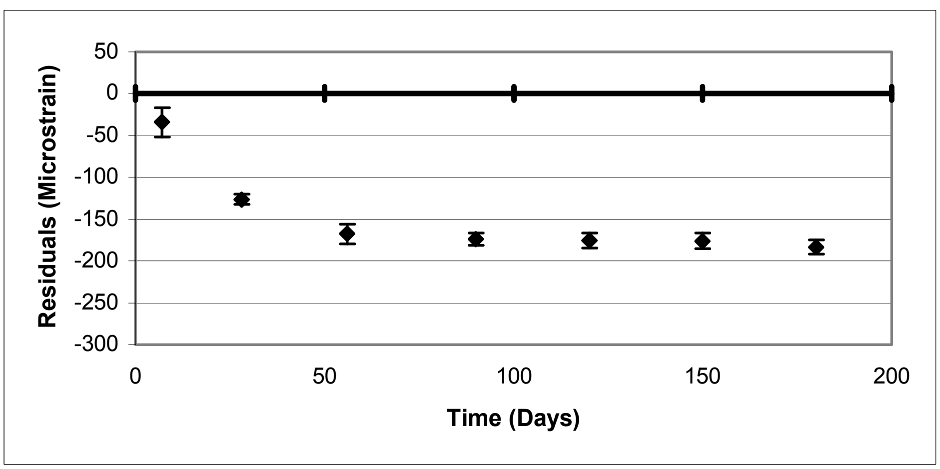

Figure 5.59 CEB90 Residuals for A4-Diabase/Fly Ash Mixtures.

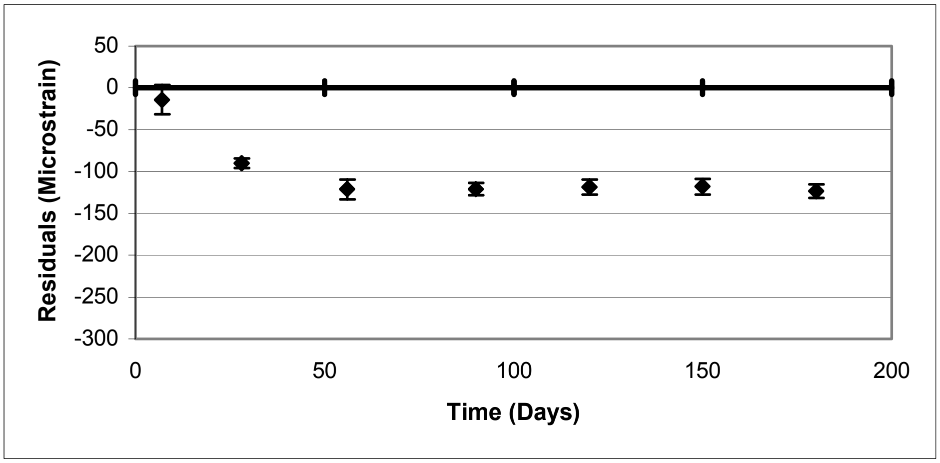

Figure 5.60 Gardner/Lockman Residuals for A4-Diabase/Fly Ash Mixtures.

5.6.6 A4-Diabase/Microsilica Mixtures

Figures 5.61 through 5.65 present the calculated residuals for the five models for the A4-diabase/microsilica mixtures. The ACI 209 model underpredicted the shrinkage at early ages and overpredicted the shrinkage at later ages, greater than 50 days. The Bazant B3, CEB90, and Gardner/Lockman models underpredicted the shrinkage at all ages. The Sakata model overpredicted the shrinkage at all ages.

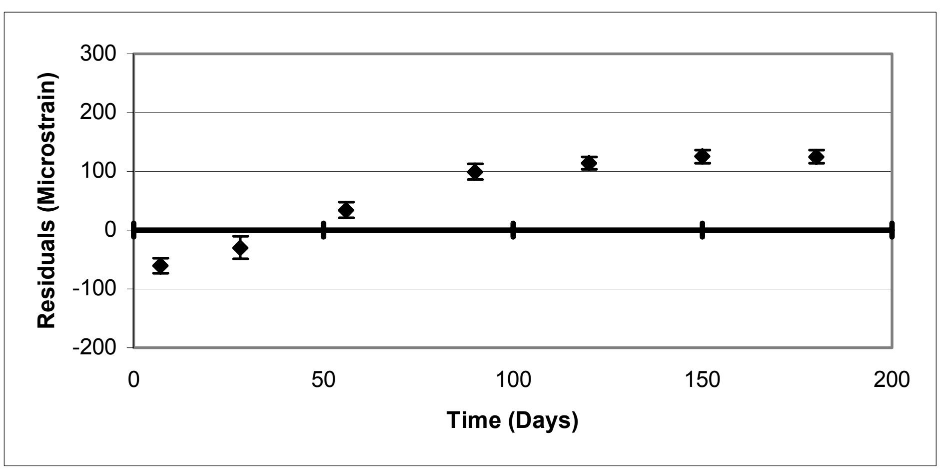

Figure 5.61 ACI 209 Residual for A4-Diabase/Microsilica Mixtures.

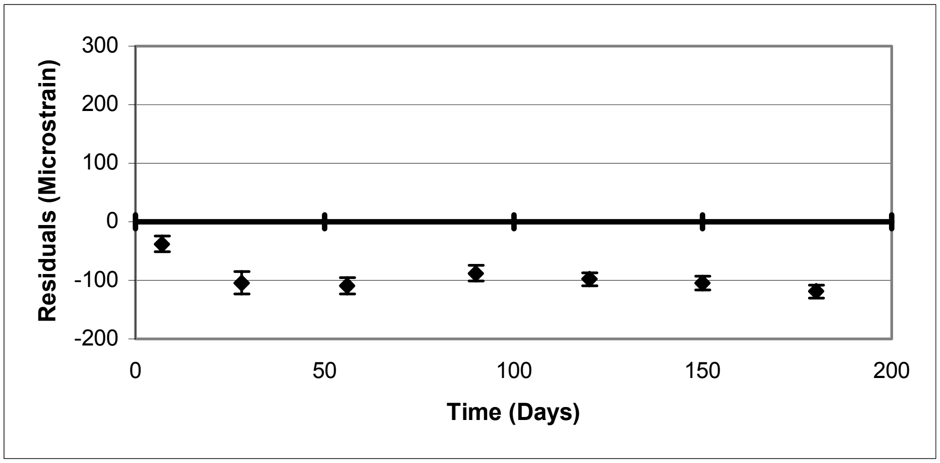

Figure 5.62 Bazant B3 Residuals for A4-Diabase/Microsilica Mixtures.

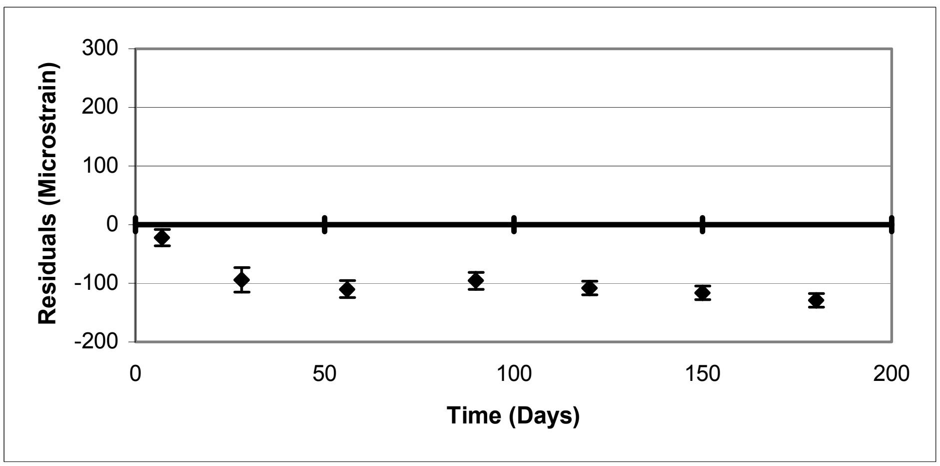

Figure 5.63 CEB90 Residuals for A4-Diabase/Microsilica Mixtures.

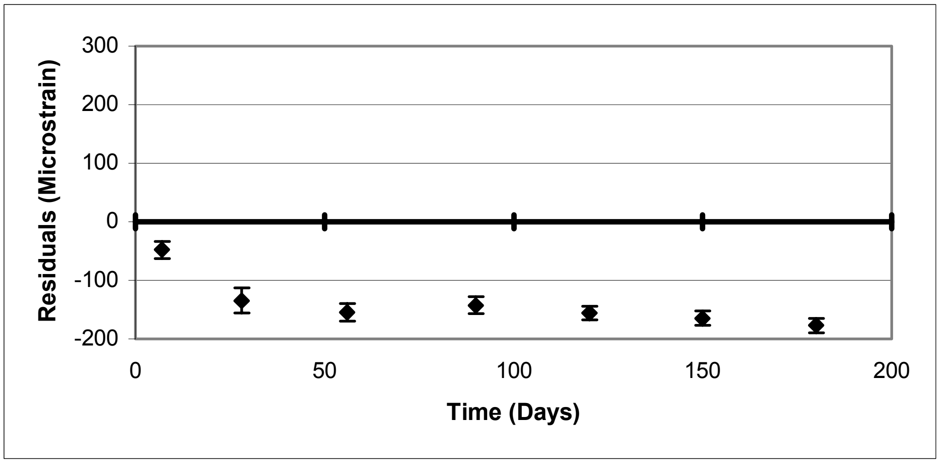

Figure 5.64 Gardner/Lockman Residuals for A4-Diabase/Microsilica Mixtures.

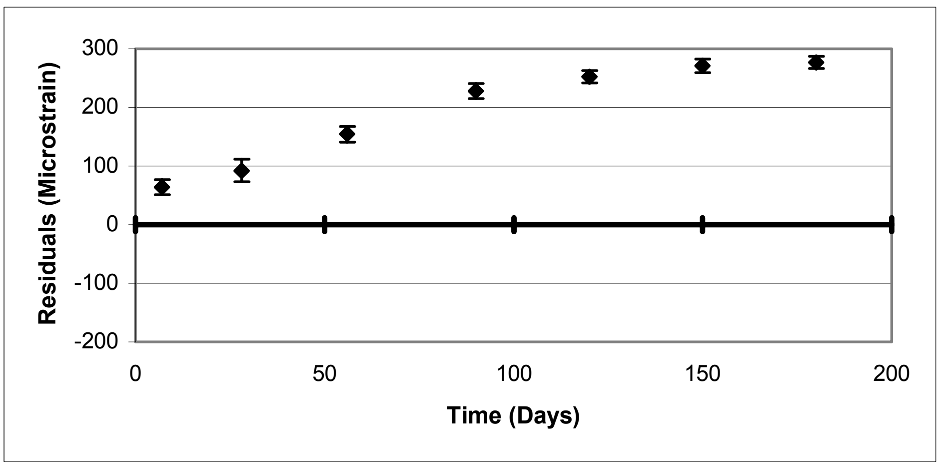

Figure 5.65 Sakata Residuals for A4-Diabase/Microsilica Mixtures.

5.6.7 A4-Diabase/Slag Cement Mixtures

Figures 5.66 through 5.68 present the calculated residuals for three models for the A4-diabase/slag cement mixtures.

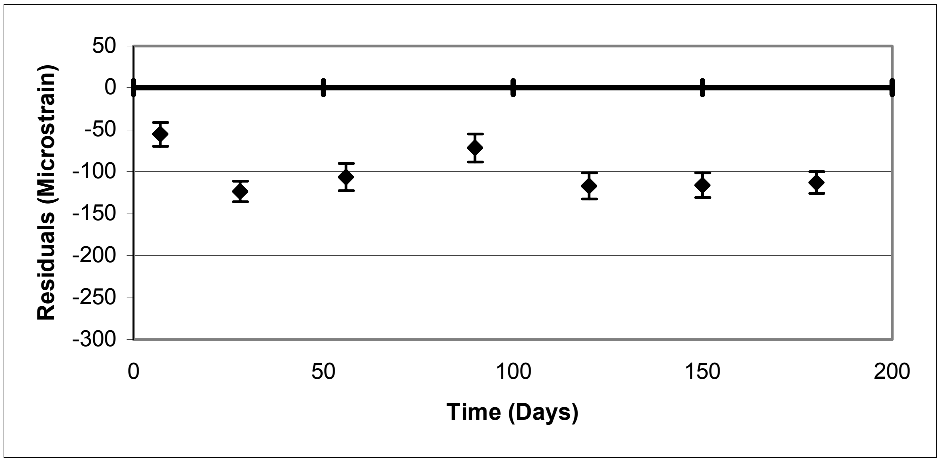

Figure 5.66 Bazant B3 Residuals for A4-Diabase/Slag Cement Mixtures.

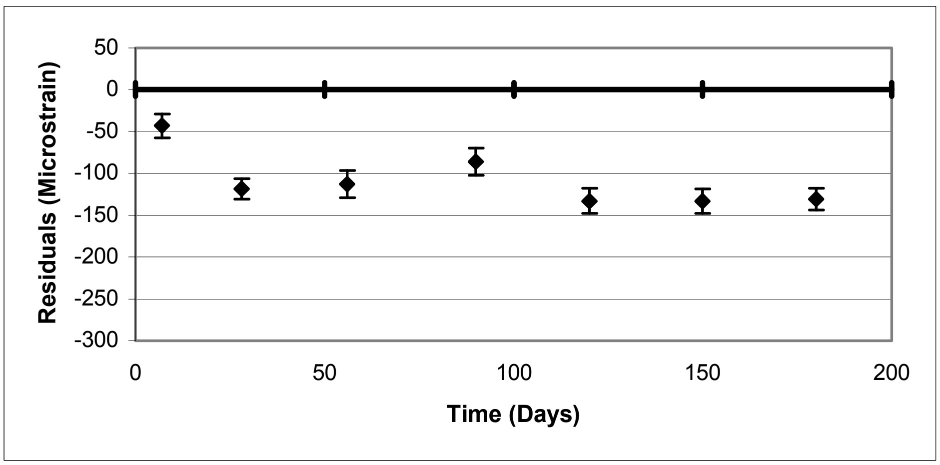

Figure 5.67 CEB90 Residuals for A4-Diabase/Slag Cement Mixtures.

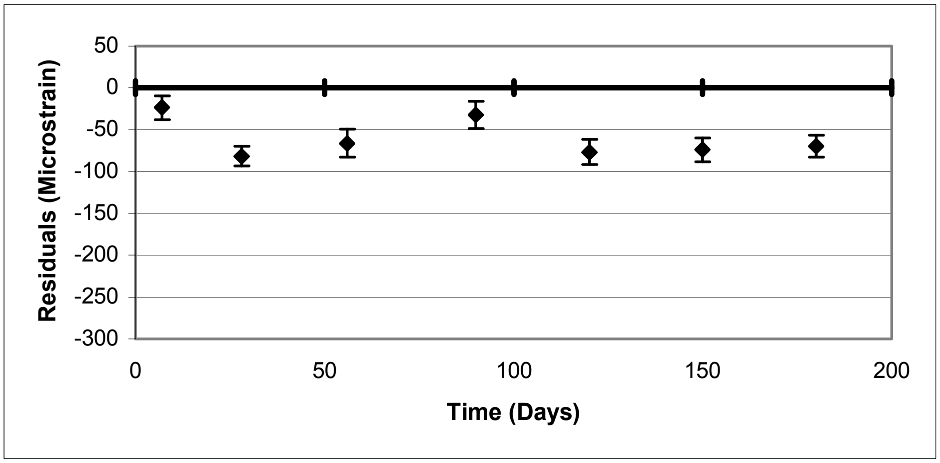

Figure 5.68 Gardner/Lockman Residuals for A4-Diabase/Slag Cement Mixtures.

5.6.8 A5-Diabase/Slag Cement Mixtures

Figures 5.69 through 5.71 present the calculated residuals for the Bazant B3, CEB90, and Gardner/Lockman models for the A5-diabase/slag cement mixtures. As shown, the three models underpredicted the shrinkage for the A5-diabase/slag cement mixtures. These results are consistent throughout the supplemental cementitious material mixtures, where these three models have underpredicted the shrinkage for the supplemental cementitious material mixture types.

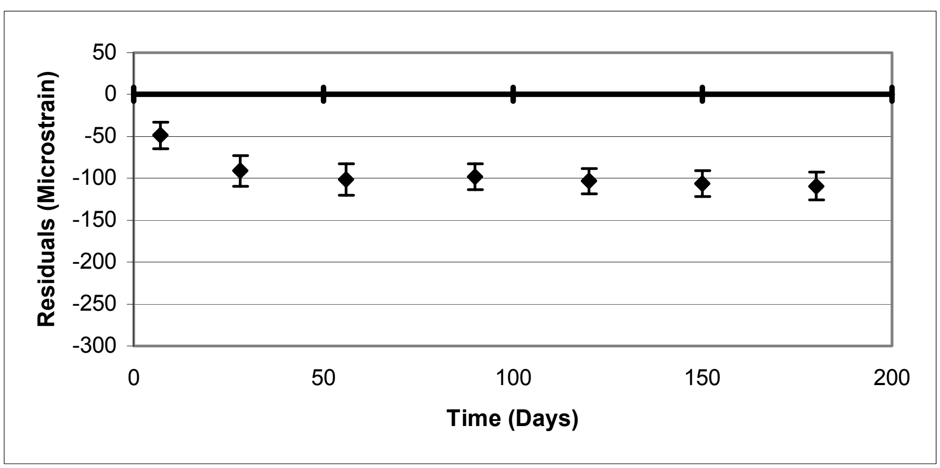

Figure 5.69 Bazant B3 Residuals for A5-Diabase/Slag Cement Mixtures.

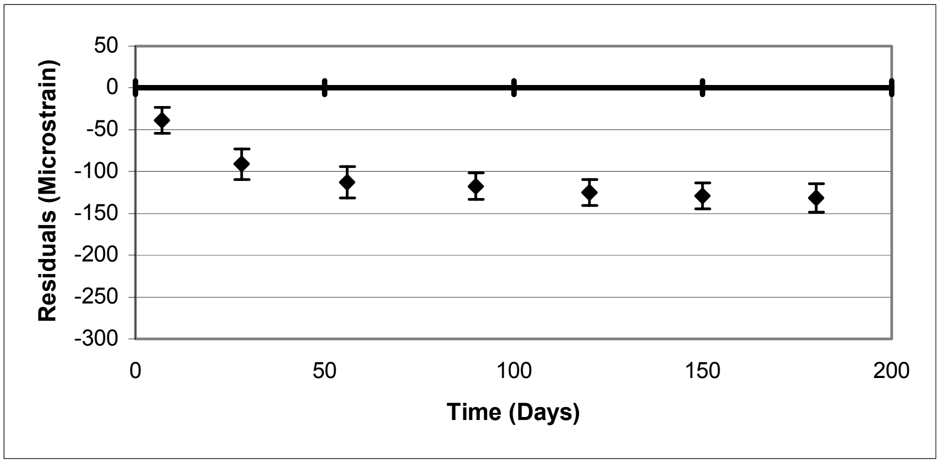

Figure 5.70 CEB90 Residuals for A5-Diabase/Slag Cement Mixtures.

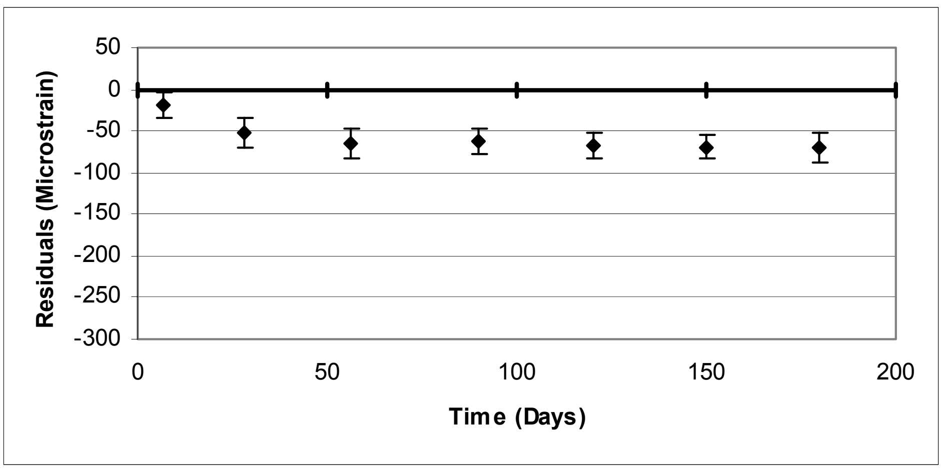

Figure 5.71 Gardner/Lockman Residuals for A5-Diabase/Slag Cement Mixtures.

CHAPTER 6: DISCUSSION AND ANALYSIS

6.1 Introduction

This chapter presents a discussion of the test results including compressive strength, modulus of elasticity, unrestrained and restrained shrinkage. An analysis of the five shrinkage prediction models is also presented.

6.2 Compressive Strength

One of the factors that contributes to the compressive strength of concrete is the water-to-cement (w/c) ratio of the mixture. In general, a mixture with a lower w/c ratio should produce a higher compressive strength. Table 6.1 presents the average compressive strengths at seven, 28, and 90 days after casting.

Table 6.1 Average Compressive Strength Test Results.

A3 - Portland Cement Concrete Mixtures

		7 Days		28 Days		90 Days	
	w/c	MPa	psi	MPa	psi	MPa	psi
Limestone	0.49	32.9	4770	39.2	5680	45.3	6570
Gravel	0.46	37.1	5380	41.3	5990	47.6	6900
Diabase	0.47	36.7	5330	41.4	6010	47.3	6860

A4 - Portland Cement Concrete Mixtures

		7 Days		28 Days		90 Days	
	w/c	MPa	psi	MPa	psi	MPa	psi
Limestone	0.45	36.3	5260	43.1	6250	47.8	6940
Gravel	0.42	38.1	5530	44.4	6440	50.7	7360
Diabase	0.43	36.7	5330	43.5	6310	48.7	7070

A5 - Portland Cement Concrete Mixtures

		7 Days		28 Days		90 Days	
	w/c	MPa	psi	MPa	psi	MPa	psi
Limestone	0.33	49.3	7150	53.2	7720	58.1	8420
Gravel	0.35	43.2	6260	48.8	7080	55.4	8035
Diabase	0.39	41.9	6070	47.4	6870	52.3	7580

Supplemental Cementitious Material Mixtures

		7 Days		28 Days		90 Days	
	w/c	MPa	psi	MPa	psi	MPa	psi
A4-D/FA	0.43	47.9	6950	53.4	7740	58.1	8430
A4-D/MS	0.43	47.4	6870	52.7	7650	60.1	8720
A4-D/S	0.43	50.2	7280	54.3	7880	61.0	8850
A5-D/S	0.39	51.4	7450	55.3	8020	62.3	9030

The compressive strengths complied with the relationship of lower w/c ratios produce higher compressive strength. For the A3 portland cement mixtures, the gravel mixtures had the lowest w/c ratios and the highest compressive strengths. The gravel and diabase mixtures had similar w/c ratios and the corresponding compressive strengths were not significantly different. The limestone mixtures had the highest w/c ratio and lowest compressive strength, and were significantly different from the gravel and diabase mixtures.

The A4 portland cement concrete mixture results were similar. The gravel mixtures had the lowest w/c ratio and the highest compressive strength. The gravel mixture compressive strengths were significantly greater than the diabase and limestone mixture compressive strengths.

The A5 portland cement concrete limestone, gravel, and diabase mixtures had w/c ratios of 0.33, 0.35, and 0.39, respectively. The limestone mixtures had the highest compressive strengths followed by the gravel mixtures, and the diabase mixtures which had the lowest compressive strengths. The limestone, gravel, and diabase mixture compressive strengths were all significantly different from each other.

For the supplemental cementitious material mixtures, the A4 mixtures had a w/c ratio of 0.43 and the A5 mixture had a w/c ratio of 0.39. The A5 mixture had the highest compressive strengths. For the A4 mixtures, the mixture using slag cement had a higher compressive strength than the mixtures using fly ash and microsilica.

The concrete mixture proportions for all of the study mixtures were VDOT approved plant mixtures. The VDOT A3, A4, and A5 concrete compressive strength requirements are 20.7 MPa (3000 psi), 27.6 MPa (4000 psi), and 35.5 MPa (5000 psi) at 28 days. As shown in Table 6.1, the mixture compressive strengths were significantly greater than the minimum specified strengths. For worst case conditions, the 28-day compressive strengths were 18 MPa (2680 psi), 8.6 MPa (1250 psi), and 12.9 MPa (1870 psi) greater than the minimum specified compressive strengths, respectively.

6.3 Modulus of Elasticity

Table 6.2 presents the average modulus of elasticity for the mixtures performed in this study at seven, 28, and 90 days after casting of the specimens. The test was performed twice at seven, 28, and 90 days, and the modulus of elasticity values in the table represent the average of the two measurements. The table also presents the estimated modulus of elasticity using the AASHTO standard specification (AASHTO, 1996). The AASHTO results were within 10% of the actual measured values. The following equation was used for the AASHTO results:

$$E_c = 0.43\gamma^{1.5}\sqrt{f'_c} \quad \text{(Eq. 2)}$$

Where: E_c = Modulus of elasticity (GPa)

γ = unit weight of concrete (kg/m^3)

f'_c = average 28-day compressive strength (MPa)

Table 6.2 Average Modulus of Elasticity Test Results.

A3 - Portland Cement Concrete Mixtures	7 Days		28 Days		90 Days		AASHTO	
	GPa	x10^6 psi	GPa	x10^6 psi	GPa	x10^6 psi	GPa	x10^6 psi
Limestone	27.0	3.91	28.8	4.17	31.2	4.52	29.0	4.20
Gravel	27.9	4.05	29.5	4.28	31.6	4.59	29.5	4.28
Diabase	27.9	4.05	29.4	4.27	31.6	4.58	29.4	4.27

A4 - Portland Cement Concrete Mixtures	7 Days		28 Days		90 Days		AASHTO	
	GPa	x10^6 psi	GPa	x10^6 psi	GPa	x10^6 psi	GPa	x10^6 psi
Limestone	27.6	4.01	29.6	4.30	33.7	4.89	31.0	4.49
Gravel	28.8	4.18	30.7	4.45	35.2	5.10	31.1	4.51
Diabase	27.6	4.00	29.9	4.34	34.3	4.97	30.0	4.35

A5 - Portland Cement Concrete Mixtures	7 Days		28 Days		90 Days		AASHTO	
	GPa	x10^6 psi	GPa	x10^6 psi	GPa	x10^6 psi	GPa	x10^6 psi
Limestone	33.2	4.81	35.0	5.08	39.0	5.66	35.6	5.16
Gravel	31.5	4.57	33.7	4.89	36.3	5.27	34.0	4.93
Diabase	30.5	4.42	32.3	4.69	35.3	5.12	33.0	4.78

Supplemental Cementitious Material Mixtures	7 Days		28 Days		90 Days		AASHTO	
	GPa	x10^6 psi	GPa	x10^6 psi	GPa	x10^6 psi	GPa	x10^6 psi
A4-D/FA	31.2	4.52	35.3	5.12	40.7	5.91	36.1	5.23
A4-D/MS	30.4	4.41	35.5	5.15	42.1	6.11	36.5	5.29
A4-D/S	33.3	4.83	37.0	5.37	42.3	6.14	38.0	5.51
A5-D/S	33.2	4.81	38.1	5.52	44.6	6.47	39.2	5.68

The modulus of elasticity increases with increasing compressive strength. For the A3 and A4 portland cement mixtures, the modulus of elasticity for the limestone, gravel and diabase mixtures were not significantly different.

For the A5 portland cement mixtures, the limestone mixtures had a significantly higher modulus of elasticity and corresponding compressive strength than the gravel and diabase mixtures. The supplemental cementitious material mixtures had significantly higher modulus of elasticity results than the portland cement concrete mixtures. This is the result of a denser bulk cement paste matrix and aggregate/cement paste transition zone than the portland cement mixtures.

A comparison was also performed between the measured modulus of elasticity and the equation used to determine modulus of elasticity by ACI 318 Building Code. The ACI equation is as follows:

$$E_c = 57{,}000\sqrt{f'_c} \quad \text{(Eq. 3)}$$

Where: E_c = modulus of elasticity (x10^6 psi)

f'_c = average 28-day compressive strength (psi)

Figure 6.1 presents the comparison between the ACI 318 Building Code and the measured modulus of elasticity results.

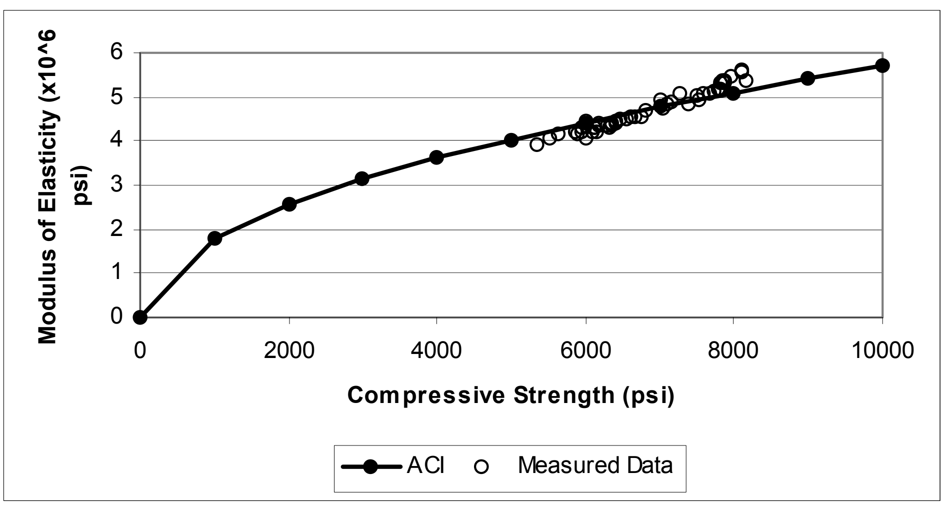

Figure 6.1 ACI 318 Building Code versus Measured Modulus of Elasticity.

As shown in Figure 6.1, the measured modulus of elasticity results were within 10% of the ACI 318 Building Code values.

6.4 Unrestrained Shrinkage

Tables 6.3 presents the average percent length change for unrestrained concrete specimens at seven, 28, 56, 90, 120, 150, and 180 days. Appendix C and Appendix E present the data and graphs for each individual mixture, as well as, an analysis of variance between the individual mixtures.

Table 6.3 Average Percentage Length Change.

	Average Percentage Length Change						
Mixture	**7 Days**	**28 Days**	**56 Days**	**90 Days**	**120 Days**	**150 Days**	**180 Days**
A3 - Limestone	-0.0162	-0.0253	-0.0380	-0.0393	-0.0431	-0.0457	-0.0468
A3 - Gravel	-0.0186	-0.0280	-0.0367	-0.0370	-0.0432	-0.0459	-0.0462
A3 - Diabase	-0.0183	-0.0286	-0.0392	-0.0458	-0.0490	-0.0507	-0.0541
Mixture	**7 Days**	**28 Days**	**56 Days**	**90 Days**	**120 Days**	**150 Days**	**180 Days**
A4 - Limestone	-0.0139	-0.0217	-0.0342	-0.0378	-0.0401	-0.0415	-0.0442
A4 - Gravel	-0.0172	-0.0258	-0.0323	-0.0368	-0.0384	-0.0402	-0.0419
A4 - Diabase	-0.0155	-0.0276	-0.0392	-0.0422	-0.0457	-0.0478	-0.0514
Mixture	**7 Days**	**28 Days**	**56 Days**	**90 Days**	**120 Days**	**150 Days**	**180 Days**
A5 - Limestone	-0.0160	-0.0225	-0.0321	-0.0351	-0.0367	-0.0378	-0.0394
A5 - Gravel	-0.0153	-0.0266	-0.0328	-0.0366	-0.0380	-0.0396	-0.0415
A5 - Diabase	-0.0180	-0.0256	-0.0364	-0.0427	-0.0453	-0.0465	-0.0494
Mixture	**7 Days**	**28 Days**	**56 Days**	**90 Days**	**120 Days**	**150 Days**	**180 Days**
A4-D/Fly Ash	-0.0197	-0.0396	-0.0487	-0.0522	-0.0537	-0.0547	-0.0561
A4-D/Microsilica	-0.0187	-0.0367	-0.0433	-0.0447	-0.0473	-0.0490	-0.0510
A4-D/Slag Cement	-0.0204	-0.0385	-0.0429	-0.0474	-0.0490	-0.0499	-0.0503
A5-D/Slag Cement	-0.0198	-0.0354	-0.0425	-0.0457	-0.0478	-0.0491	-0.0500

For the A3 portland cement concrete mixtures, the diabase specimens exhibited the highest percent length change. The limestone and gravel specimens had similar percent length changes, which was significantly less than the diabase values at later ages. For the first 56 days of drying, there is not a significant difference in the percent length change between the three mixtures. However, after 56 days of drying, the diabase specimens began to experience greater percent length changes than the limestone and gravel specimens.

For the A4 portland cement concrete mixtures the gravel mixtures exhibited the smallest percent length change. Again, the diabase mixture exhibited the highest percentage length change. The gravel mixtures had a w/c ratio of 0.42, while the limestone and diabase mixtures had w/c ratios of 0.45 and 0.43, respectively. The gravel and limestone mixtures agree with the general relationship of a lower w/c ratio produces lower shrinkage, however, the diabase mixture had a lower w/c ratio than the limestone and exhibited higher shrinkage. There was not a significant difference between the percent length change values for the limestone and gravel mixtures. However, both the limestone and gravel percent length changes were significantly less than those of the diabase mixtures.

The A5 portland cement concrete mixtures had a greater range of w/c ratios than the A3 and A4 mixtures. The w/c ratios were 0.33, 0.35, and 0.39 for the limestone, gravel, and diabase mixtures, respectively. The limestone mixtures, which had the lowest w/c ratio, exhibited the lowest shrinkage values. While the diabase mixtures, with the highest w/c ratio, exhibited the highest amount of shrinkage. The limestone and gravel percent length change values were not significantly different, but they were both significantly lower than the diabase mixtures.

Overall, for the portland cement concrete mixtures, the diabase mixtures consistently exhibited higher shrinkage values than the limestone and gravel mixtures. It appears that the aggregate type has an effect on the drying shrinkage. One of the factors that may influence shrinkage is the absorption of the aggregate. The fine aggregate used with the diabase aggregate had an absorption of 1.04%, whereas the limestone and gravel were 0.48% and 0.75%, respectively. A higher absorption value indicates a higher percent of aggregate voids are filled with water, which may lead to an increase in drying shrinkage. Another factor that may influence shrinkage is the modulus of elasticity of the aggregate. A lower aggregate modulus of elasticity would result in a lower restraining effect on the cement paste during drying shrinkage.

For the supplemental cementitious material mixtures the mixture containing the fly ash exhibited the greatest amount of shrinkage. The mixtures containing microsilica and slag cement were not significantly different. The A4 mixtures containing supplemental cementitious materials had the same w/c ratio and aggregate type, diabase.

The w/c ratios for the A4 and A5 slag cement mixtures were 0.43 and 0.39, respectively. For the slag cement mixtures, the w/c ratio did not have a significant effect on the shrinkage values.

The supplemental cementitious material mixtures exhibited greater drying shrinkage than the associated portland cement concrete mixtures. This could be due to the denser matrix produced by the fly ash, microsilica, and slag cement. This denser matrix would create smaller capillary voids, and the bulk of drying shrinkage in concrete occurs from the loss of water from the smaller capillary voids.

6.5 Restrained Shrinkage

Tables 6.4 presents the average microstrain values for the restrained concrete specimens at seven, 28, 56, 90, 120, 150, and 180 days. The average microstrain for the portland cement mixtures are the average of eight strain gages on two rings. The supplemental cementitious material microstrain is the average of 24 strain gages on six rings. Appendix D presents the data and graphs for each of the individual mixtures.

	Average Microstrain						
Mixture	**7 Days**	**28 Days**	**56 Days**	**90 Days**	**120 Days**	**150 Days**	**180 Days**
A3 - Limestone	-63	-91	-164	-224	-234	-177	-179
A3 - Gravel	-71	-103	-127	-141	-123	-133	-139
A3 - Diabase	-45	-57	-90	-106	-117	-125	-132
Mixture	**7 Days**	**28 Days**	**56 Days**	**90 Days**	**120 Days**	**150 Days**	**180 Days**
A4 - Limestone	-54	-80	-127	-157	-162	-165	-168
A4 - Gravel	-56	-90	-142	-176	-183	-188	-194
A4 - Diabase	-50	-110	-152	-179	-187	-193	-200
Mixture	**7 Days**	**28 Days**	**56 Days**	**90 Days**	**120 Days**	**150 Days**	**180 Days**
A5 - Limestone	-59	-85	-118	-139	-142	-145	-148
A5 - Gravel	-61	-96	-132	-184	-194	-202	-149
A5 - Diabase	-52	-83	-116	-164	-179	-201	-158
Mixture	**7 Days**	**28 Days**	**56 Days**	**90 Days**	**120 Days**	**150 Days**	**180 Days**
A4-D/Fly Ash	-60	-119	-136	-178	-184	-188	-193
A4-D/Microsilica	-61	-93	-106	-141	-154	-163	-172
A4-D/Slag Cement	-52	-83	-96	-122	-129	-136	-142
A5-D/Slag Cement	-57	-103	-114	-125	-137	-148	-157

Table 6.4 Average Microstrain.

For the A3 portland cement concrete mixtures, the limestone mixture exhibited the greatest microstrain followed by the gravel and diabase mixtures. Concrete rings from the limestone and gravel mixtures experienced cracking, while rings from the diabase mixture did not crack. One of the concrete rings from the limestone mixture cracked after 125 days. The measured average microstrain value for that ring was -234 microstrain at 120 days. Thus, the ring cracked after experiencing an average microstrain of slightly greater than –234. One of the rings from the gravel mixture also cracked, the ring cracked after 117 days. The average microstrain for this ring was –141 after 90 days. The estimated microstrain was –220 at cracking. The diabase mixture rings did not crack during the test period of 180 days. The average microstrain for these rings –132 at 180 days. This is significantly less strain than was experienced by the limestone and gravel rings. The modulus of elasticity for the limestone and gravel mixtures were higher than those for the diabase mixture. This may have been a factor in the cracking of the limestone and gravel rings. With a higher modulus, the concrete is stiffer and it may be able to resist shrinkage in an unrestrained condition. However, in a restrained condition, the stiffer concrete may create higher strains on the ring.

For the A4 portland cement concrete mixtures, none of the rings experienced cracking. The diabase rings experienced the greatest amount of strain while the limestone rings experienced the least. The average microstrain results at 180 days were –168, -194, and –200, for the limestone, gravel, and diabase, respectively. The modulus of elasticity for the gravel and diabase mixtures were higher than those for the limestone mixtures, which may account for the higher restrained shrinkage strains.

For the A5 portland cement concrete mixtures, the gravel and diabase mixtures experienced cracking. One of the diabase rings cracked after 165 days, the most recent average microstrain reading for that ring was –201 at 150 days. The estimated microstrain at cracking was –220. The same is true for the gravel mixture. One of the rings cracked after 172 days with the most recent average microstrain reading being –202 at 150 days. The estimated microstrain cracking was –210. One of the factors that may have influenced the cracking tendency of the A5 portland cement concrete mixtures was the w/c ratios of the mixtures. The w/c ratios were 0.33, 0.35, and 0.39 for the limestone, gravel, and diabase, respectively. The lower w/c ratio should produce less shrinkage, which in turn may produce less strain. Throughout the testing of the A5 mixtures, the limestone mixture, which had the lowest w/c ratio, exhibited significantly less strain.

None of the supplemental cementitious material rings experienced cracking. The average microstrain values ranged from –142 to –193, with the fly ash mixtures experiencing the highest strain, and the A4 slag cement mixture experiencing the least strain. The A4 and A5 slag cement mixtures had less strain than the microsilica and fly ash mixtures. It should be noted that the fly ash mixtures experienced higher shrinkage values for both the unrestrained and restrained conditions. Thus, it appears that an average microstrain in excess of –200 will result in the cracking of the restrained drying shrinkage rings.

6.6 Relationship Between Percentage Length Change and Microstrain

A total of 42 ring specimens were fabricated for this study and only four of the rings experienced cracking. However, all of the rings that cracked had average microstrain values in excess of -200 με. Therefore, it appears that if the strain produced in a restrained situation is greater than 200 με, there is an increased probability of cracking. The percentage length change was plotted versus the microstrain for each mixture to determine if there was a correlation. The values were from measurements taken at seven, 28, 56, 90, 120, 150, and 180 days. Figure 6.2 presents the percent length change versus microstrain for the A3 portland cement concrete mixtures.

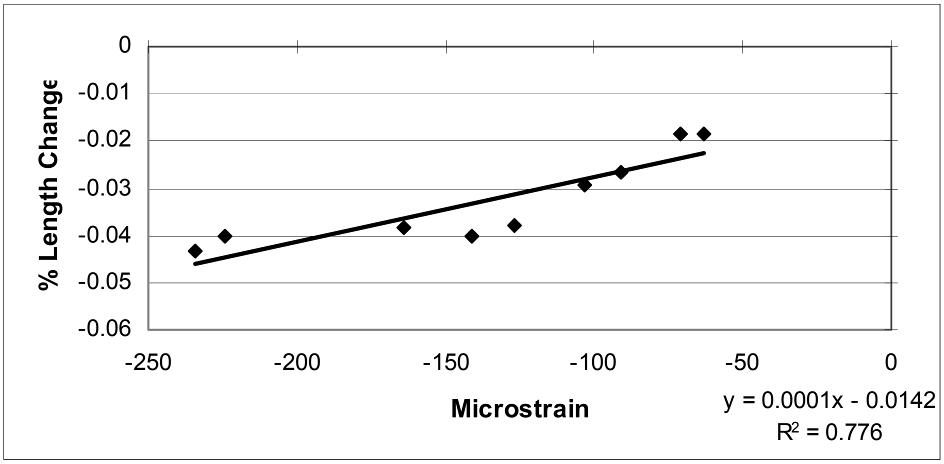

Figure 6.2 Percentage Length Change vs. Microstrain for A3 Portland Cement Concrete Mixtures.

For the A3 portland cement concrete mixtures, there is a fairly strong correlation between the percentage length change and microstrain. If you are to use a value of -200 με in the linear equation from Figure 6.2, you would obtain a value of -0.0342 for the percentage length change. Since there is a higher probability for cracking when the strain value is greater than 200 με, the probability for cracking is increased if the percent length change is greater than 0.0342.

Figure 6.3 presents the percent length change versus microstrain for the A4 portland cement concrete mixtures.

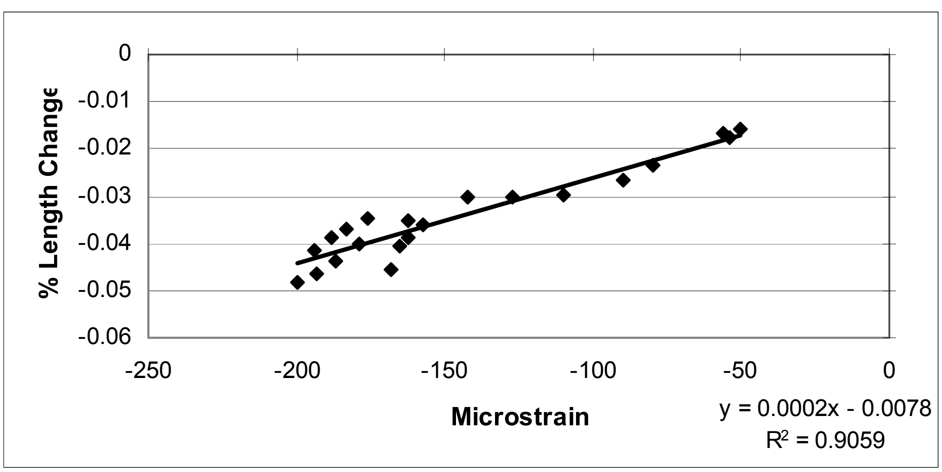

Figure 6.3 Percentage Length Change vs. Microstrain for A4 Portland Cement Concrete Mixtures.

There is a stronger correlation between percentage length change and microstrain for the A4 portland cement concrete mixtures. Using a value of -200 με in the linear equation from Figure 6.3, you would obtain a value of -0.0478 for the percentage length change. This would mean that if the percent length change is greater than 0.0478, there is an increased probability of cracking.

Figure 6.4 presents the percentage length change versus microstrain for the A5 portland cement concrete mixtures.

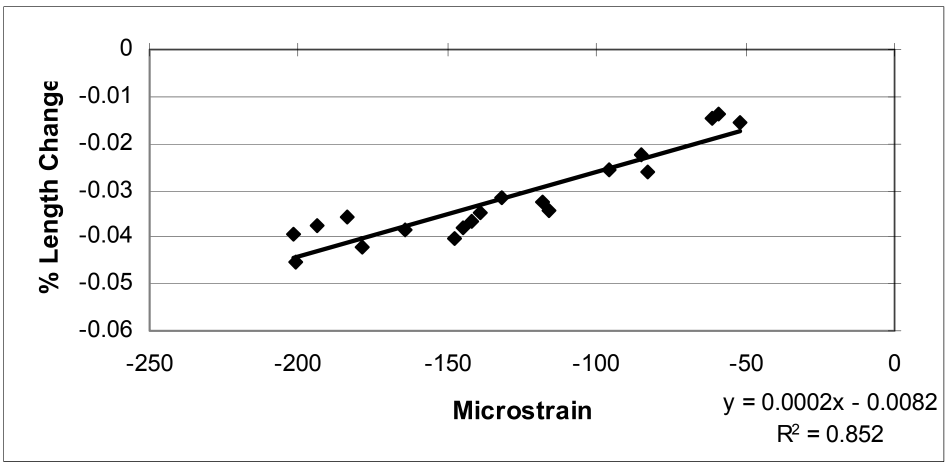

Figure 6.4 Percentage Length Change vs. Microstrain for A5 Portland Cement Concrete Mixtures.

For the A5 portland cement concrete mixtures there is a strong correlation between the percentage length change and microstrain. Using a value of -200 με in the linear equation from Figure 6.4, you would obtain a value of -0.0482 for the percentage length change. Thus, if the percent length change is greater than 0.0482, there is an increased probability of cracking.

Figure 6.5 presents the percentage length change versus microstrain for the supplemental cementitious material mixtures. Note that these mixtures used the same aggregate type, diabase, and the associated fine aggregate. Also the water to cement plus pozzolan ratios were the same, 0.43.

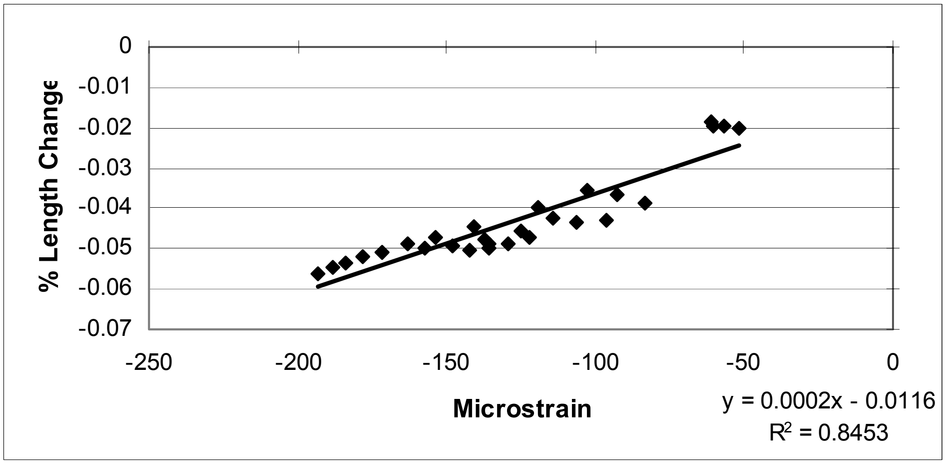

Figure 6.5 Percentage Length Change vs. Microstrain for Supplemental Cementitious Material Mixtures.

For the supplemental cementitious concrete material mixtures there is a strong correlation between the percentage length change and microstrain. Using a value of -200 με in the linear equation from Figure 6.5, you would obtain a value of -0.0516 for the percentage length change. Thus, if the percentage length change is greater than 0.0516, there is an increased probability of cracking for these mixtures.

Based on the results obtained from the correlation between percentage length change and microstrain, a performance specification can be developed. It has been shown that if the microstrain in the restrained shrinkage specimens is greater than 200με, there is an increased probability of cracking. The associated percentage length change was calculated from linear equations for each mixture group. It appears that the percent length change for the portland cement concrete mixtures is between 0.0342 and 0.0485 for a restrained shrinkage of 200με. Therefore, if the percent length change for the portland cement concrete mixtures is limited to 0.0300 at 28 days and 0.0400 at 90 days, there is a reduced probability of cracking due to drying shrinkage. For the supplemental cementitious material mixtures, at restrained shrinkage of 200με, the associated percent length change is 0.0516. Therefore, if the percentage length change is limited to 0.0400 at 28 days and 0.500 at 90 days for these mixtures, there is a reduced probability of cracking due to drying shrinkage.

Table 6.5 presents a comparison of the proposed performance specification and other proposed performance specifications. The other performance specifications were proposed for the Fairfax County Water Authority, the Port Authority of New York and New Jersey, repair materials, and the Pennsylvania Department of Transportation.

Table 6.5 Comparison of Performance Specifications

	Percentage Length Change Limits		
Source	**At 21 Days**	**At 28 Days**	**At 90 Days**
Fairfax County Water Authority (Lab)	0.0360 – 0.0480	---	---
Fairfax County Water Authority (Field)	0.0480 – 0.0640	---	---
Port Authority of New York and New Jersey	---	0.0400	---
Repair Materials	---	0.0400	---
Penn DOT	---	0.0400	---
Current Study (VDOT) PCC	---	0.0300	0.0400
Current Study (VDOT) SCM	---	0.0400	0.0500

As shown, the majority of the performance specifications limit the percentage length change to 0.0400 at 28 days. The Fairfax County Water Authority has limits at 21 days. The limits are for both lab and field mixtures. For the lab mixtures, the percentage length change limit is 0.0360 for concrete to be used in liquid-containing structures, and 0.0480 for concrete to be used in other structures. For the field mixtures, the percentage length change limits are 0.0480 and 0.0640 for liquid-containing and other concrete structures, respectively. All of the shrinkage tests were performed in accordance with ASTM C157.

6.7 Prediction Model Analysis

Five existing shrinkage prediction models were analyzed in this study, they are as follows:

- ACI – 209 Code Model (ACI 209)
- Bazant Model B3 (Bazant)
- Comite Euro-International Du Beton Model Code 1990 (CEB90)
- Gardner – Lockman Model (Gardner/Lockman)
- Sakata Model (Sakata)

Section 5.6 presented the residuals of these models to a drying shrinkage age of 180 days. The residuals are an indication of the models ability to either overestimate or underestimate shrinkage. However, the residuals do not necessarily determine which model is the best predictor. To determine which model is the best predictor, two analyses were performed, an error percentage analysis and the Chi square test. The error percentage was calculated as follows for the residual values at seven, 28, 56, 90, 120, 150, and 180 days:

$$ErrorPercentage = \frac{Residual * 100}{Experimental(Measured)Value} \qquad \text{(Eq. 4)}$$

The error percentage values as a function of time are presented in Appendix C. An average error percentage for the seven time periods was calculated, a smaller error percentage over the 180 day time period indicates a better fit model.

The Chi square test is the summation of the residuals squared. Thus, the model with the smallest value indicates the best predictor.

6.7.1 Error Percentage Analysis

6.7.1.1 Portland Cement Concrete Mixtures

Table 6.6 presents the rank order of the average error percentage for each model for the limestone, gravel, and diabase portland cement concrete mixtures.

Table 6.6 Average Error Percentage for Limestone, Gravel, and Diabase Mixtures.

Prediction Model	Limestone	Gravel	Diabase
CEB90	22	17	10
Bazant	25	17	11
Gardner/Lockman	26	19	12
ACI 209	42	40	25
Sakata	80	72	57

As shown, the rank order is the same for the three aggregate types with little difference between the CEB90, Bazant, and Gardner/Lockman models. The average error percentage results indicate that the ACI 209 and Sakata models were not as accurate.

The rank order from best to worst fit among aggregate types is diabase, gravel, and limestone. However, all of the models overestimate the shrinkage during the 180 day test period. Note that the diabase mixtures, which had displayed the greatest amount of shrinkage, had the lowest error percentage for the CEB90, Bazant, and Gardner/Lockman models, 10, 11, and 12 percent, respectively.

6.7.1.2 Supplemental Cementitious Material Mixtures

Table 6.7 presents the models average error percentages for the supplemental cementitious material mixtures.

Table 6.7 Average Error Percentage for Supplemental Cementitious Material Mixtures.

Prediction Model	A4-D/FA	A4-D/S	A5-D/S	A4-D/MS
Gardner/Lockman	20	14	13	67
CEB90	30	25	24	78
Bazant	30	24	22	78
ACI 209	--	--	--	110
Sakata	--	--	--	145

For the fly ash and slag cement mixtures the Bazant, CEB90, and Gardner/Lockman models were used in shrinkage prediction analyses because these cementing materials are closer in hydration characteristics to a Type II Cement rather than a Type I.

The Bazant, CEB90, and Gardner/Lockman models include an adjustment factor for cement types, whereas, the ACI 209 and Sakata models do not consider the influence of various cementing materials.

As shown in Table 6.6, the rank order of the best to worst prediction model for the A4 fly ash and the A4 and A5 slag cement mixtures is the Gardner/Lockman model, with the CEB90 and Bazant models being equivalents. The ACI 209 and Sakata models were not as accurate for the A4 microsilica mixture.

Overall, for the error percentage analysis of the data, the models tended to overestimate the shrinkage of the portland cement concrete mixtures and underestimate the shrinkage of the supplemental cementitious material mixtures. One of the probably reasons, which shall be discuss further in the sensitivity analysis of these models at the end of this chapter, is that these models predict shrinkage largely based on the average 28-day compressive strength of the mixture. This parameter does not directly account for the pore volume and pore size distribution of the mixture, which greatly affects drying shrinkage. For the portland cement concrete mixtures, the CEB90 model was the best predictor followed closely by the Bazant and Gardner/Lockman models. The Sakata model was the worst predictor for these mixtures. For the supplemental cementitious material mixtures, the Gardner/Lockman model was the best predictor. It was consistently better than the Bazant and CEB90 models for the mixtures that were considered to be type II cement.

6.7.2 Chi Squared Test Statistic Analysis

6.7.2.1 Portland Cement Concrete Mixtures

Figure 6.6 presents the Chi squared test statistic analysis for the limestone, gravel, and diabase portland cement concrete mixtures. The Chi squared test statistic is the summation of the residuals squared. A lower total summation indicates that the model is a better predictor.

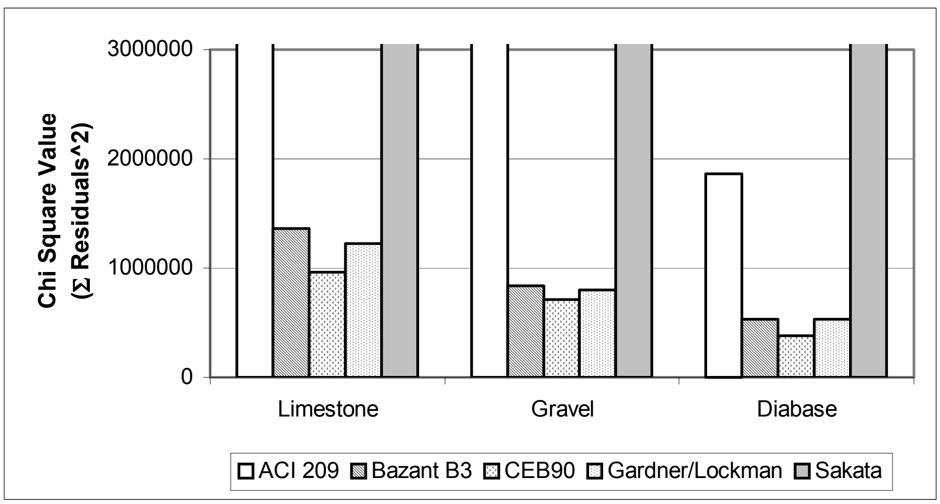

Figure 6.6 Chi Squared Test Statistic for Limestone, Gravel, and Diabase Mixtures.

For the limestone portland cement concrete mixtures, the Chi square values demonstrate that the CEB90 model was the best predictor of shrinkage. It was followed by the Gardner/Lockman and Bazant models.

For the gravel portland cement concrete mixtures, the CEB90 model was the again the best predictor based on the Chi square values. The Gardner/Lockman and Bazant models followed closely. The ACI 209 and Sakata models performed significantly worse for these mixtures.

For the diabase portland cement concrete mixtures, the Chi square values demonstrate that the CEB90 model was the best predictor of shrinkage. The Gardner/Lockman and Bazant models were similar in predicting shrinkage and closely reemble the CEB90 model.

6.7.2.2 Supplemental Cementitious Material Mixtures

Figures 6.7 and 6.8 present the Chi square values for the supplemental cementitious material mixtures. Figure 6.7 presents the Chi square values for the fly ash and slag cement mixtures. Figure 6.8 presents the Chi square values for the microsilica mixture.

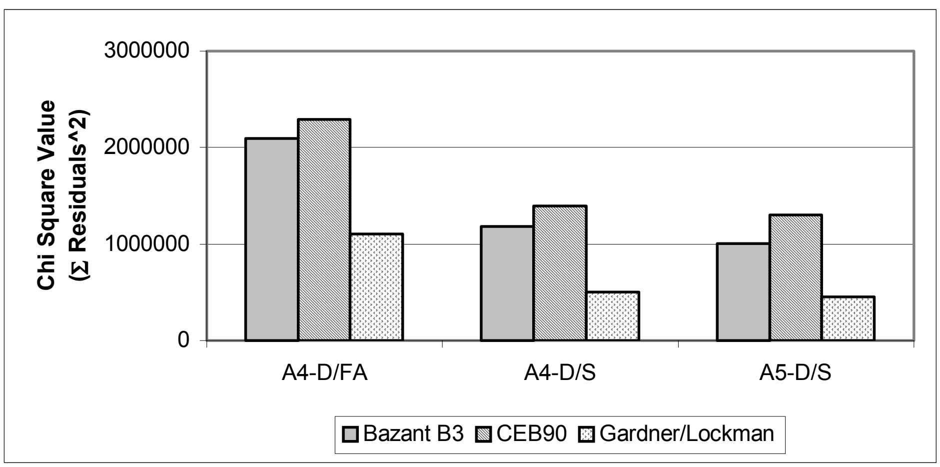

Figure 6.7 Chi Squared Test Statistic for Fly Ash and Slag Cement Mixtures.

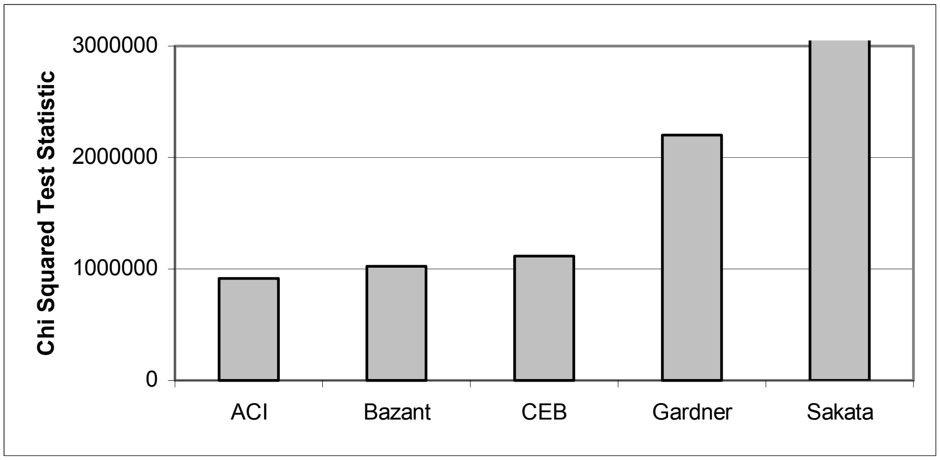

Figure 6.8 Chi Squared Test Statistic for Microsilica Mixture.

For the fly ash and slag cement mixtures, only the Bazant, CEB90, and Gardner/Lockman models were analyzed because of limitations on cement type for the ACI 209 and Sakata models.

For the fly ash mixtures, the Gardner/Lockman model was the best predictor followed by the Bazant and CEB90 models. The Chi square values for the A4 slag cement mixture demonstrate that the Gardner/Lockman model is the best predictor, followed by the Bazant and CEB90 models. The same is true of the A5 slag cement mixtures.

For the microsilica mixture, the Chi square values demonstrated that the ACI 209 model is the best predictor. The Bazant and CEB90 models followed closely. The Gardner/Lockman model was the fourth best predictor. These mixtures were considered to be type I cement mixtures, the ACI 209 and Sakata models overestimated the shrinkage, while the Bazant, CEB90, and Gardner/Lockman models underestimated the shrinkage. The same analysis was performed assuming that the mixtures were a type II cement. In this case, the Gardner/Lockman model was the best predictor. The reason for the skewed results using a type I cement analysis, is that the actual measured shrinkage values were high, and the models are strongly based on compressive strength. The models assume that a higher 28-day compressive strength will have less shrinkage, however, that may not be true.

For the Gardner/Lockman model, the parameter associated with cement type is given a value according to the type of cement. In the case of a Type II cement, this value is 0.70.

However, for the data presented in this study, if this value is changed to 0.80, the predicted values are the same as the measured values from this study. Figures 6.9 through 6.11 presents the comparison of the Gardner/Lockman model using K=0.80 and the actual measured percent length change.

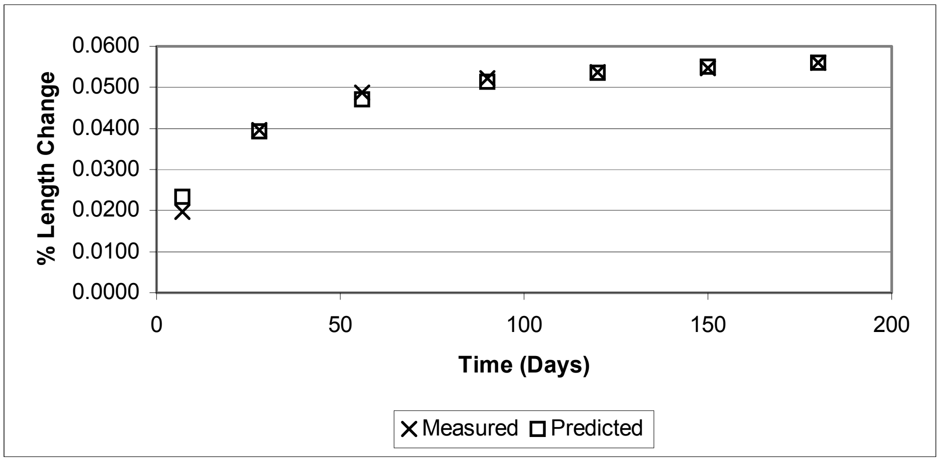

Figure 6.9 Gardner/Lockman Model for Type II Cement, K=0.80 (A4-Diabase/Fly Ash).

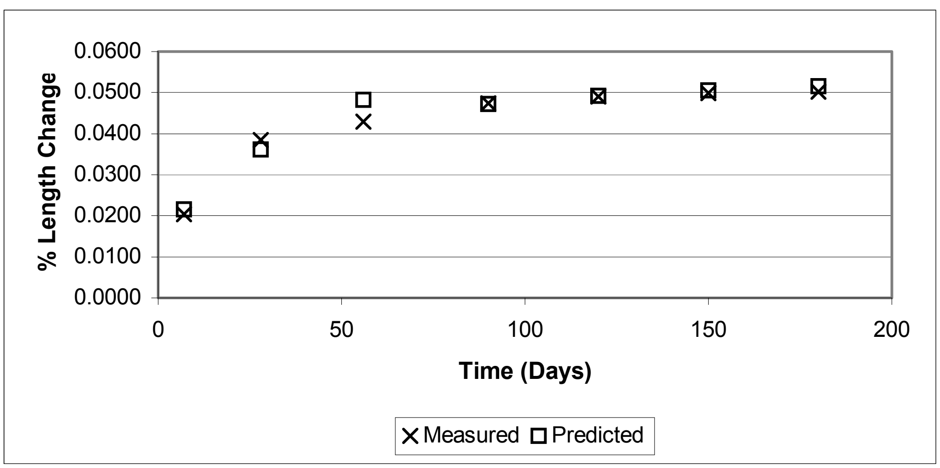

Figure 6.10 Gardner/Lockman Model for Type II Cement, K=0.80 (A4-Diabase/Slag Cement).

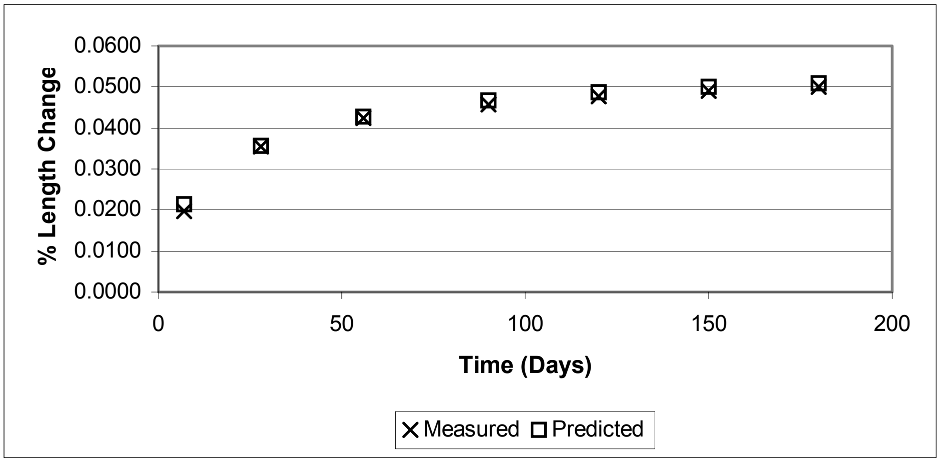

Figure 6.11 Gardner/Lockman Model for Type II Cement, K=0.80 (A5-Diabase/Slag Cement).

6.7.3 Summary of Error Percentage and Chi Squared Test Statistic Analysis

The error percentage and Chi squared test statistic analyses demonstrated the same results in terms of the model performance from best to worst. Table 6.8 presents a summary of the error percentage and Chi square test results. The error percentage result is the average for the mixtures according to aggregate type. The Chi square result is the summation of the residuals squared of a mixture according to aggregate type. The error percentage and Chi square results for the supplemental cementitious material (SCM) mixtures are also presented.

Table 6.8 Summary of Error Percentage and Chi Squared Test Statistic Analysis

Model	Test	Limestone	Gravel	Diabase	SCM
ACI 209	Error %	42	40	25	110
	Chi Square	4,550,038	4,230,628	1,861,072	917,183
Bazant	Error %	25	17	11	39
	Chi Square	1,360,508	835,433	529,537	1,070,029
CEB90	Error %	22	17	10	39
	Chi Square	961,924	714,085	378,416	1,247,254
Gardner/	Error %	26	19	12	29
Lockman	Chi Square	1,224,848	797,398	528,312	515,258
Sakata	Error %	80	72	57	145
	Chi Square	13,501,862	12,505,781	8,859,553	4,367,955

For the portland cement concrete mixtures the models overestimated shrinkage, while for the supplemental cementitious material mixtures the models underestimated shrinkage. The CEB90 model was the best predictor for the portland cement concrete mixtures, while the

Gardner/Lockman model was the best predictor for the supplemental cementitious material mixtures. It should be noted that the portland cement concrete mixtures were analyzed using a type I cement, while the supplemental cementitious material mixtures were analyzed using a type II cement. The Bazant, CEB90, and Gardner/Lockman models were used for the type II cement analysis, with each having a correction factor for type II cement. These correction factors varied between the models.

As mentioned previously, the models predict shrinkage largely based on the 28-day compressive strength of a mixture. A lower compressive strength results in a higher predicted shrinkage for these models. The compressive strength parameter is used in an effort to account for the effects of water and cement, a lower w/c ratio should indicate a lower water content, thus less shrinkage. Although compressive strength influences the amount of shrinkage, there are other factors that need to be considered. These factors include the pore volume and pore size distribution. The majority of drying shrinkage is associated with the loss of water from the smaller capillary voids in the concrete. A concrete mixture using supplemental cementitious materials such as fly ash, microsilica, and slag cement have a more refined pore structure than ordinary portland cement concrete mixtures. There are more smaller capillary voids in these mixtures and the removal of water from these voids may result in more shrinkage.

From the results obtained in this study, it appears that the type of aggregate may also influence shrinkage. In this study, the mixtures using diabase as the aggregate consistently had more shrinkage than mixtures using limestone or gravel as the aggregate. The diabase fine aggregate had higher absorption values than the limestone and gravel aggregate. The absorption values for the fine aggregate was 0.48, 0.75, and 1.04 for the limestone, gravel, and diabase, respectively. This may have contributed to the higher shrinkage values in the sense that the diabase aggregate, which absorb more water than the limestone and gravel aggregate, would shrink more during drying.

6.8 Prediction Model Sensitivity Analysis

Based on the results of this study, a sensitivity analysis was performed on the three best predictors, the Bazant, CEB90, and Gardner/Lockman models. This analysis took into consideration the parameters for each of these models and how the predicted values would change over time based on changing one factor, while leaving the other factors constant. The predicted shrinkage was calculated at 28, 56, 90, and 180 days for each model. The factors that were common in all three models were 28-day compressive strength and relative humidity. The Bazant model includes a water content parameter.

6.8.1 Bazant B3 Model Sensitivity Analysis

The three factors that were analyzed for the Bazant model were 28-day compressive strength, water content, and relative humidity. Figure 6.12 presents the sensitivity of the predicted shrinkage as a function of compressive strength, keeping the water content (10pcf) and relative humidity (50%) constant.

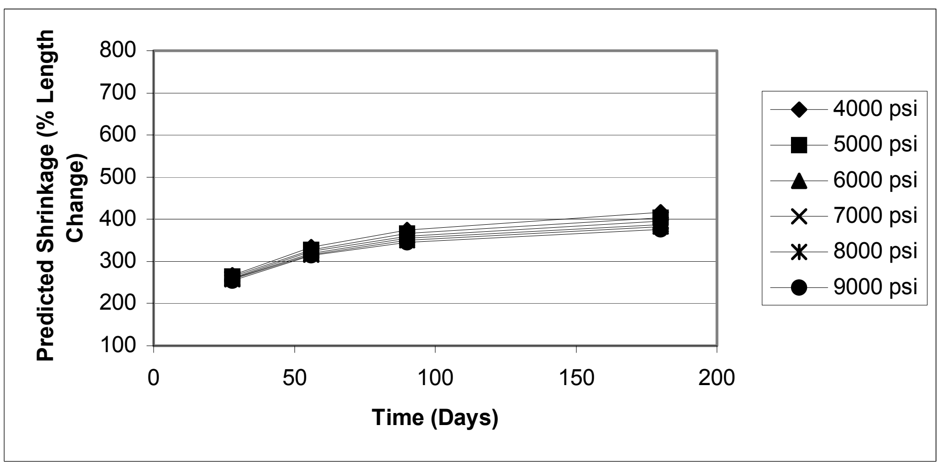

Figure 6.12 Bazant Sensitivity as a Function of Compressive Strength (Water Content, Relative Humidity Constant)

Figure 6.12 shows that the 28-day compressive strength has an increasing affect on predicted shrinkage with increasing time. However, the predicted shrinkage values do not appear to be significantly different, even at 180 days. Therefore, it does not appear that 28-day compressive strength has a significant effect on the predicted shrinkage values.

Figures 6.13 and 6.14 present the sensitivity of the predicted shrinkage as a function of water content. Figure 6.13 presents the sensitivity while keeping the compressive strength constant at 3000 psi, and the relative humidity at 50%. Figure 6.14 presents the influence of water content while keeping the compressive strength constant at 5000 psi, and the relative humidity at 50%.

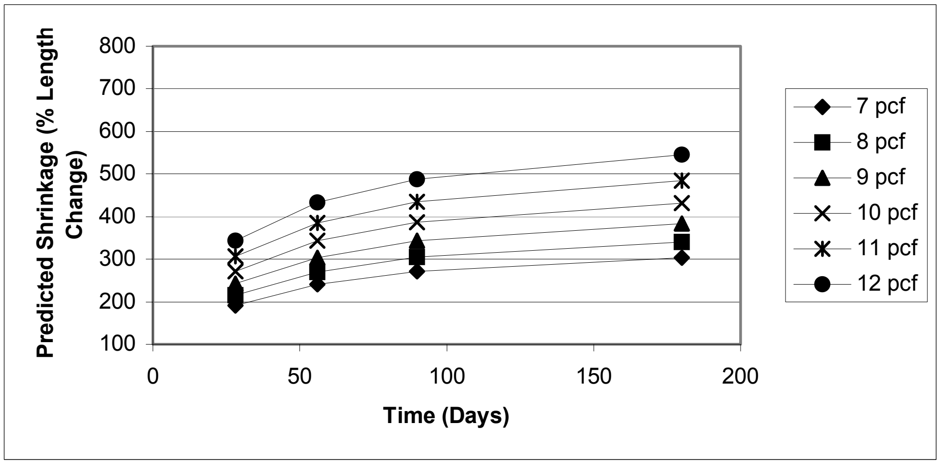

Figure 6.13 Bazant Sensitivity as a Function of Water Content (Compressive Strength=3000 psi, Relative Humidity=50%)

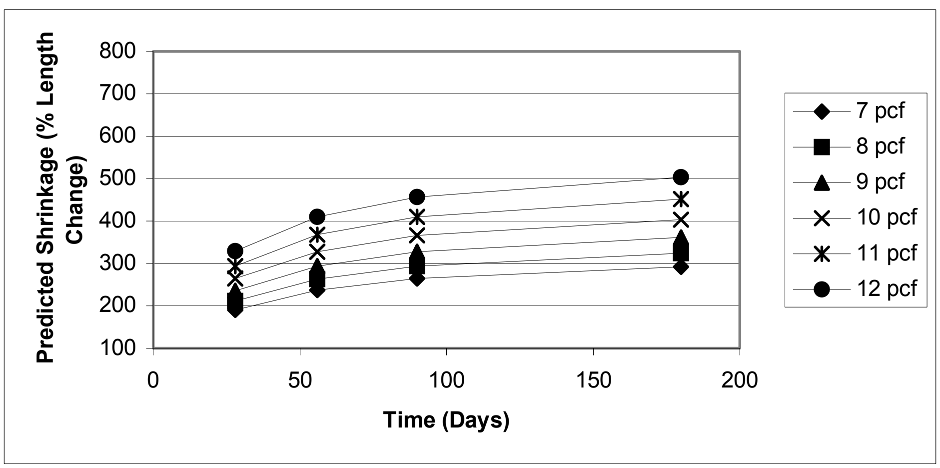

Figure 6.14 Bazant Sensitivity as a Function of Water Content (Compressive Strength=5000 psi, Relative Humidity=50%)

Figures 6.13 and 6.14 show that changing water content has a greater affect on the predicted shrinkage than changing the 28-day compressive strength presented in Figure 6.12. The only difference between Figures 6.13 and 6.14 are the level at which the 28-day compressive strengths are kept constant (3000 psi and 5000 psi). However, there is not a significant difference in the predicted shrinkage values of the two figures. This further reinforces the fact that the 28-day compressive strength has little affect on the predicted shrinkage value. Figures 6.13 and 6.14 also show that changing the water content has an increasing effect on the predicted shrinkage value as time increases.

Figures 6.15 and 6.16 present the sensitivity of the predicted shrinkage as a function of relative humidity. Figure 6.15 presents the sensitivity of the relative humidity while keeping the compressive strength constant at 3000 psi, and the water content at 10 pcf. Figure 6.16 presents the sensitivity of the relative humidity while keeping the compressive strength constant at 5000 psi, and the water content at 10 pcf.

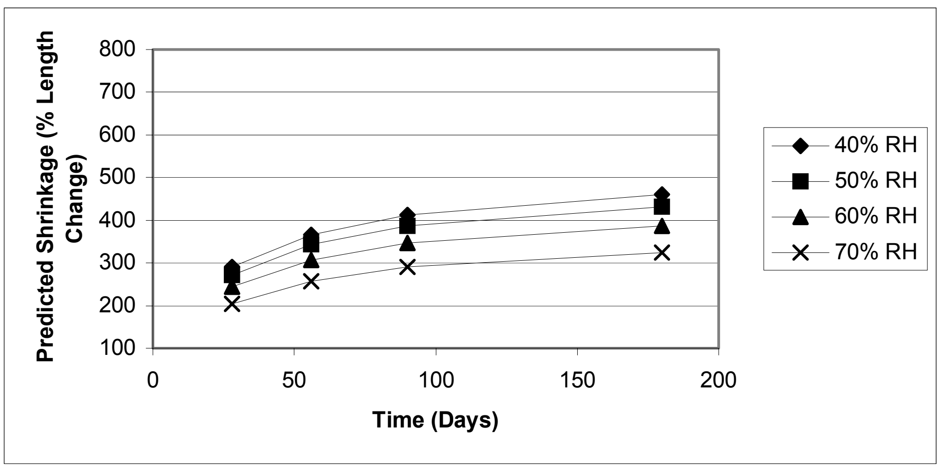

Figure 6.15 Bazant Sensitivity as a Function of Relative Humidity (Compressive Strength=3000 psi, Water Content=10 pcf)

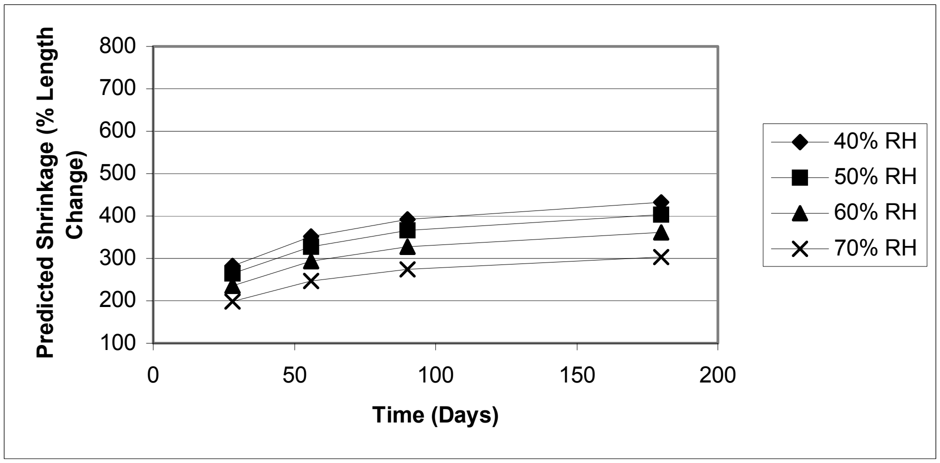

Figure 6.16 Bazant Sensitivity as a Function of Relative Humidity (Compressive Strength=5000 psi, Water Content=10 pcf)

Figures 6.15 and 6.16 show that changing relative humidity also has a greater effect on the predicted shrinkage than changing the 28-day compressive strength presented in Figure 6.12. Figures 6.15 and 6.16 also show that changing the relative humidity has an increasing effect on the predicted shrinkage value as time increases. It should also be noted that the difference in changing the relative humidity is less as the relative humidity decreases. The reason for this is that below 50% relative humidity, there is less moisture in the system that can be removed by drying.

Of the three factors that were analyzed for sensitivity on the Bazant model, changing water content had the greatest affect on predicted shrinkage values. The changing of the relative humidity also had an affect on the predicted shrinkage values, however, it was not as significant and changing the water content. And changing the 28-day compressive strength had virtually no effect on the predicted shrinkage values.

6.8.2 CEB90 Model Sensitivity Analysis

Two factors were analyzed for sensitivity analysis of the CEB90 model parameters, the 28-day compressive strength and relative humidity. Figure 6.17 presents the sensitivity of the predicted shrinkage as a function of compressive strength, keeping the relative humidity constant at 50%.

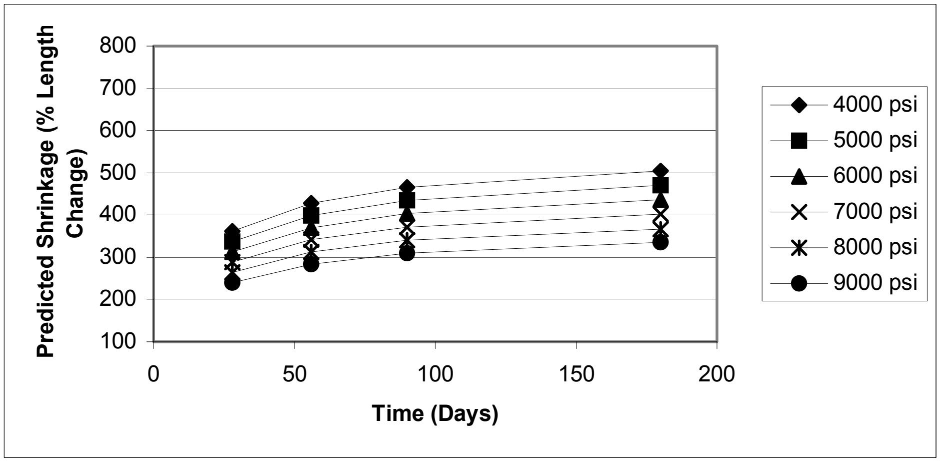

Figure 6.17 CEB90 Sensitivity as a Function of Compressive Strength (Relative Humidity Constant at 50%)

Figure 6.17 shows that changing the 28-day compressive strength has an effect on the predicted shrinkage values for the CEB90 model. The change appears to be the same for the each increment of 1000 psi increase in compressive strength.

Figures 6.18 and 6.19 present the sensitivity of the predicted shrinkage values for the CEB90 model when changing the relative humidity while keeping the 28-day compressive strength constant. Figure 6.18 keeps the 28-day compressive strength constant at 3000 psi, while Figure 6.19 keeps the 28-day compressive strength constant at 5000 psi.

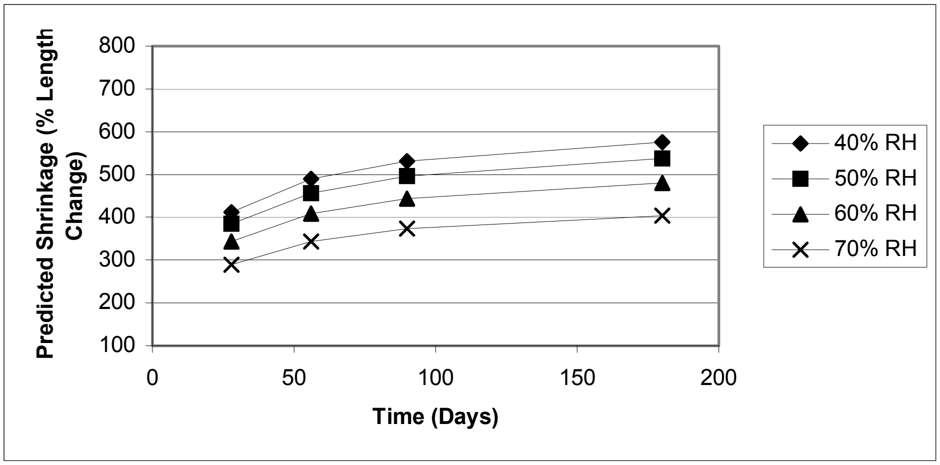

Figure 6.18 CEB90 Sensitivity as a Function of Relative Humidity (Compressive Strength Constant at 3000 psi)

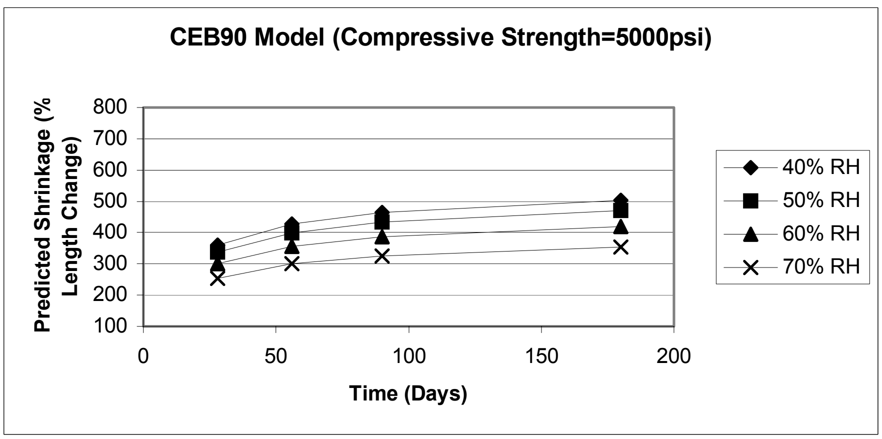

Figure 6.19 CEB90 Sensitivity as a Function of Relative Humidity (Compressive Strength Constant at 5000 psi)

Figures 6.18 and 6.19 show that changing the relative humidity for the CEB90 model does have an effect on the predicted shrinkage value over time. Again, it is shown that as the relative humidity decreases, the effect on the predicted shrinkage value is less. The two figures also show that the compressive strength along with the relative humidity have an influence on the predicted shrinkage value. The lower compressive strength (3000 psi) coupled with the change in relative humidity, has a greater effect on the predicted shrinkage value than the higher compressive strength (5000 psi).

6.8.3 Gardner/Lockman Model Sensitivity Analysis

The two factors analyzed for sensitivity analysis of the Gardner/Lockman model were the 28-day compressive strength and relative humidity. Figure 6.20 presents the sensitivity of the predicted shrinkage as a function of compressive strength, keeping the relative humidity constant at 50%.

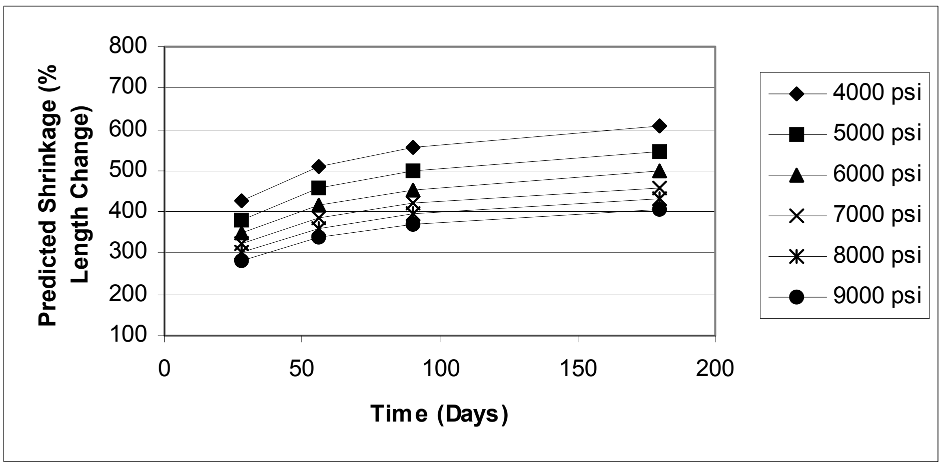

Figure 6.20 Gardner/Lockman Sensitivity as a Function of Compressive Strength (Relative Humidity Constant at 50%)

Figure 6.20 shows that changing the 28-compressive strength for the Gardner/Lockman model does have an affect on the predicted shrinkage values. The model is more sensitive at lower compressive strengths, there is a greater change between 4000 psi and 5000 psi, than there is between 8000 psi and 9000 psi. The model is also more sensitive at later ages.

Figures 6.21 and 6.22 present the sensitivity of the predicted shrinkage values of the Gardner/Lockman model when changing the relative humidity while keeping the 28-day compressive strength constant at 3000 psi and 5000 psi.

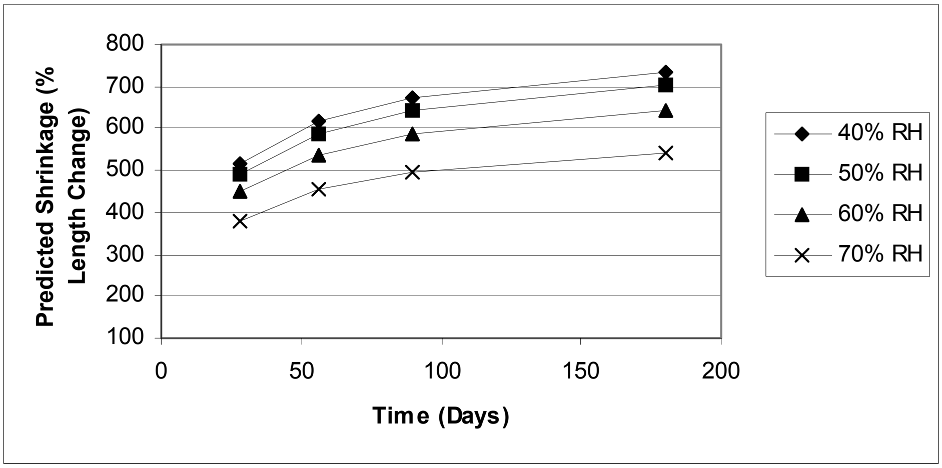

Figure 6.21 Gardner/Lockman Sensitivity as a Function of Relative Humidity (Compressive Strength Constant at 3000 psi)

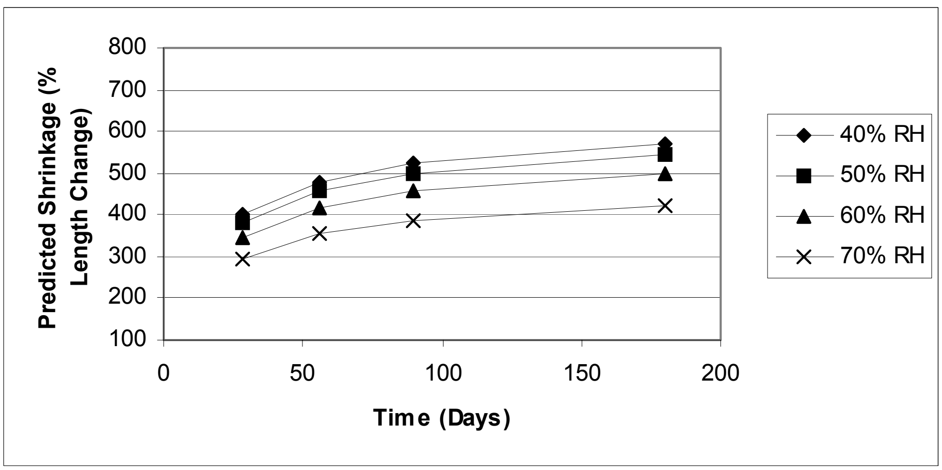

Figure 6.22 Gardner/Lockman Sensitivity as a Function of Relative Humidity (Compressive Strength Constant at 5000 psi)

Figures 6.21 and 6.22 show that the predicted shrinkage values for the Gardner/Lockman model are sensitive to changes in humidity over time. The changes are more sensitive at higher relative humidities and lower compressive strengths. As with the CEB90 model, the Gardner/Lockman model is more sensitive when changing the relative humidity is coupled with lower compressive strengths.

6.8.4 Summary of Prediction Model Sensitivity Analysis

The model sensitivity analyses demonstrate which parameters have the greatest effect on the predicted shrinkage values. The Bazant model was most sensitive to changes in the water content. This is in agreement with higher water losses from the smaller pores producing a greater amount of shrinkage. However, Bazant uses the 28-day compressive strength as a parameter, yet this parameter has little or no effect on the predicted shrinkage value. For concrete mixtures, there is a real question on the independence of water content and water-to-cement ratio. Prediction improvement may be accomplished by dropping the strength parameter and incorporating a more sensitive pore characteristic parameter for various groups of cementing materials.

The CEB90 and Gardner/Lockman models are sensitive to changes in compressive strength. From these models, a lower compressive strength will produce a greater amount of shrinkage. Lower compressive strength is an indication of a higher w/c ratio, which means that the mixture has large water content. Here again, the models may be improved by replacing compressive strength with a parameter that better reflects the influence of pore characteristics (volume and size distribution). A possible parameter would be a permeability-age function. Although the loss of water from the concrete pore system is a diffusion process, diffusion and permeability are related for saturated systems.

From the data obtained in this study, the compressive strength and water content do influence the amount of shrinkage; however, there seem to be other factors that have an influence on the shrinkage. The supplemental cementitious material mixtures had higher compressive strengths than the portland cement concrete mixtures. They also had a greater amount of shrinkage. According to the prediction models, they should have less shrinkage. One of the reasons for the greater shrinkage in these mixtures is probably due to the denser matrix of the system. As mentioned previously, the supplemental cementitious material mixtures have more small capillary voids than the ordinary portland cement concrete mixtures. The removal of water from these smaller capillary voids contributes more to the amount of shrinkage in the system than the removal of water from the larger voids.

Another factor that appears to influence shrinkage in this study is the type of aggregate used in the mixture. The diabase aggregate, with higher absorption values, consistently showed a greater amount of shrinkage than the mixtures using limestone and gravel aggregate. This could be due to the diabase aggregate contributing more to the water loss from the system than the limestone and gravel aggregate.

It appears that the models try to take into account the void structure through the use of compressive strength and water content. However, the amount of shrinkage is influenced the most by the removal of water from the smaller capillary voids, and compressive strength is more an indication of the volume of the voids and not the pore size distribution. As for the influence of the aggregate on shrinkage, the models do not address the physical properties of the aggregate, such as absorption, that may have an influence on the amount of shrinkage.

CHAPTER 7: CONCLUSIONS

1. The portland cement concrete mixtures containing diabase as the aggregate consistently exhibited greater drying shrinkage than the mixtures containing limestone and gravel as the aggregate.

2. The type of aggregate used in a mixture had an influence on the drying shrinkage of the mixture.

3. The mixtures containing fly ash exhibited greater drying shrinkage than those containing microsilica and slag cement.

4. There is a correlation between the percentage length change for unrestrained shrinkage specimens and microstrain for restrained shrinkage specimens. Thus, the unrestrained shrinkage test may be used as a performance based specification for restrained concrete systems.

5. Based on the results of this study, the percentage length change for the portland cement concrete specimens should be limited to 0.0300 at 28 days and 0.0400 at 90 days to reduce the probablility of cracking due to drying shrinkage.

6. Based on the results of this study, the percentage length change for the supplemental cementitious material mixtures should be limited to 0.0400 at 28 days and 0.0500 at 90 days to reduce the probability of cracking due to drying shrinkage.

7. The CEB90 model is the best predictor of drying shrinkage for the portland cement concrete mixtures followed by the Bazant B3, Gardner/Lockman, ACI 209, and Sakata models.

8. The Gardner/Lockman model is the best predictor of drying shrinkage for the fly ash and slag cement mixtures followed by the Bazant B3, and CEB90 models.

9. For Type II cements, when using the Gardner/Lockman model, the correction factor assigned for Type II cement is 0.70. By changing this value to 0.80, the predicted values are the same as the measured values for the A4-diabase/fly ash, A4-diabase/slag cement, and the A5-diabase/slag cement mixtures.

CHAPTER 8: RECOMMENDATIONS

1. The unrestrained shrinkage test method, ASTM C 157, may be used as a performance based specification for restrained concrete systems for concrete mixtures purchased by the Virginia Department of Transportation.

2. The percentage length change should be limited to 0.0300 at 28 days and 0.0400 at 90 days for portland cement concrete mixtures, and 0.0400 at 28 days and 0.0500 at 90 days for supplemental cementitious material mixtures purchased by the Virginia Department of Transportation. This will aid in reducing the probability of cracking due to drying shrinkage.

3. Measurements should be continued on the existing unrestrained shrinkage specimens fabricated in this study to obtain percentage length changes at later ages.

4. Further research is needed in the area of aggregate influence on drying shrinkage.

5. Further research is needed on the influence of the pore size distribution of the cement paste on drying shrinkage.

6. There is a need to develop a prediction model that takes into account the aggregate influence and cement paste pore size distribution on drying shrinkage.

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APPENDIX A

Material Properties and Batch Quantities

Table A1: Aggregate Properties

Coarse Aggregate Properties

Gradation	Percent Passing			
Particle Size	**Limestone**	**Gravel**	**Diabase**	**VDOT Spec.**
25 mm	100	99	99	90-100
19 mm	81	72	79	
12.7 mm	19	25	34	26-60
9.6 mm	3	12	8	
4.75 mm	0	2	1	max 7
2.36 mm	0	0	1	max 3
Unit Weight, kg	1577	1673	1752	
Bulk Dry Specific Gravity	2.81	2.59	2.92	
Absorption, %	0.36	0.81	0.73	

Associated Natural Fine Aggregate Properties

Gradation	Percent Passing			
Particle Size	**Limestone**	**Gravel**	**Diabase**	**VDOT Spec.**
9.6 mm	100	100	100	min 100
4.75 mm	97	99	99	94-100
2.36 mm	80	90	83	80-100
1.18 mm	70	78	68	49-85
0.6 mm	53	46	42	25-59
0.3 mm	16	17	12	8-26
0.15 mm	2	2	4	max 10
0.075 mm	0.4	0.54	2	
Fineness Modulus	2.82	2.68	2.92	
Bulk Dry Specific Gravity	2.59	2.55	2.53	
Absorption, %	0.48	0.75	1.04	

Table A2. Cement Properties

Potland Cement Type I/II

Chemical Analysis

Analyte	Percent by Weight DWM-1	DWM-2	ASTM C 150 - 98 Type II
SiO_2	21.25	21.17	20.0 min
Al_2O_3	4.49	4.49	6.0 max
Fe_2O_3	3.04	3.03	6.0 max
CaO	63.51	63.41	-
MgO	2.48	2.5	6.0 max
SO_3	2.47	2.46	3.0 max
Na_2O	0.17	0.17	-
K_2O	0.82	0.81	-
TiO_2	0.21	0.22	-
P_2O_5	0.11	0.11	-
Mn_2O_3	0.06	0.06	-
SrO	0.14	0.14	-
L.O.I. (950 C)	1.06	1.07	3.0 max
Total	99.83	99.65	-
Alkalis as Na_2O	0.72	0.71	*0.6 max

Compounds

Calculated ASTM C 150-97	DWM-1	DWM-2	Mass Estimated by QXRD	ASTM C 150 - 98 Type II
C3S	55	56	65	-
C2S	19	19	16	-
C3A	7	7	4.2	8.0 max
C4AF	9	9	10	-

*Low alkali cement requirement.

Table A3: A3 -Mixtures/Portland Cement (Test Series 1)

Ingredient	Limestone	Gravel	Diabase
Cement Type I/II, kg	20.14	20.08	20.07
Fine Aggregate, kg	46.55	40.80	40.78
Coarse Aggregate, kg	59.19	65.32	64.98
Water, kg	9.87	9.23	9.43
Total, kg	135.75	135.43	135.26
AEA, mL	10	10	10
HRWR, mL	0	0	0

Table A4: A4 -Mixtures/Portland Cement (Test Series 1)

Ingredient	Limestone	Gravel	Diabase
Cement Type I/II, kg	21.85	22.76	21.91
Fine Aggregate, kg	44.66	37.31	38.75
Coarse Aggregate, kg	59.45	65.77	66.07
Water, kg	9.83	9.56	9.42
Total, kg	135.79	135.40	136.15
AEA, mL	11	11	11
HRWR, mL	0	0	0
Retarder, mL	50	52	50

Table A5: A5 -Mixtures/Portland Cement (Test Series 1)

Ingredient	Limestone	Gravel	Diabase
Cement Type I/II, kg	21.79	22.69	23.86
Fine Aggregate, kg	40.82	34.40	37.79
Coarse Aggregate, kg	54.59	59.00	64.37
Water, kg	7.19	7.94	9.31
Total, kg	124.39	124.03	135.33
AEA, mL	11	11	12
HRWR, mL	175	74	78

Table A6: A4 -Diabase/Fly ash (Test Series 2)

Ingredient	Batch 1	Batch 2	Batch 3
Cement Type I/II, kg	18.70	18.70	18.70
Fly Ash, kg	4.39	4.39	4.39
Fine Aggregate, kg	36.94	36.94	36.94
Coarse Aggregate, kg	65.78	65.78	65.78
Water, kg	9.93	9.93	9.93
Total, kg	135.74	135.74	135.74
AEA, mL	10	11	10
HRWR, mL	140	150	150
Retarder, mL	40	45	45
w/c+p	0.43	0.43	0.43
Slump, mm	102	102	102
Air Content, %	5.0	5.0	5.1
Temperature, ^{o}C	18	19	22
Unit Weight$_{prop}$, kg/m^3	2346	2346	2346
Unit Weight$_{meas}$, kg/m^3	2424	2440	2430
Relative Yield	0.97	0.96	0.97

Table A7: A4 -Diabase/Microsilica (Test Series 2)

Ingredient	Batch 1	Batch 2	Batch 3
Cement Type I/II, kg	20.34	20.34	20.34
Microsilica, kg	1.54	1.54	1.54
Fine Aggregate, kg	38.42	38.42	38.42
Coarse Aggregate, kg	65.54	65.54	65.54
Water, kg	9.41	9.41	9.41
Total, kg	135.25	135.25	135.25
AEA, mL	10	11	11
HRWR, mL	40	43	50
Retarder, mL	90	108	100
w/c+p	0.43	0.43	0.43
Slump, mm	102	102	102
Air Content, %	6.0	6.8	6.5
Temperature, ^{o}C	21	19	27
Unit Weight$_{prop}$, kg/m^3	2346	2346	2346
Unit Weight$_{meas}$, kg/m^3	2340	2321	2325
Relative Yield	1.00	1.01	1.01

Table A8: A4 -Diabase/Slag Cement (Test Series 2)

Ingredient	Batch 1	Batch 2	Batch 3
Cement Type I/II, kg	12.35	12.35	12.35
Slag Cement, kg	8.23	8.23	8.23
Fine Aggregate, kg	36.02	36.02	36.02
Coarse Aggregate, kg	61.62	61.62	61.62
Water, kg	8.91	8.91	8.91
Total, kg	127.13	127.13	127.13
AEA, mL	10	10	10
HRWR, mL	100	100	100
Retarder, mL	40	40	40
w/c+p	0.43	0.43	0.43
Slump, mm	102	76	102
Air Content, %	5.2	5.2	5.6
Temperature, ^oC	18	21	18
Unit Weight$_{prop}$, kg/m^3	2346	2346	2346
Unit Weight$_{meas}$, kg/m^3	2463	2409	2457
Relative Yield	0.95	0.97	0.95

Table A9: A5 -Diabase/Slag cement (Test Series 2)

Ingredient	Batch 1	Batch 2	Batch 3
Cement Type I/II, kg	13.45	13.45	13.45
Slag cement, kg	8.96	8.96	8.96
Fine Aggregate, kg	35.50	35.50	35.50
Coarse Aggregate, kg	60.46	60.46	60.46
Water, kg	8.74	8.74	8.74
Total, kg	127.11	127.11	127.11
AEA, mL	10	10	10
HRWR, mL	195	195	195
w/c+p	0.39	0.39	0.39
Slump, mm	102	102	102
Air Content, %	5.5	4.7	4.9
Temperature, ^oC	18	19	19
Unit Weight$_{prop}$, kg/m^3	2378	2378	2378
Unit Weight$_{meas}$, kg/m^3	2458	2485	2472
Relative Yield	0.97	0.96	0.96

Table A10: A3 -Limestone/Portland Cement (Test Series 3

Ingredient	Batch 1	Batch 2	Batch 3
Cement Type I/II, kg	8.08	8.08	8.08
Fine Aggregate, kg	18.68	18.68	18.68
Coarse Aggregate, kg	23.75	23.75	23.75
Water, kg	3.97	3.97	3.97
Total, kg	54.48	54.48	54.48
AEA, mL	4	4	4
HRWR, mL	0	53	20
w/c	0.49	0.49	0.49
Slump, mm	127	127	127
Air Content, %	4.8	4.1	6.4
Temperature, ^{o}C	27	23	26
Unit Weight$_{prop}$, kg/m^3	2348	2348	2348
Unit Weight$_{meas}$, kg/m^3	2300	2380	2366
Relative Yield	1.02	0.99	0.99

Table A11: A4 -Limestone/Portland Cement (Test Series 3

Ingredient	Batch 1	Batch 2	Batch 3
Cement Type I/II, kg	8.76	8.76	8.76
Fine Aggregate, kg	17.91	17.91	17.91
Coarse Aggregate, kg	23.85	23.85	23.85
Water, kg	3.95	3.95	3.95
Total, kg	54.47	54.47	54.47
AEA, mL	4	4	4
HRWR, mL	0	57	15
Retarder, mL	20	6	6
w/c	0.45	0.45	0.45
Slump, mm	102	89	102
Air Content, %	5.0	5.1	6.0
Temperature, ^{o}C	23	23	26
Unit Weight$_{prop}$, kg/m^3	2338	2338	2338
Unit Weight$_{meas}$, kg/m^3	2317	2415	2380
Relative Yield	1.01	0.97	0.98

Table A12: A5 -Limestone/Portland Cement (Test Series 3

Ingredient	Batch 1	Batch 2	Batch 3
Cement Type I/II, kg	9.55	9.55	9.55
Fine Aggregate, kg	17.87	17.87	17.87
Coarse Aggregate, kg	23.90	23.90	23.90
Water, kg	3.16	3.16	3.16
Total, kg	54.48	54.48	54.48
AEA, mL	5	5	5
HRWR, mL	77	77	77
w/c	0.33	0.33	0.33
Slump, mm	102	102	102
Air Content, %	5.9	4.3	6.0
Temperature, ^oC	24	23	26
Unit Weight$_{prop}$, kg/m^3	2367	2367	2367
Unit Weight$_{meas}$, kg/m^3	2395	2422	2385
Relative Yield	0.99	0.98	0.99

Table A13: A3 -Gravel/Portland Cement (Test Series 3)

Ingredient	Batch 1	Batch 2	Batch 3
Cement Type I/II, kg	8.08	8.08	8.08
Fine Aggregate, kg	16.42	16.42	16.42
Coarse Aggregate, kg	26.29	26.29	26.29
Water, kg	3.70	3.70	3.70
Total, kg	54.49	54.49	54.49
AEA, mL	4	4	4
HRWR, mL	25	25	25
w/c	0.46	0.46	0.46
Slump, mm	102	102	102
Air Content, %	5.1	5.2	4.4
Temperature, ^oC	27	22	22
Unit Weight$_{prop}$, kg/m^3	2245	2245	2245
Unit Weight$_{meas}$, kg/m^3	2291	2299	2365
Relative Yield	0.98	0.98	0.95

Table A14: A4 -Gravel/Portland Cement (Test Series 3)

Ingredient	Batch 1	Batch 2	Batch 3
Cement Type I/II, kg	9.15	9.15	9.15
Fine Aggregate, kg	15.01	15.01	15.01
Coarse Aggregate, kg	26.46	26.46	26.46
Water, kg	3.86	3.86	3.86
Total, kg	54.48	54.48	54.48
AEA, mL	5	5	5
HRWR, mL	30	10	10
Retarder, mL	21	21	7
w/c	0.42	0.42	0.42
Slump, mm	102	102	102
Air Content, %	5.5	5.1	5.0
Temperature, ^{o}C	27	23	22
Unit Weight$_{prop}$, kg/m^3	2235	2235	2235
Unit Weight$_{meas}$, kg/m^3	2344	2350	2349
Relative Yield	0.95	0.95	0.95

Table A15: A5 -Gravel/Portland Cement (Test Series 3)

Ingredient	Batch 1	Batch 2	Batch 3
Cement Type I/II, kg	9.95	9.95	9.95
Fine Aggregate, kg	15.10	15.10	15.10
Coarse Aggregate, kg	25.90	25.90	25.90
Water, kg	3.53	3.53	3.53
Total, kg	54.48	54.48	54.48
AEA, mL	5	5	5
HRWR, mL	70	60	60
w/c	0.35	0.35	0.35
Slump, mm	102	102	102
Air Content, %	4.3	5.8	3.9
Temperature, ^{o}C	25	22	22
Unit Weight$_{prop}$, kg/m^3	2295	2295	2295
Unit Weight$_{meas}$, kg/m^3	2349	2319	2393
Relative Yield	0.98	0.99	0.96

Table A16: A3 -Diabase/Portland Cement (Test Series 3)

Ingredient	Batch 1	Batch 2	Batch 3
Cement Type I/II, kg	8.08	8.08	8.08
Fine Aggregate, kg	16.42	16.42	16.42
Coarse Aggregate, kg	26.16	26.16	26.16
Water, kg	3.82	3.82	3.82
Total, kg	54.48	54.48	54.48
AEA, mL	4	4	4
HRWR, mL	20	20	20
w/c	0.47	0.47	0.47
Slump, mm	127	102	127
Air Content, %	4.2	4.0	4.1
Temperature, ^{o}C	24	23	22
Unit $Weight_{prop}$, kg/m^3	2355	2355	2355
Unit $Weight_{meas}$, kg/m^3	2381	2464	2406
Relative Yield	0.99	0.96	0.98

Table A17: A4 -Diabase/Portland Cement (Test Series 3)

Ingredient	Batch 1	Batch 2	Batch 3
Cement Type I/II, kg	8.78	8.78	8.78
Fine Aggregate, kg	15.60	15.60	15.60
Coarse Aggregate, kg	26.30	26.30	26.30
Water, kg	3.80	3.80	3.80
Total, kg	54.48	54.48	54.48
AEA, mL	4	4	4
HRWR, mL	20	20	20
Retarder, mL	6	6	6
w/c	0.43	0.43	0.43
Slump, mm	102	102	102
Air Content, %	5.2	5.5	6.1
Temperature, ^{o}C	23	23	22
Unit $Weight_{prop}$, kg/m^3	2346	2346	2346
Unit $Weight_{meas}$, kg/m^3	2467	2446	2387
Relative Yield	0.95	0.96	0.98

Table A18: A5 -Diabase/Portland Cement (Test Series 3)

Ingredient	Batch 1	Batch 2	Batch 3
Cement Type I/II, kg	9.61	9.61	9.61
Fine Aggregate, kg	15.21	15.21	15.21
Coarse Aggregate, kg	25.91	25.91	25.91
Water, kg	3.75	3.75	3.75
Total, kg	54.48	54.48	54.48
AEA, mL	5	5	5
HRWR, mL	30	40	40
w/c	0.39	0.39	0.39
Slump, mm	102	102	102
Air Content, %	3.5	4.3	4.0
Temperature, ^{o}C	24	23	23
Unit Weight$_{prop}$, kg/m^3	2378	2378	2378
Unit Weight$_{meas}$, kg/m^3	2505	2481	2463
Relative Yield	0.95	0.96	0.97

APPENDIX B

Error Percentage Analysis

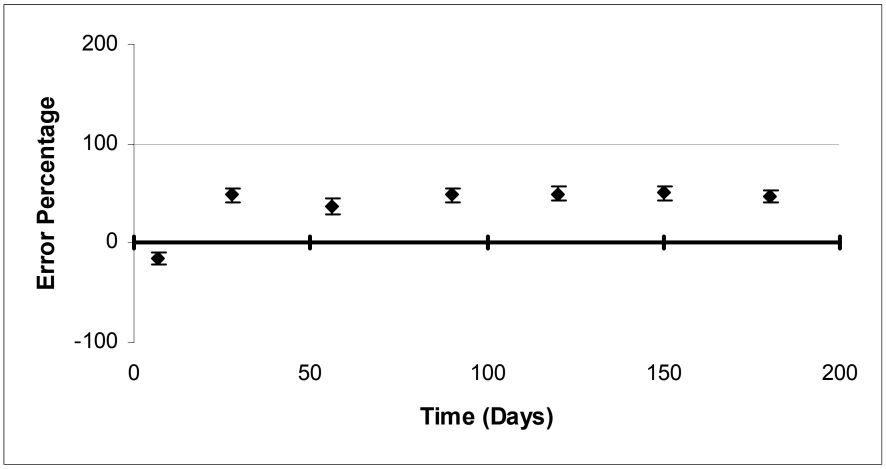


Figure B1: Error Percentage for ACI 209 Model (Limestone Mixtures)

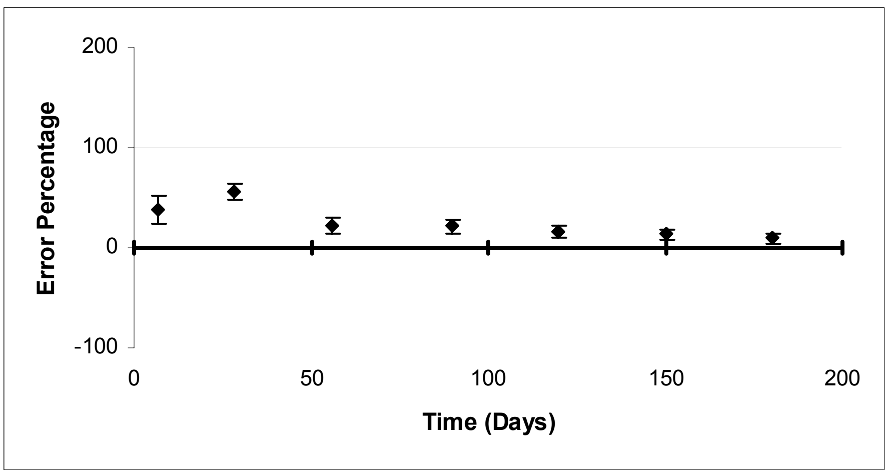


Figure B2: Error Percentage for Bazant Model (Limestone Mixtures)

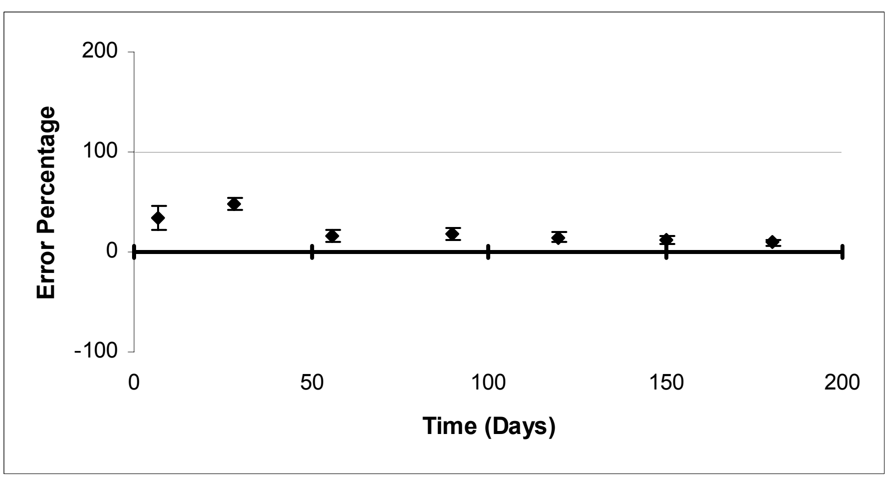


Figure B3: Error Percentage for CEB Model (Limestone Mixtures)

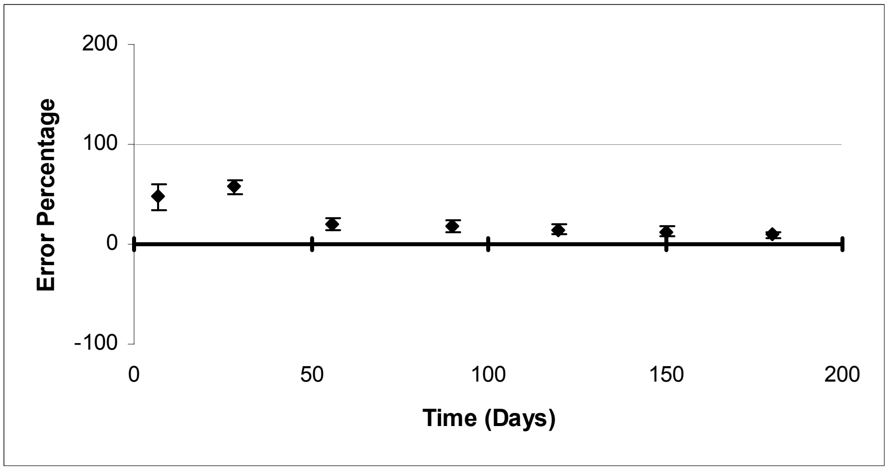


Figure B4: Error Percentage for Gardner/Lockman Model (Limestone Mixtures)

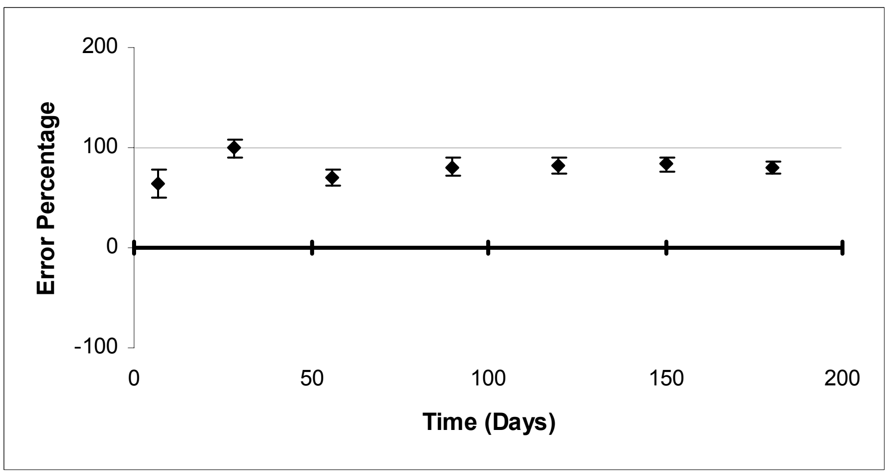


Figure B5: Error Percentage for Sakata Model (Limestone Mixtures)

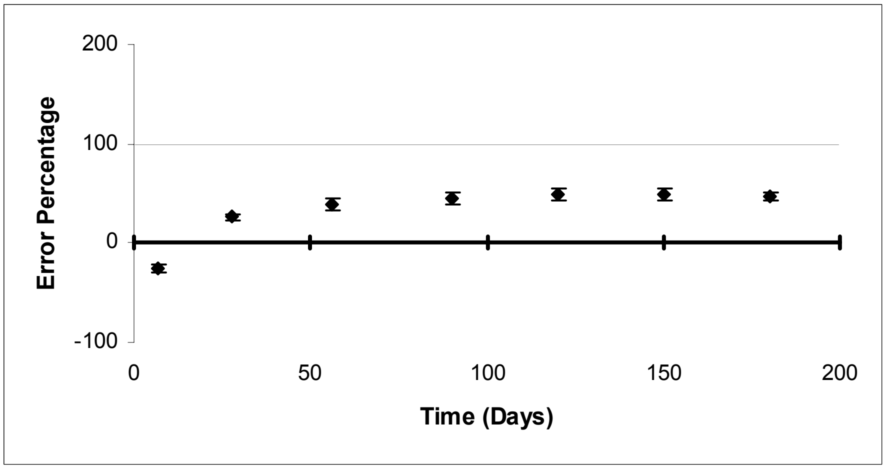


Figure B6: Error Percentage for ACI 209 Model (Gravel Mixtures)

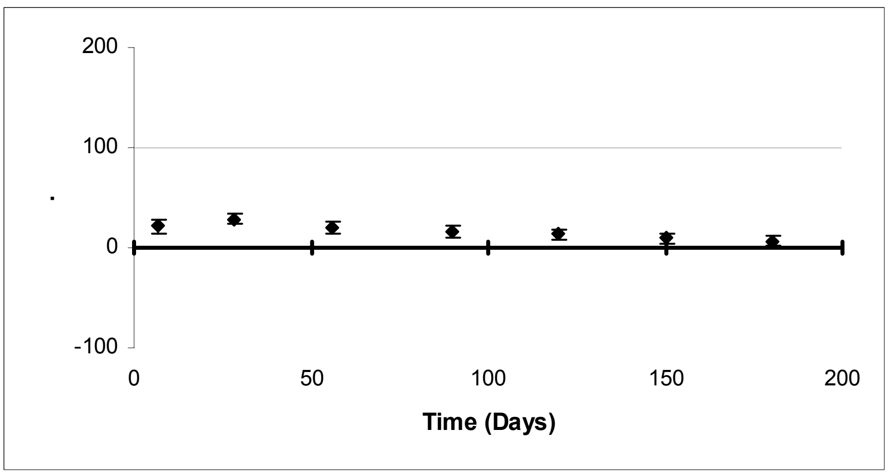


Figure B7: Error Percentage for Bazant Model (Gravel Mixtures)

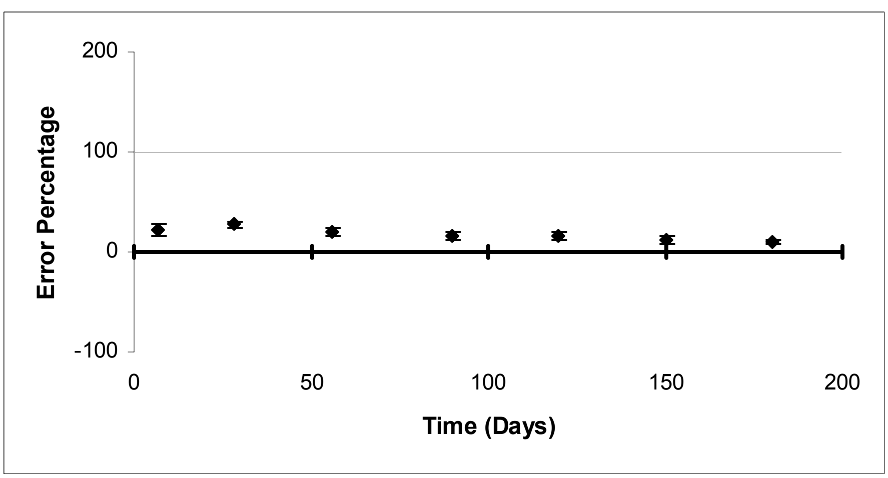


Figure B8: Error Percentage for CEB90 Model (Gravel Mixtures)

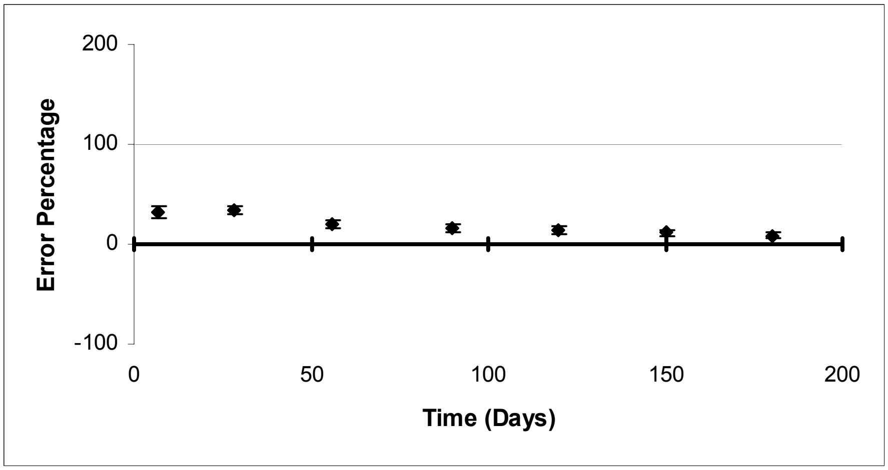


Figure B9: Error Percentage for Gardner/Lockman Model (Gravel Mixtures)

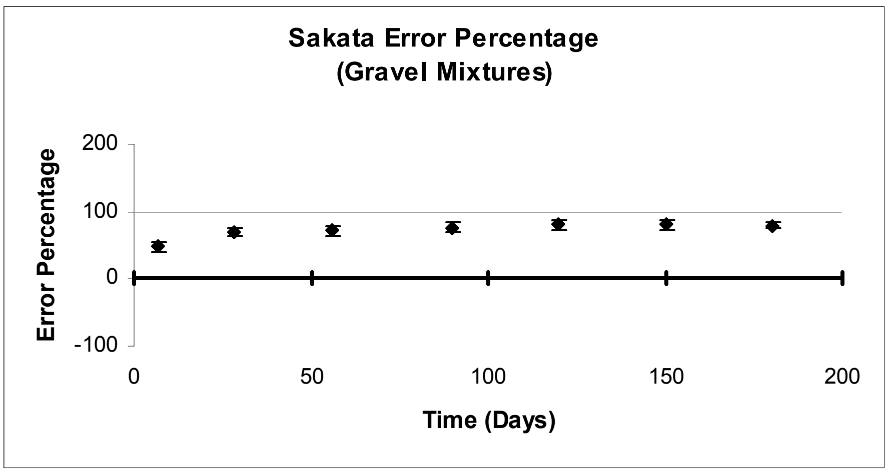


Figure B10: Error Percentage for Sakata Model (Gravel Mixtures)

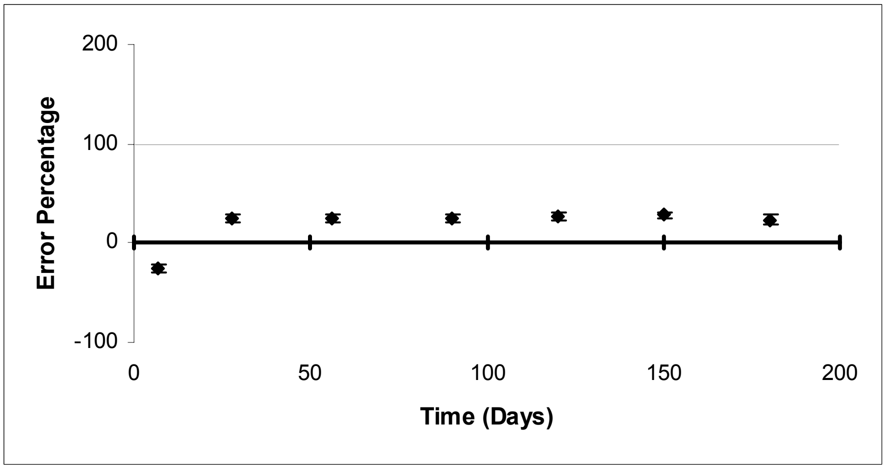


Figure B11: Error Percentage for ACI 209 Model (Diabase Mixtures)

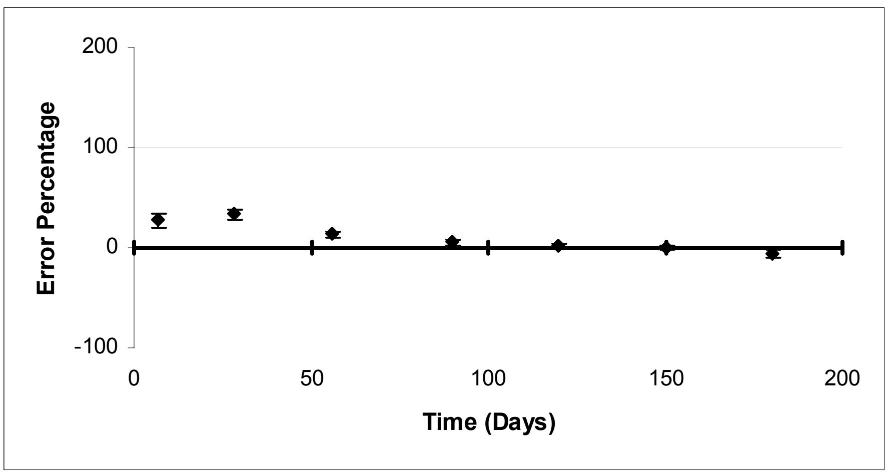


Figure B12: Error Percentage for Bazant Model (Diabase Mixtures)

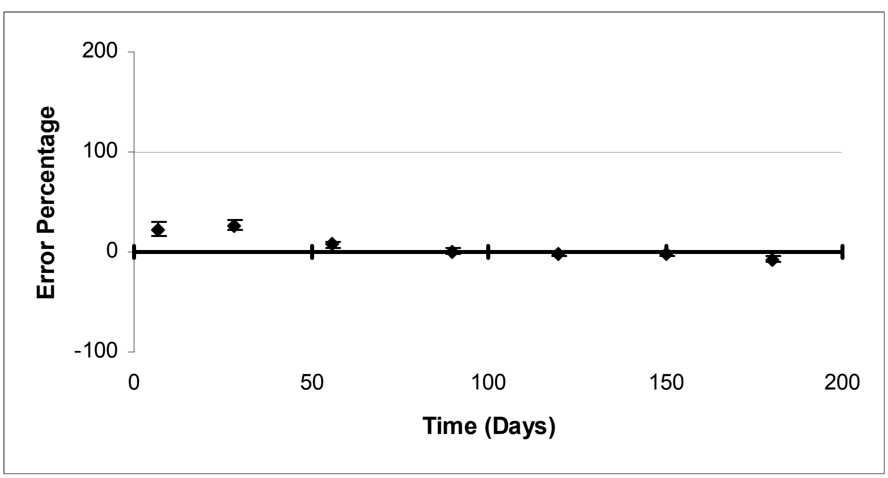


Figure B13: Error Percentage for CEB90 Model (Diabase Mixtures)

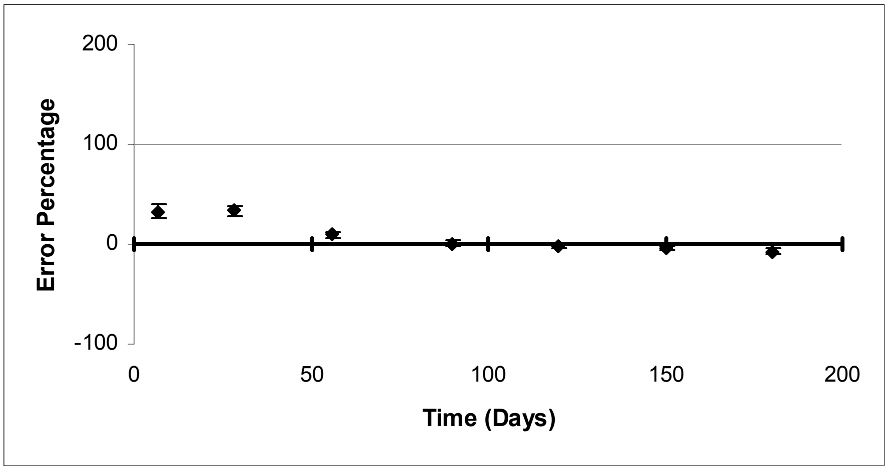


Figure B14: Error Percentage for Gardner/Lockman Model (Diabase Mixtures)

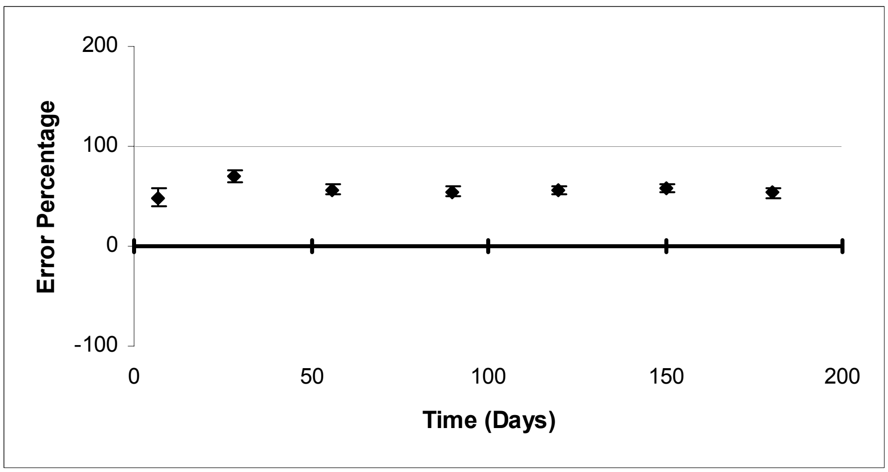


Figure B15: Error Percentage for Sakata Model (Diabase Mixtures)

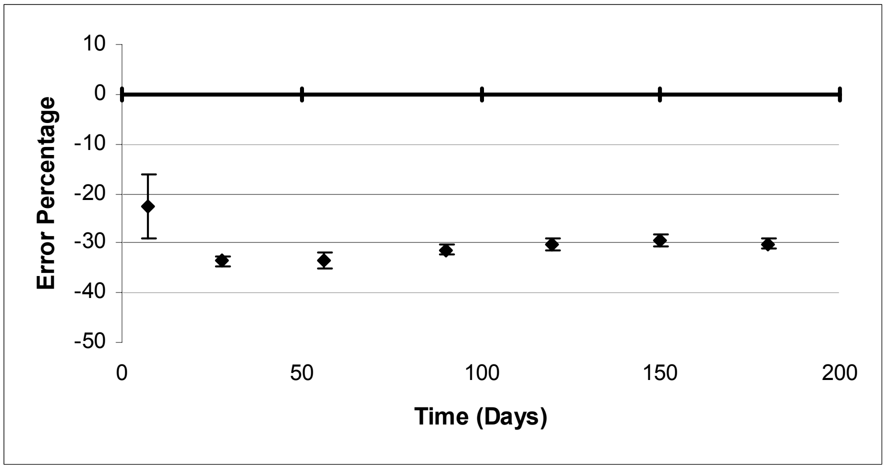


Figure B16: Error Percentage for Bazant Model (A4-D/FA Mixtures)

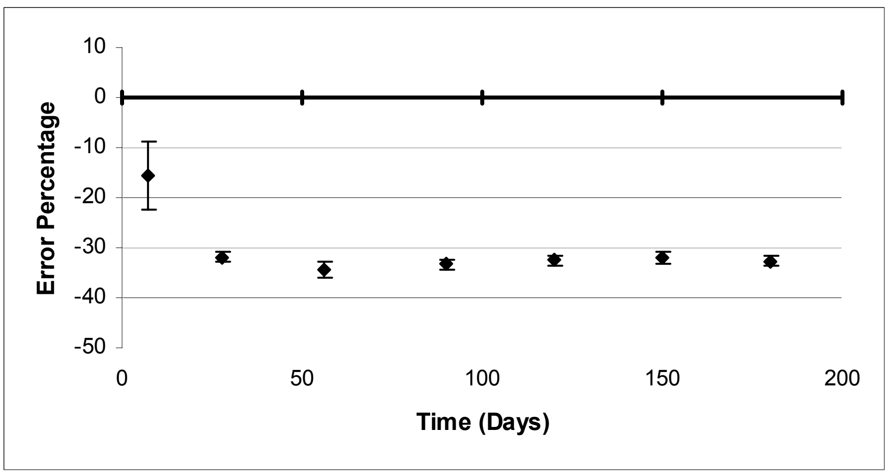


Figure B17: Error Percentage for CEB90 Model (A4-D/FA Mixtures)

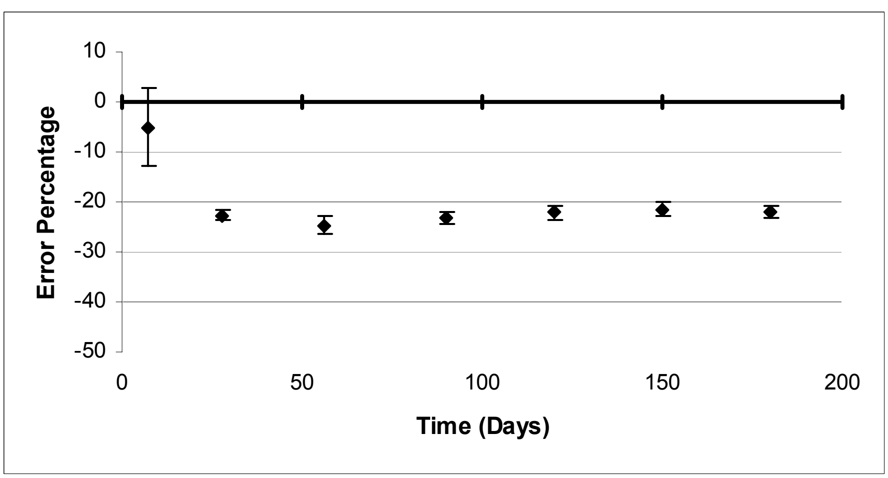


Figure B18: Error Percentage for Gardner/Lockman Model (A4-D/FA Mixtures)

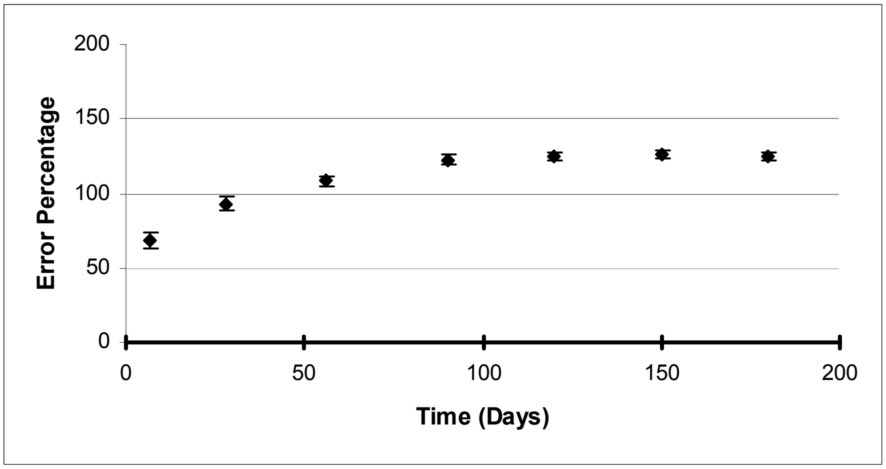


Figure B19: Error Percentage for ACI 209 Model (A4-D/MS Mixtures)

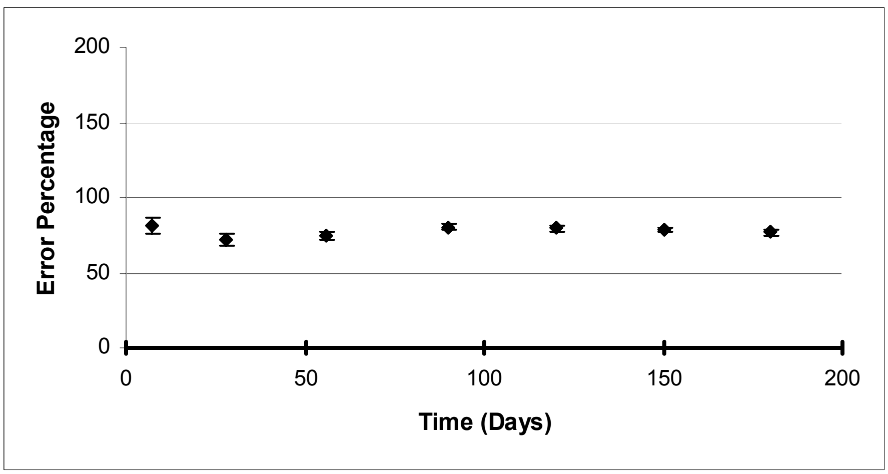


Figure B20: Error Percentage for Bazant Model (A4-D/MS Mixtures)

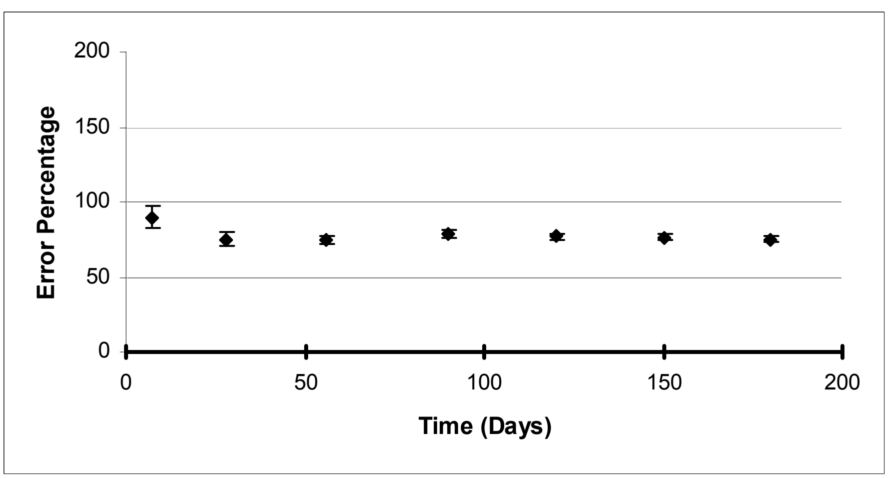


Figure B21: Error Percentage for CEB90 Model (A4-D/MS Mixtures)

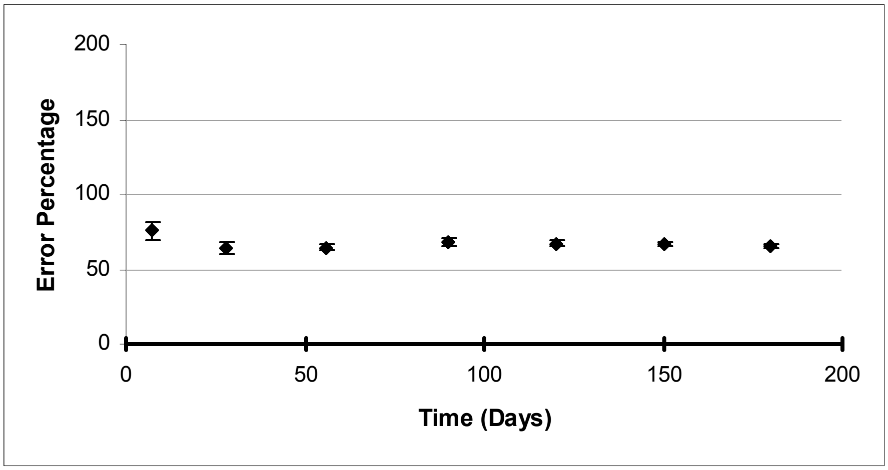


Figure B22: Error Percentage for Gardner/Lockman Model (A4-D/MS Mixtures)

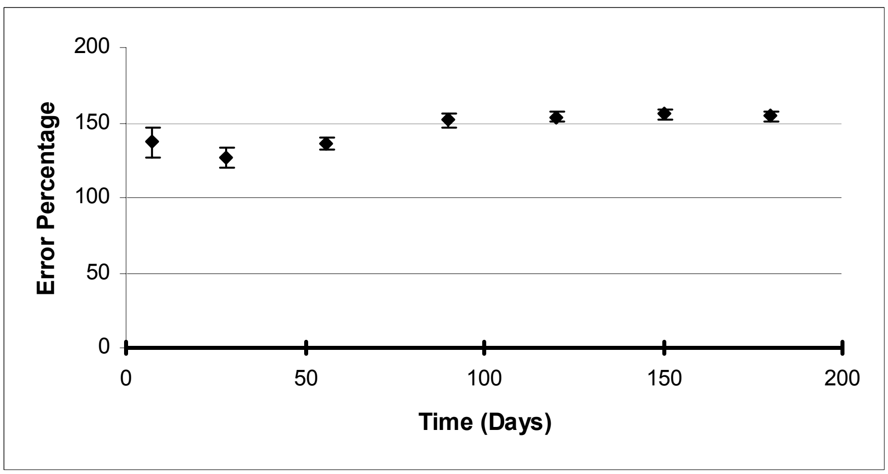


Figure B23: Error Percentage for Sakata Model (A4-D/MS Mixtures)

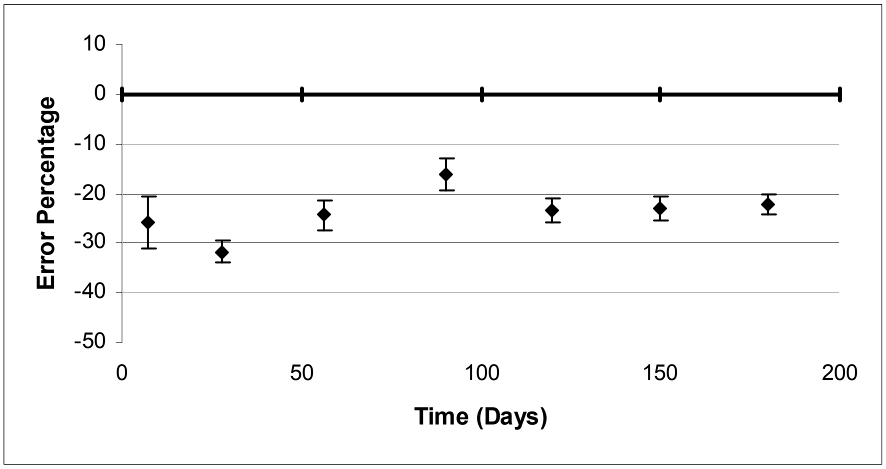


Figure B24: Error Percentage for Bazant Model (A4-D/S Mixtures)

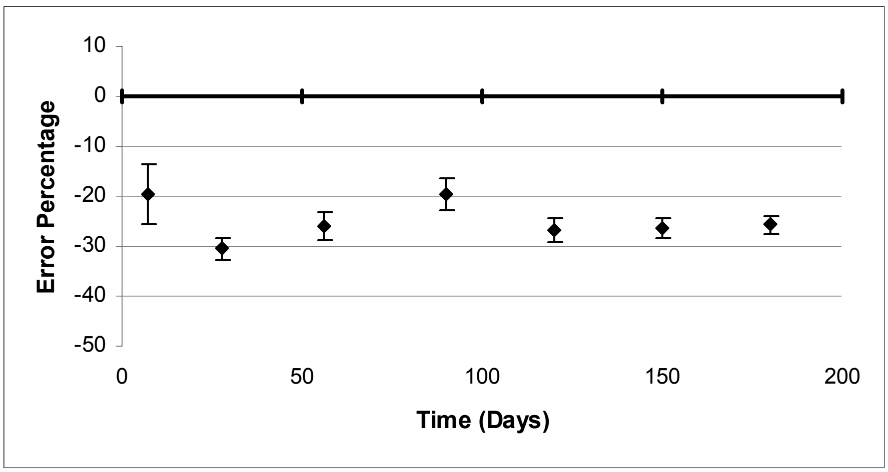


Figure B25: Error Percentage for CEB90 Model (A4-D/S Mixtures)

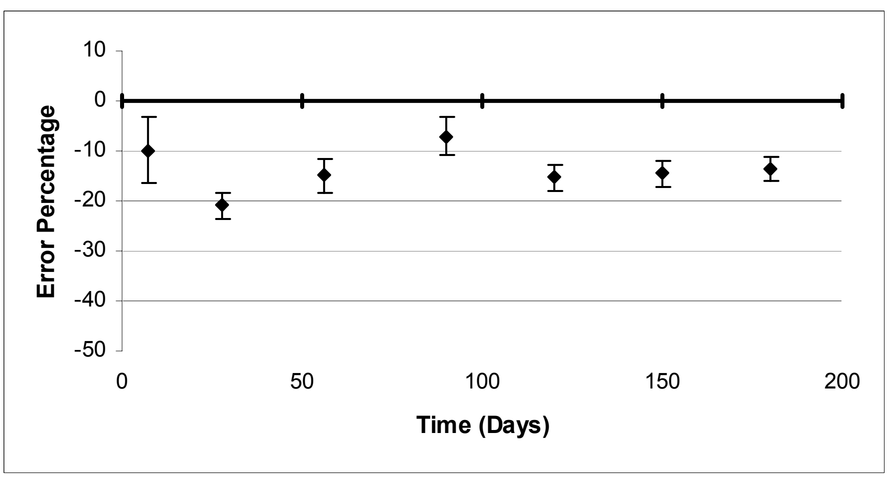


Figure B26: Error Percentage for Gardner/Lockman Model (A4-D/S Mixtures)

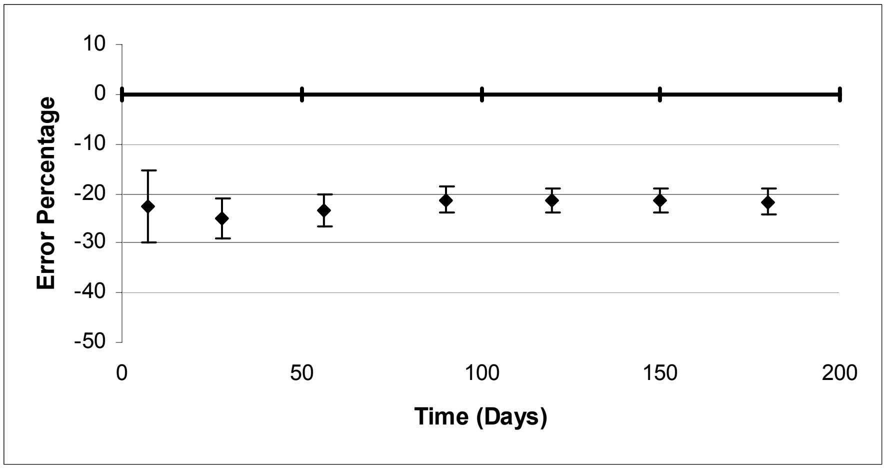


Figure B27: Error Percentage for Bazant Model (A5-D/S Mixtures)

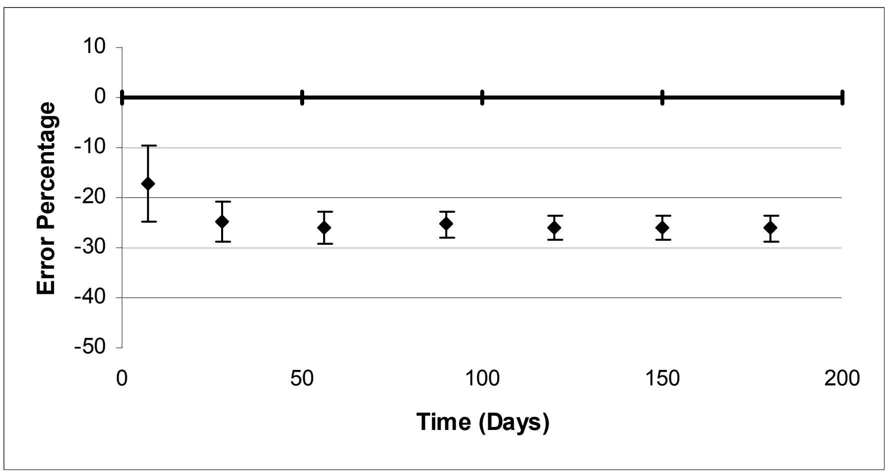


Figure B28: Error Percentage for CEB90 Model (A5-D/S Mixtures)

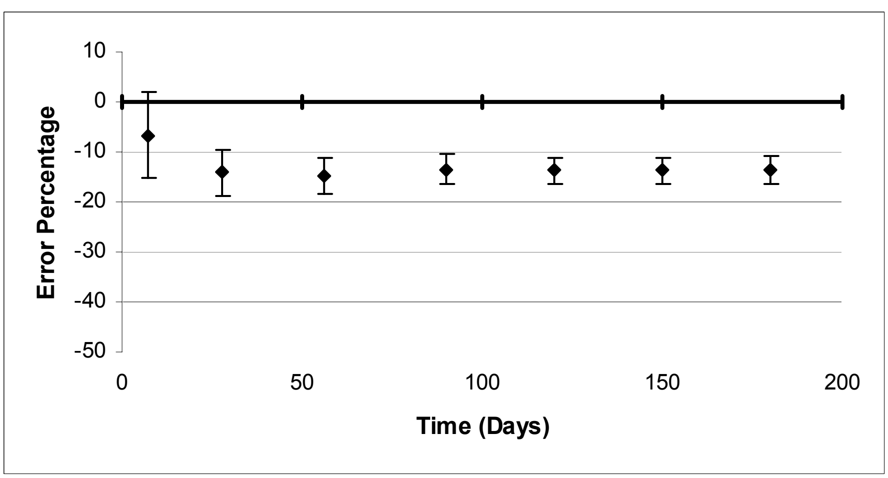


Figure B29: Error Percentage for Gardner/Lockman Model (A5-D/S Mixtures)

APPENDIX C

Unrestrained Shrinkage Mixture Data and Graphs

Table C1: Percentage Length Change for A3 Portland Cement Concrete Mixtures (Test Series 1)

A3 - Limestone/Portland Cement			A3 - Gravel/Portland Cement			A3 - Diabase/Portland Cement		
Percentage Length Change			Percentage Length Change			Percentage Length Change		
Age	Readings		Age	Readings		Age	Readings	
7	-0.0193	-0.0173	7	-0.0177	-0.0197	7	-0.0150	-0.0170
28	-0.0247	-0.0283	28	-0.0283	-0.0304	28	-0.0290	-0.0314
56	-0.0370	-0.0398	56	-0.0366	-0.0388	56	-0.0355	-0.0401
90	-0.0390	-0.0410	90	-0.0390	-0.0410	90	-0.0420	-0.0437
120	-0.0420	-0.0446	120	-0.0420	-0.0433	120	-0.0462	-0.0501
150	-0.0455	-0.0466	150	-0.0430	-0.0458	150	-0.0500	-0.0509
180	-0.0466	-0.0488	180	-0.0450	-0.0470	180	-0.0520	-0.0540

Table C2: A3-Limestone/Portland Cement Statisitical Analysis (Test Series 1)

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev.**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	2	-0.0183	0.0014	7.7	0.0020	-0.0203	-0.0163
28	2	-0.0265	0.0025	9.6	0.0035	-0.0300	-0.0230
56	2	-0.0384	0.0020	5.2	0.0027	-0.0411	-0.0357
90	2	-0.0400	0.0014	3.5	0.0020	-0.0420	-0.0380
120	2	-0.0433	0.0018	4.2	0.0025	-0.0458	-0.0408
150	2	-0.0461	0.0008	1.7	0.0011	-0.0471	-0.0450
180	2	-0.0477	0.0016	3.3	0.0022	-0.0499	-0.0455

Table C3: A3-Gravel/Portland Cement Statisitical Analysis (Test Series 1)

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev.**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	2	-0.0187	0.0014	7.6	0.0020	-0.0207	-0.0167
28	2	-0.0294	0.0015	5.1	0.0021	-0.0314	-0.0273
56	2	-0.0377	0.0016	4.1	0.0022	-0.0399	-0.0355
90	2	-0.0400	0.0014	3.5	0.0020	-0.0420	-0.0380
120	2	-0.0427	0.0009	2.2	0.0013	-0.0439	-0.0414
150	2	-0.0444	0.0020	4.5	0.0027	-0.0471	-0.0417
180	2	-0.0460	0.0014	3.1	0.0020	-0.0480	-0.0440

Table C4: A3-Diabase/Portland Cement Statisitical Analysis (Test Series 1)

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev.**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	2	-0.0160	0.0014	8.8	0.0020	-0.0180	-0.0140
28	2	-0.0302	0.0017	5.6	0.0024	-0.0326	-0.0278
56	2	-0.0378	0.0033	8.6	0.0045	-0.0423	-0.0333
90	2	-0.0429	0.0012	2.8	0.0017	-0.0445	-0.0412
120	2	-0.0482	0.0028	5.7	0.0038	-0.0520	-0.0443
150	2	-0.0505	0.0006	1.3	0.0009	-0.0513	-0.0496
180	2	-0.0530	0.0014	2.7	0.0020	-0.0550	-0.0510

Table C5: Percentage Length Change for A4 Portland Cement Concrete Mixtures (Test Series 1)

A4 - Limestone/Portland Cement			A4 - Gravel/Portland Cement			A4 - Diabase/Portland Cement		
Percentage Length Change			Percentage Length Change			Percentage Length Change		
Age	Readings		Age	Readings		Age	Readings	
7	-0.0160	-0.0196	7	-0.0145	-0.0192	7	-0.0140	-0.0180
28	-0.0220	-0.0245	28	-0.0250	-0.0277	28	-0.0280	-0.0318
56	-0.0285	-0.0320	56	-0.0290	-0.0318	56	-0.0330	-0.0373
90	-0.0348	-0.0375	90	-0.0331	-0.0360	90	-0.0390	-0.0413
120	-0.0385	-0.0395	120	-0.0350	-0.0385	120	-0.0420	-0.0452
150	-0.0400	-0.0414	150	-0.0370	-0.0404	150	-0.0450	-0.0475
180	-0.0415	-0.0493	180	-0.0400	-0.0433	180	-0.0470	-0.0492

Table C6: A4-Limestone/Portland Cement Statisitical Analysis (Test Series 1)

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev.**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	2	-0.0178	0.0025	14.3	0.0035	-0.0213	-0.0143
28	2	-0.0233	0.0018	7.6	0.0024	-0.0257	-0.0208
56	2	-0.0303	0.0025	8.2	0.0034	-0.0337	-0.0268
90	2	-0.0362	0.0019	5.3	0.0026	-0.0388	-0.0335
120	2	-0.0390	0.0007	1.8	0.0010	-0.0400	-0.0380
150	2	-0.0407	0.0010	2.4	0.0014	-0.0421	-0.0393
180	2	-0.0454	0.0055	12.1	0.0076	-0.0530	-0.0378

Table C7: A4-Gravel/Portland Cement Statisitical Analysis (Test Series 1)

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev.**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	2	-0.0169	0.0033	19.7	0.0046	-0.0215	-0.0122
28	2	-0.0264	0.0019	7.2	0.0026	-0.0290	-0.0237
56	2	-0.0304	0.0020	6.5	0.0027	-0.0331	-0.0277
90	2	-0.0346	0.0021	5.9	0.0028	-0.0374	-0.0317
120	2	-0.0368	0.0025	6.7	0.0034	-0.0402	-0.0333
150	2	-0.0387	0.0024	6.2	0.0033	-0.0420	-0.0354
180	2	-0.0417	0.0023	5.6	0.0032	-0.0449	-0.0384

Table C8: A4-Diabase/Portland Cement Statisitical Analysis (Test Series 1)

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev.**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	2	-0.0160	0.0028	17.7	0.0039	-0.0199	-0.0121
28	2	-0.0299	0.0027	9.0	0.0037	-0.0336	-0.0262
56	2	-0.0352	0.0030	8.7	0.0042	-0.0394	-0.0309
90	2	-0.0402	0.0016	4.1	0.0023	-0.0424	-0.0379
120	2	-0.0436	0.0023	5.2	0.0031	-0.0467	-0.0405
150	2	-0.0463	0.0018	3.8	0.0024	-0.0487	-0.0438
180	2	-0.0481	0.0016	3.2	0.0022	-0.0503	-0.0459

Table C9: Percentage Length Change for A5 Portland Cement Concrete Mixtures (Test Series 1)

A5 - Limestone/Portland Cement			A5 - Gravel/Portland Cement			A5 - Diabase/Portland Cement		
Percentage Length Change			Percentage Length Change			Percentage Length Change		
Age	Readings		Age	Readings		Age	Readings	
7	-0.0120	-0.0155	7	-0.0130	-0.0163	7	-0.0140	-0.0170
28	-0.0210	-0.0237	28	-0.0240	-0.0272	28	-0.0240	-0.0283
56	-0.0305	-0.0341	56	-0.0305	-0.0331	56	-0.0335	-0.0353
90	-0.0334	-0.0362	90	-0.0343	-0.0373	90	-0.0370	-0.0404
120	-0.0350	-0.0380	120	-0.0362	-0.0391	120	-0.0410	-0.0433
150	-0.0368	-0.0396	150	-0.0380	-0.0410	150	-0.0440	-0.0468
180	-0.0390	-0.0418	180	-0.0405	-0.0418	180	-0.0460	-0.0480

Table C10: A5-Limestone/Portland Cement Statisitical Analysis (Test Series 1)

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev.**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	2	-0.0138	0.0025	18.0	0.0034	-0.0172	-0.0103
28	2	-0.0224	0.0019	8.5	0.0026	-0.0250	-0.0197
56	2	-0.0323	0.0025	7.9	0.0035	-0.0358	-0.0288
90	2	-0.0348	0.0020	5.7	0.0027	-0.0375	-0.0321
120	2	-0.0365	0.0021	5.8	0.0029	-0.0394	-0.0336
150	2	-0.0382	0.0020	5.2	0.0027	-0.0409	-0.0355
180	2	-0.0404	0.0020	4.9	0.0027	-0.0431	-0.0377

Table C11: A5-Gravel/Portland Cement Statisitical Analysis (Test Series 1)

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev.**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	2	-0.0147	0.0023	15.9	0.0032	-0.0179	-0.0114
28	2	-0.0256	0.0023	8.8	0.0031	-0.0287	-0.0225
56	2	-0.0318	0.0018	5.8	0.0025	-0.0343	-0.0293
90	2	-0.0358	0.0021	5.9	0.0029	-0.0387	-0.0329
120	2	-0.0377	0.0021	5.4	0.0028	-0.0405	-0.0348
150	2	-0.0395	0.0021	5.4	0.0029	-0.0424	-0.0366
180	2	-0.0412	0.0009	2.2	0.0013	-0.0424	-0.0399

Table C12: A5-Diabase/Portland Cement Statisitical Analysis (Test Series 1)

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev.**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	2	-0.0155	0.0021	13.7	0.0029	-0.0184	-0.0126
28	2	-0.0262	0.0030	11.6	0.0042	-0.0304	-0.0219
56	2	-0.0344	0.0013	3.7	0.0018	-0.0362	-0.0326
90	2	-0.0387	0.0024	6.2	0.0033	-0.0420	-0.0354
120	2	-0.0422	0.0016	3.9	0.0023	-0.0444	-0.0399
150	2	-0.0454	0.0020	4.4	0.0027	-0.0481	-0.0427
180	2	-0.0470	0.0014	3.0	0.0020	-0.0490	-0.0450

Table C13: A4-Diabase/Fly Ash Percentage Length Change

Age	Readings				
7	-0.0249	-0.0240	-0.0231	-0.0231	
	-0.0187	-0.0168	-0.0169	-0.0178	
	-0.0195	-0.0178	-0.0169	-0.0169	
28	-0.0409	-0.0391	-0.0400	-0.0400	-0.0400
	-0.0381	-0.0397	-0.0401	-0.0379	-0.0420
	-0.0395	-0.0379	-0.0397	-0.0400	
56	-0.0484	-0.0456	-0.0465	-0.0483	
	-0.0474	-0.0493	-0.0493	-0.0447	-0.0501
	-0.0512	-0.0479	-0.0529	-0.0500	-0.0507
90	-0.0538	-0.0512	-0.0511		
	-0.0519	-0.0530	-0.0536	-0.0495	-0.0527
	-0.0523	-0.0533	-0.0505	-0.0523	-0.0531
120	-0.0551	-0.0527	-0.0535	-0.0507	
	-0.0535	-0.0549	-0.0545	-0.0506	-0.0551
	-0.0548	-0.0556	-0.0537	-0.0529	
150	-0.0559	-0.0531	-0.0549	-0.0522	
	-0.0549	-0.0555	-0.0553	-0.0512	-0.0564
	-0.0562	-0.0565	-0.0549	-0.0537	
180	-0.0560	-0.0542	-0.0560	-0.0533	
	-0.0563	-0.0560	-0.0560	-0.0578	
	-0.0573	-0.0578	-0.0560	-0.0542	-0.0578

Table C14: A4-Diabase/Fly Ash Statistical Analysis

	Sample			C. O. V.	95% Confidence Limits		
Age	Size	Mean	Std. Dev.	(%)	C. I.	L. L.	U. L.
7	12	-0.0197	0.0031	16.0	0.0018	-0.0215	-0.0179
28	14	-0.0396	0.0011	2.9	0.0006	-0.0402	-0.0390
56	14	-0.0487	0.0022	4.6	0.0012	-0.0499	-0.0476
90	13	-0.0522	0.0013	2.5	0.0007	-0.0529	-0.0515
120	13	-0.0537	0.0016	3.0	0.0009	-0.0545	-0.0528
150	13	-0.0547	0.0017	3.0	0.0009	-0.0556	-0.0538
180	13	-0.0561	0.0015	2.6	0.0008	-0.0568	-0.0553

Table C15: A4-Diabase/Microsilica Percentage Length Change

Age	Readings				
7	-0.0222	-0.0203	-0.0204	-0.0213	-0.0222
	-0.0143	-0.0178	-0.0160	-0.0151	-0.0168
	-0.0192	-0.0213	-0.0186	-0.0169	-0.0178
28	-0.0426	-0.0427	-0.0391	-0.0409	-0.0408
	-0.0329	-0.0328	-0.0353	-0.0337	-0.0348
	-0.0388	-0.0370	-0.0342	-0.0318	-0.0329
56	-0.0474	-0.0411	-0.0429	-0.0456	-0.0456
	-0.0388	-0.0461	-0.0447	-0.0402	-0.0447
	-0.0455	-0.0443	-0.0415	-0.0398	-0.0411
90	-0.0488	-0.0426	-0.0435	-0.0469	-0.0483
	-0.0408	-0.0418	-0.0452	-0.0427	-0.0455
	-0.0473	-0.0470	-0.0443	-0.0415	-0.0439
120	-0.0494	-0.0452	-0.0449	-0.0481	-0.0502
	-0.0448	-0.0453	-0.0485	-0.0452	-0.0479
	-0.0504	-0.0502	-0.0473	-0.0452	-0.0469
150	-0.0498	-0.0465	-0.0459	-0.0493	-0.0517
	-0.0462	-0.0475	-0.0504	-0.0471	-0.0499
	-0.0522	-0.0525	-0.0509	-0.0465	-0.0485
180	-0.0504	-0.0515	-0.0524		
	-0.0478	-0.0489	-0.0515	-0.0480	-0.0515
	-0.0530	-0.0532	-0.0533	-0.0507	

Table C16: A4-Diabase/Microsilica Statistical Analysis

Age	Sample Size	Mean	Std. Dev.	C. O. V. (%)	95% Confidence Limits C. I.	L. L.	U. L.
7	15	-0.0187	0.0026	13.7	0.0013	-0.0200	-0.0174
28	15	-0.0367	0.0038	10.4	0.0019	-0.0386	-0.0348
56	15	-0.0433	0.0027	6.2	0.0014	-0.0446	-0.0419
90	15	-0.0447	0.0026	5.7	0.0013	-0.0460	-0.0434
120	15	-0.0473	0.0021	4.5	0.0011	-0.0484	-0.0462
150	15	-0.0490	0.0023	4.7	0.0012	-0.0501	-0.0478
180	12	-0.0510	0.0019	3.8	0.0011	-0.0521	-0.0499

Table C17: A4-Diabase/Slag Cement Percentage Length Change

Age	Readings				
7	-0.0249	-0.0213	-0.0249	-0.0213	-0.0222
	-0.0213	-0.0205	-0.0222	-0.0213	-0.0204
	-0.0160	-0.0178	-0.0178	-0.0160	-0.0187
28	-0.0391	-0.0409	-0.0338	-0.0364	
	-0.0400	-0.0382	-0.0409	-0.0409	-0.0409
	-0.0383	-0.0349	-0.0384	-0.0397	-0.0370
56	-0.0431	-0.0367	-0.0438	-0.0376	-0.0412
	-0.0470	-0.0457	-0.0465	-0.0474	-0.0447
	-0.0424	-0.0391	-0.0424	-0.0447	-0.0417
90	-0.0498	-0.0426	-0.0489	-0.0409	-0.0435
	-0.0519	-0.0506	-0.0520	-0.0478	-0.0483
	-0.0472	-0.0442	-0.0473	-0.0492	-0.0473
120	-0.0506	-0.0451	-0.0503	-0.0431	-0.0452
	-0.0525	-0.0522	-0.0535	-0.0500	-0.0500
	-0.0489	-0.0456	-0.0482	-0.0511	-0.0492
150	-0.0512	-0.0460	-0.0517	-0.0442	-0.0469
	-0.0531	-0.0526	-0.0541	-0.0504	-0.0504
	-0.0495	-0.0463	-0.0495	-0.0525	-0.0507
180	-0.0516	-0.0471	-0.0524	-0.0453	-0.0480
	-0.0542	-0.0480	-0.0533	-0.0507	-0.0506
	-0.0506	-0.0471	-0.0506	-0.0533	-0.0515

Table C18: A4-Diabase/Slag Cement Statistical Analysis

Age	Sample Size	Mean	Std. Dev.	C. O. V. (%)	95% Confidence Limits C. I.	L. L.	U. L.
7	15	-0.0204	0.0027	13.4	0.0014	-0.0218	-0.0191
28	14	-0.0385	0.0023	6.0	0.0012	-0.0397	-0.0373
56	15	-0.0429	0.0033	7.6	0.0017	-0.0446	-0.0413
90	15	-0.0474	0.0033	7.0	0.0017	-0.0491	-0.0458
120	15	-0.0490	0.0030	6.2	0.0015	-0.0506	-0.0475
150	15	-0.0499	0.0029	5.8	0.0015	-0.0514	-0.0485
180	15	-0.0503	0.0026	5.2	0.0013	-0.0516	-0.0490

Table C19: A5-Diabase/Slag Cement Percentage Length Change

Age	Readings				
7	-0.0204	-0.0204	-0.0222	-0.0231	-0.0222
	-0.0213	-0.0222	-0.0231	-0.0195	-0.0222
	-0.0142	-0.0187	-0.0142	-0.0151	-0.0178
28	-0.0355	-0.0346	-0.0382	-0.0364	-0.0355
	-0.0373	-0.0409	-0.0400	-0.0382	-0.0382
	-0.0302	-0.0318	-0.0286	-0.0314	-0.0343
56	-0.0411	-0.0439	-0.0439	-0.0421	
	-0.0438	-0.0483	-0.0474	-0.0447	-0.0429
	-0.0384	-0.0390	-0.0365	-0.0404	
90	-0.0453	-0.0433	-0.0472	-0.0461	-0.0448
	-0.0464	-0.0519	-0.0504	-0.0483	-0.0468
	-0.0416	-0.0423	-0.0413	-0.0432	-0.0462
120	-0.0474	-0.0456	-0.0502	-0.0472	-0.0461
	-0.0479	-0.0531	-0.0522	-0.0501	-0.0475
	-0.0452	-0.0475	-0.0422	-0.0461	-0.0482
150	-0.0503	-0.0471	-0.0512	-0.0485	-0.0474
	-0.0487	-0.0548	-0.0530	-0.0512	-0.0483
	-0.0466	-0.0495	-0.0434	-0.0470	
180	-0.0515	-0.0480	-0.0489	-0.0489	
	-0.0497	-0.0560	-0.0542	-0.0515	-0.0497
	-0.0471	-0.0516	-0.0444	-0.0480	

Table C20: A5-Diabase/Slag Cement Statistical Analysis

Age	Sample Size	Mean	Std. Dev.	C. O. V. (%)	95% Confidence Limits		
					C. I.	L. L.	U. L.
7	15	-0.0198	0.0031	15.9	0.0016	-0.0214	-0.0182
28	15	-0.0354	0.0036	10.2	0.0018	-0.0372	-0.0336
56	13	-0.0425	0.0034	8.0	0.0019	-0.0443	-0.0406
90	15	-0.0457	0.0031	6.7	0.0016	-0.0472	-0.0441
120	15	-0.0478	0.0028	5.8	0.0014	-0.0492	-0.0464
150	14	-0.0491	0.0029	5.9	0.0015	-0.0506	-0.0476
180	13	-0.0500	0.0030	6.1	0.0017	-0.0516	-0.0483

Table C21: A3-Limestone/Portland Cement

Percentage Length Change			
Age	**Readings**		
7	-0.0159	-0.0160	
	-0.0151	-0.0154	
	-0.0142		
28	-0.0267	-0.0276	-0.0240
	-0.0240	-0.0231	-0.0249
	-0.0249		
56	-0.0373	-0.0373	
	-0.0409	-0.0373	-0.0364
	-0.0391	-0.0373	
90	-0.0356	-0.0347	-0.0364
	-0.0453	-0.0409	
	-0.0427	-0.0382	
120	-0.0409	-0.0418	-0.0400
	-0.0484	-0.0435	
	-0.0459	-0.0412	
150	-0.0427	-0.0462	-0.0436
	-0.0501	-0.0456	
	-0.0479	-0.0433	
180	-0.0436	-0.0489	-0.0462

Table C22: A3-Limestone/Portland Cement Statistical Analysis (Test Series 3)

Age	Sample Size	Mean	Std. Dev.	C. O. V. (%)	95% Cinfidence Limits		
					C. I.	**L. L.**	**U. L.**
7	5	-0.0153	0.0007	4.7	0.0006	-0.0160	-0.0147
28	7	-0.0250	0.0016	6.4	0.0012	-0.0262	-0.0238
56	7	-0.0379	0.0015	4.0	0.0011	-0.0391	-0.0368
90	7	-0.0391	0.0040	10.1	0.0029	-0.0421	-0.0362
120	7	-0.0431	0.0031	7.1	0.0023	-0.0454	-0.0408
150	7	-0.0456	0.0027	5.9	0.0020	-0.0476	-0.0436
180	3	-0.0462	0.0027	5.7	0.0030	-0.0492	-0.0432

Table C23: A3-Gravel/Portland Cement

Percentage Length Change			
Age	**Readings**		
7	-0.0186	-0.0187	
	-0.0187	-0.0186	
	-0.0186	-0.0178	
28	-0.0276	-0.0284	-0.0276
	-0.0258	-0.0267	
	-0.0267	-0.0302	-0.0284
56	-0.0356	-0.0338	-0.0356
	-0.0409	-0.0418	
	-0.0347	-0.0356	-0.0338
90	-0.0418	-0.0400	
	-0.0453	-0.0453	
	-0.0409	-0.0409	-0.0382
120	-0.0453	-0.0373	-0.0418
	-0.0465	-0.0472	
	-0.0441	-0.0432	-0.0409
150	-0.0472	-0.0421	-0.0449
	-0.0482	-0.0494	
	-0.0469	-0.0481	-0.0432
180	-0.0484	-0.0453	-0.0453

Table C24: A3-Gravel/Portland Cement Statistical Analysis (Test Series 3)

	Sample			**C. O. V.**	**95% Cinfidence Limits**		
Age	**Size**	**Mean**	**Std. Dev.**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	6	-0.0185	0.0003	1.9	0.0003	-0.0188	-0.0182
28	8	-0.0277	0.0014	4.9	0.0009	-0.0286	-0.0267
56	8	-0.0365	0.0031	8.5	0.0022	-0.0386	-0.0343
90	7	-0.0418	0.0027	6.4	0.0020	-0.0437	-0.0398
120	8	-0.0433	0.0033	7.5	0.0023	-0.0455	-0.0410
150	8	-0.0463	0.0026	5.6	0.0018	-0.0480	-0.0445
180	3	-0.0463	0.0018	3.9	0.0020	-0.0484	-0.0443

Table C25: A3-Diabase/Portland Cement

Percentage Length Change			
Age	**Readings**		
7	-0.0205	-0.0205	
	-0.0181	-0.0188	
	-0.0178	-0.0187	
28	-0.0302	-0.0258	-0.0284
	-0.0311	-0.0320	-0.0320
	-0.0267	-0.0240	-0.0240
56	-0.0400	-0.0427	
	-0.0400	-0.0409	-0.0400
	-0.0409	-0.0329	
90	-0.0471	-0.0489	
	-0.0453	-0.0471	-0.0462
	-0.0462		
120	-0.0489	-0.0516	
	-0.0472	-0.0495	-0.0487
	-0.0490		
150	-0.0507	-0.0525	
	-0.0495	-0.0512	-0.0502
	-0.0505		
180	-0.0587	-0.0524	-0.0533

Table C26: A3-Diabase/Portland Cement Statistical Analysis (Test Series 3)

Age	**Sample Size**	**Mean**	**Std. Dev.**	**C. O. V. (%)**	**95% Cinfidence Limits C. I.**	**L. L.**	**U. L.**
7	6	-0.0191	0.0012	6.1	0.0009	-0.0200	-0.0181
28	9	-0.0282	0.0033	11.5	0.0021	-0.0304	-0.0261
56	7	-0.0396	0.0031	7.9	0.0023	-0.0419	-0.0373
90	6	-0.0468	0.0012	2.6	0.0010	-0.0478	-0.0458
120	6	-0.0492	0.0014	2.9	0.0011	-0.0503	-0.0480
150	6	-0.0508	0.0010	2.0	0.0008	-0.0516	-0.0500
180	3	-0.0548	0.0034	6.2	0.0039	-0.0587	-0.0509

TableC27: A4-Limestone/Portland Cement

Percentage Length Change			
Age	Readings		
7	-0.0098	-0.0098	
	-0.0124		
	-0.0154	-0.0146	
28	-0.0187	-0.0196	-0.0178
	-0.0222	-0.0231	-0.0222
	-0.0204	-0.0258	-0.0222
56	-0.0249	-0.0258	
	-0.0391	-0.0400	
	-0.0391	-0.0409	-0.0373
90	-0.0284	-0.0276	
	-0.0444	-0.0462	
	-0.0400	-0.0436	-0.0382
120	-0.0311	-0.0293	
	-0.0462	-0.0484	
	-0.0421	-0.0456	-0.0402
150	-0.0329	-0.0319	
	-0.0471	-0.0495	
	-0.0430	-0.0462	-0.0415
180	-0.0418	-0.0445	-0.0438

Table C28: A4-Limestone/Portland Cement Statistical Analysis (Test Series 3)

Age	Sample Size	Mean	Std. Dev.	C. O. V. (%)	95% Cinfidence Limits		
					C. I.	L. L.	U. L.
7	5	-0.0124	0.0026	21.1	0.0023	-0.0147	-0.0101
28	9	-0.0213	0.0025	11.6	0.0016	-0.0229	-0.0197
56	7	-0.0353	0.0069	19.5	0.0051	-0.0404	-0.0302
90	7	-0.0383	0.0076	19.7	0.0056	-0.0439	-0.0327
120	7	-0.0404	0.0075	18.6	0.0056	-0.0460	-0.0349
150	7	-0.0417	0.0069	16.5	0.0051	-0.0468	-0.0366
180	3	-0.0434	0.0014	3.2	0.0016	-0.0450	-0.0418

Table C29: A4-Gravel/Portland Cement

Percentage Length Change			
Age	**Readings**		
7	-0.0205		
	-0.0182	-0.0196	
	-0.0142	-0.0142	
28	-0.0284	-0.0284	
	-0.0267	-0.0258	
	-0.0231	-0.0231	-0.0240
56	-0.0320	-0.0302	
	-0.0356	-0.0356	
	-0.0320	-0.0320	-0.0329
90	-0.0382	-0.0364	-0.0364
	-0.0382	-0.0480	-0.0391
	-0.0347	-0.0320	-0.0329
120	-0.0409	-0.0391	-0.0409
	-0.0395	-0.0408	
	-0.0364	-0.0338	
150	-0.0418	-0.0409	-0.0427
	-0.0415	-0.0427	
	-0.0384	-0.0364	
180	-0.0427	-0.0409	-0.0427

Table C30: A4-Gravel/Portland Cement Statistical Analysis (Test Series 3)

Age	Sample Size	Mean	Std. Dev.	C. O. V. (%)	95% Cinfidence Limits C. I.	L. L.	U. L.
7	5	-0.0173	0.0030	17.2	0.0026	-0.0200	-0.0147
28	7	-0.0256	0.0023	9.0	0.0017	-0.0274	-0.0239
56	7	-0.0329	0.0020	6.1	0.0015	-0.0344	-0.0314
90	9	-0.0373	0.0047	12.5	0.0031	-0.0404	-0.0343
120	7	-0.0388	0.0027	7.0	0.0020	-0.0408	-0.0368
150	7	-0.0406	0.0024	5.8	0.0018	-0.0424	-0.0389
180	3	-0.0421	0.0010	2.5	0.0012	-0.0433	-0.0409

Table C31: A4-Diabase/Portland Cement

Percentage Length Change			
Age	**Readings**		
7	-0.0120	-0.0138	
	-0.0157	-0.0161	-0.0162
	-0.0166	-0.0164	
28	-0.0267	-0.0276	-0.0231
	-0.0293	-0.0240	-0.0240
	-0.0240	-0.0338	-0.0311
56	-0.0364	-0.0391	-0.0356
	-0.0418	-0.0373	-0.0373
	-0.0391	-0.0444	
90	-0.0436	-0.0453	-0.0409
	-0.0498	-0.0444	-0.0436
120	-0.0456	-0.0467	-0.0431
	-0.0512	-0.0464	-0.0456
150	-0.0478	-0.0482	-0.0449
	-0.0525	-0.0491	-0.0472
180	-0.0502	-0.0576	-0.0531

Table C32: A4-Diabase/Portland Cement Statistical Analysis (Test Series 3)

	Sample			**C. O. V.**	**95% Cinfidence Limits**		
Age	**Size**	**Mean**	**Std. Dev.**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	7	-0.0153	0.0017	11.2	0.0013	-0.0165	-0.0140
28	9	-0.0271	0.0037	13.8	0.0024	-0.0295	-0.0246
56	8	-0.0389	0.0030	7.6	0.0020	-0.0409	-0.0368
90	6	-0.0446	0.0029	6.6	0.0024	-0.0470	-0.0422
120	6	-0.0464	0.0027	5.7	0.0021	-0.0486	-0.0443
150	6	-0.0483	0.0025	5.2	0.0020	-0.0503	-0.0463
180	3	-0.0536	0.0037	7.0	0.0042	-0.0579	-0.0494

Table C33: A5-Limestone/Portland Cement

Percentage Length Change			
Age	**Readings**		
7	-0.0160	-0.0160	
	-0.0160	-0.0166	-0.0164
	-0.0169	-0.0169	-0.0170
28	-0.0249		
	-0.0204	-0.0204	-0.0187
	-0.0267	-0.0240	
56	-0.0320	-0.0311	-0.0338
	-0.0302	-0.0320	-0.0302
	-0.0347		
90	-0.0347	-0.0356	-0.0364
	-0.0338	-0.0347	-0.0347
	-0.0356	-0.0364	
120	-0.0364	-0.0373	-0.0373
	-0.0352	-0.0364	-0.0368
	-0.0372	-0.0378	
150	-0.0373	-0.0373	-0.0382
	-0.0365	-0.0372	-0.0377
	-0.0384	-0.0386	
180	-0.0388	-0.0379	-0.0397

Table C34: A5-Limestone/Portland Cement Statistical Analysis (Test Series 3)

	Sample			C. O. V.	95% Cinfidence Limits		
Age	**Size**	**Mean**	**Std. Dev.**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	8	-0.0165	0.0004	2.7	0.0003	-0.0168	-0.0162
28	6	-0.0225	0.0031	13.9	0.0025	-0.0250	-0.0200
56	7	-0.0320	0.0017	5.4	0.0013	-0.0333	-0.0307
90	8	-0.0352	0.0009	2.6	0.0006	-0.0359	-0.0346
120	8	-0.0368	0.0008	2.2	0.0006	-0.0374	-0.0362
150	8	-0.0377	0.0007	1.9	0.0005	-0.0381	-0.0372
180	3	-0.0388	0.0009	2.3	0.0010	-0.0398	-0.0378

Table C35: A5-Gravel/Portland Cement

Percentage Length Change			
Age	**Readings**		
7	-0.0151	-0.0160	
	-0.0160	-0.0160	
	-0.0160	-0.0138	
28	-0.0258	-0.0276	
	-0.0276	-0.0284	
	-0.0231	-0.0284	-0.0276
56	-0.0364	-0.0364	
	-0.0373	-0.0364	
	-0.0267	-0.0302	-0.0284
90	-0.0391	-0.0391	
	-0.0427	-0.0409	-0.0418
	-0.0284	-0.0320	-0.0302
120	-0.0403	-0.0400	
	-0.0436	-0.0409	-0.0436
	-0.0307	-0.0339	-0.0321
150	-0.0417	-0.0412	
	-0.0444	-0.0427	-0.0453
	-0.0325	-0.0352	-0.0334
180	-0.0428	-0.0402	-0.0419

Table C36: A5-Gravel/Portland Cement Statistical Analysis (Test Series 3)

	Sample			**C. O. V.**	**95% Cinfidence Limits**		
Age	**Size**	**Mean**	**Std. Dev.**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	6	-0.0155	0.0009	5.8	0.0007	-0.0162	-0.0148
28	7	-0.0269	0.0019	7.0	0.0014	-0.0283	-0.0255
56	7	-0.0331	0.0045	13.6	0.0033	-0.0365	-0.0298
90	8	-0.0368	0.0057	15.4	0.0039	-0.0407	-0.0329
120	8	-0.0381	0.0051	13.5	0.0036	-0.0417	-0.0346
150	8	-0.0396	0.0051	12.8	0.0035	-0.0431	-0.0360
180	3	-0.0416	0.0013	3.2	0.0015	-0.0431	-0.0401

Table C37: A5-Diabase/Portland Cement

Percentage Length Change			
Age	**Readings**		
7	-0.0169	-0.0171	-0.0177
	-0.0204	-0.0200	
	-0.0204	-0.0187	
28	-0.0231	-0.0249	-0.0276
	-0.0267	-0.0258	
	-0.0258	-0.0249	-0.0249
56	-0.0329	-0.0329	-0.0347
	-0.0382	-0.0391	
	-0.0409	-0.0400	
90	-0.0382	-0.0400	-0.0436
	-0.0453	-0.0471	
	-0.0462	-0.0462	
120	-0.0412	-0.0422	-0.0464
	-0.0489		
	-0.0489	-0.0471	-0.0489
150	-0.0419	-0.0428	-0.0467
	-0.0495		
	-0.0494	-0.0482	-0.0492
180	-0.0533	-0.0480	-0.0516

Table C38: A5-Diabase/Portland Cement Statistical Analysis (Test Series 3)

Age	Sample Size	Mean	Std. Dev.	C. O. V. (%)	95% Cinfidence Limits		
					C. I.	**L. L.**	**U. L.**
7	7	-0.0187	0.0015	8.2	0.0011	-0.0199	-0.0176
28	8	-0.0255	0.0014	5.3	0.0009	-0.0264	-0.0245
56	7	-0.0370	0.0034	9.2	0.0025	-0.0395	-0.0344
90	7	-0.0438	0.0034	7.8	0.0025	-0.0463	-0.0413
120	7	-0.0462	0.0033	7.0	0.0024	-0.0486	-0.0438
150	7	-0.0468	0.0032	6.9	0.0024	-0.0492	-0.0444
180	3	-0.0510	0.0027	5.3	0.0031	-0.0540	-0.0479

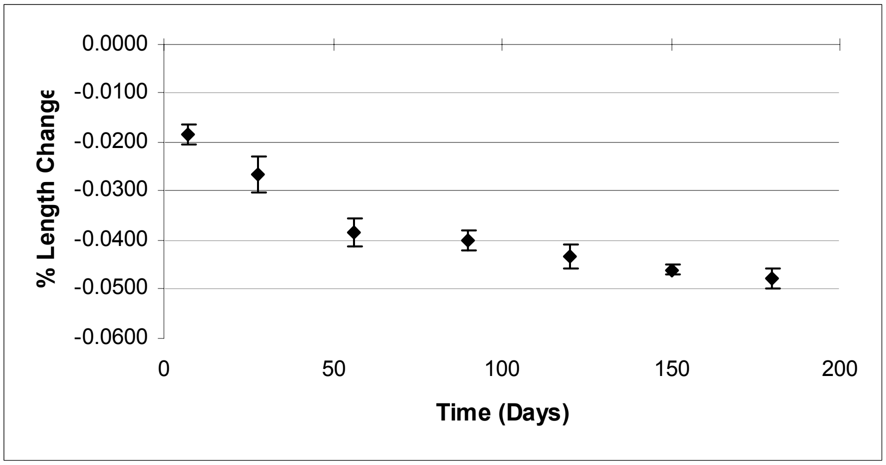


Figure C1: A3-Limestone Percentage Length Change (Test Series 1)

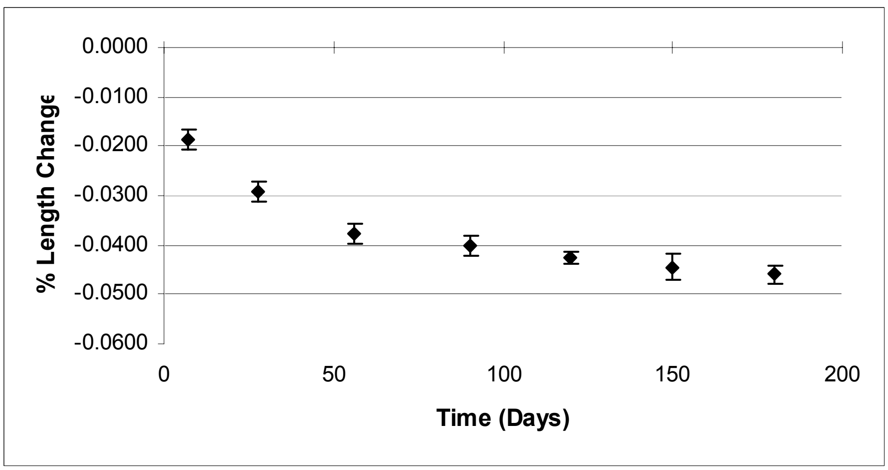


Figure C2: A3-Gravel Percentage Length Change (Test Series 1)

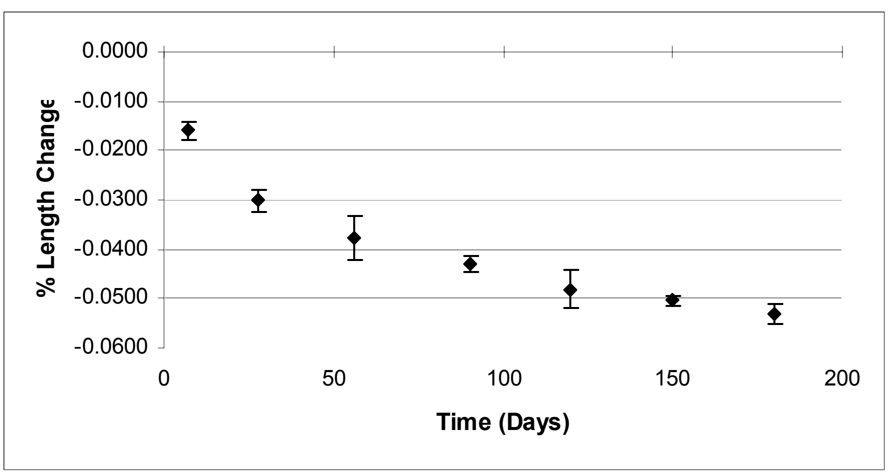


Figure C3: A3-Diabase Percentage Length Change (Test Series 1)

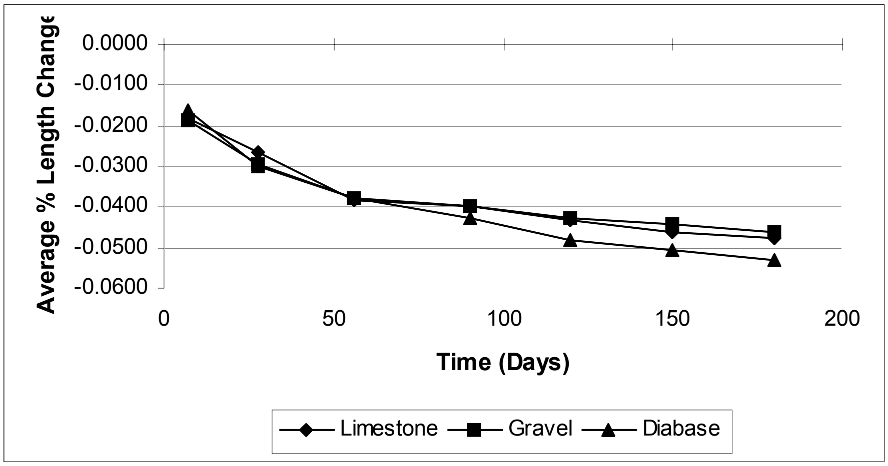


Figure C4: A3-Portland Cement Percentage Length Change (Test Series 1)

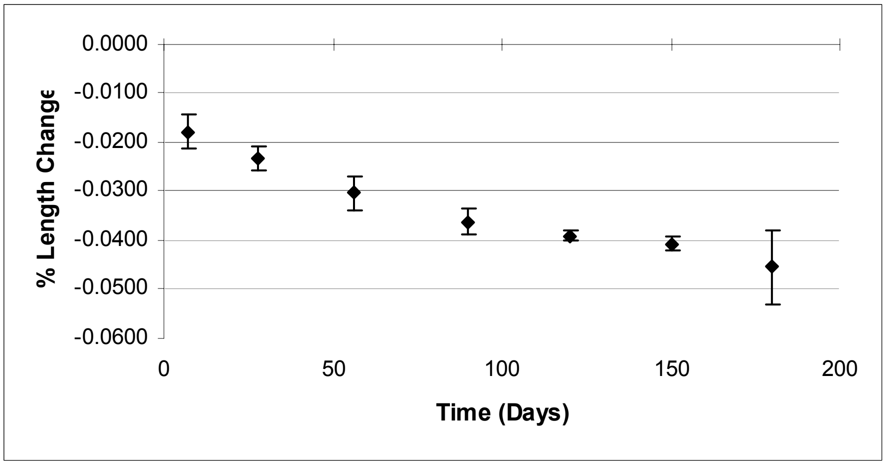


Figure C5: A4-Limestone Percentage Length Change (Test Series 1)

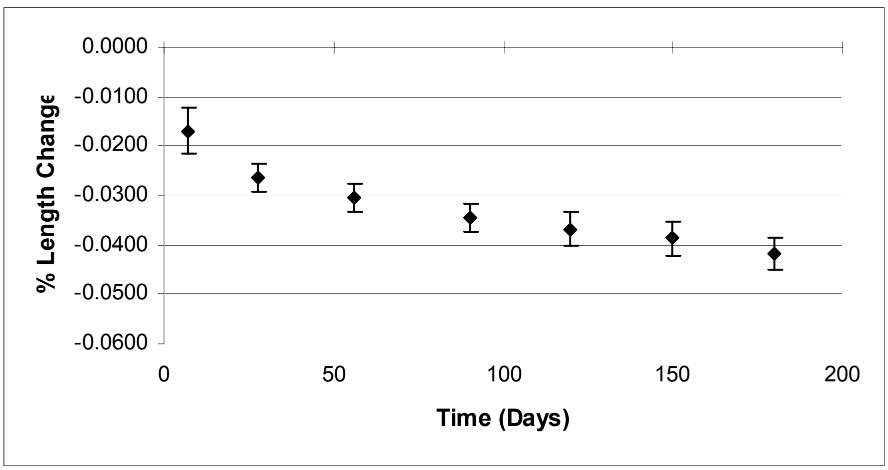


Figure C6: A4-Gravel Percentage Length Change (Test Series 1)

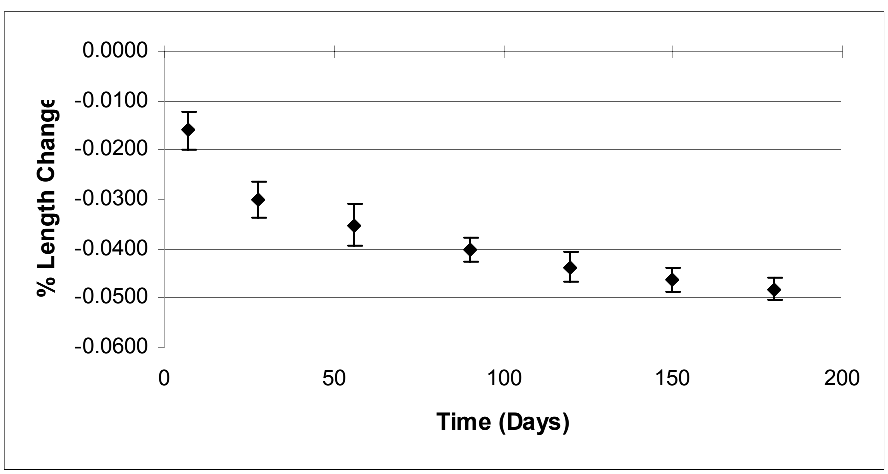


Figure C7: A4-Diabase Percentage Length Change (Test Series 1)

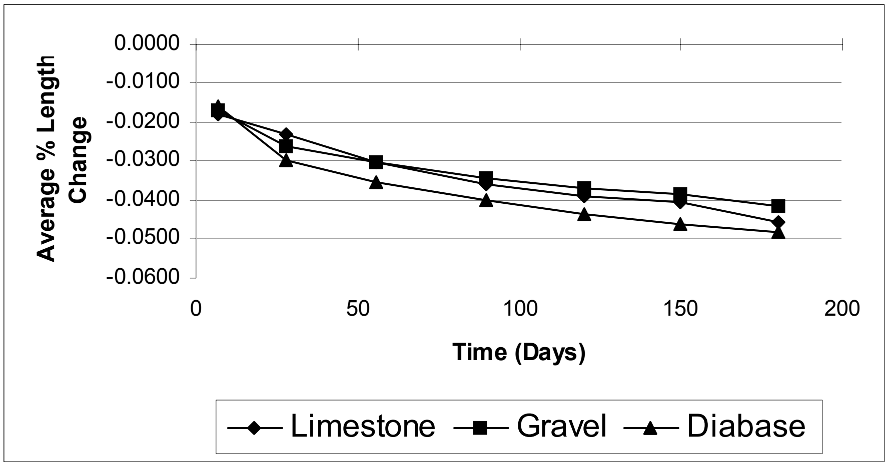


Figure C8: A4 Portland Cement Percentage Length Change (Test Series 1)

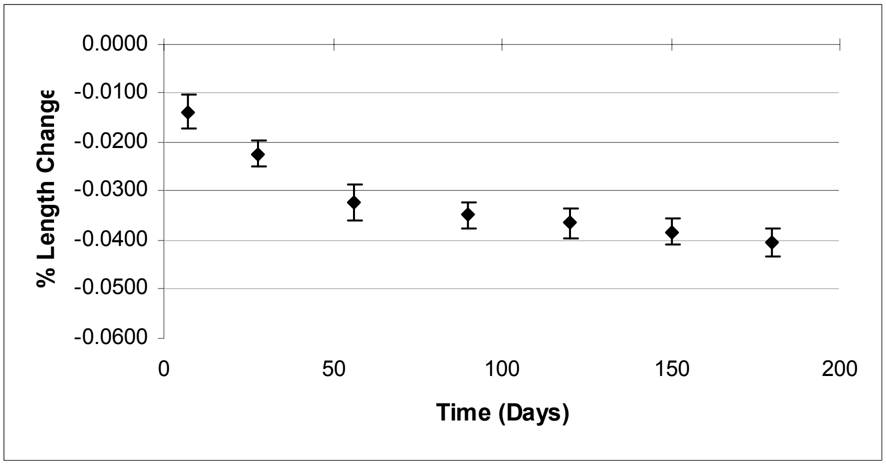


Figure C9: A5-Limestone Percentage Length Change (Test Series 1)

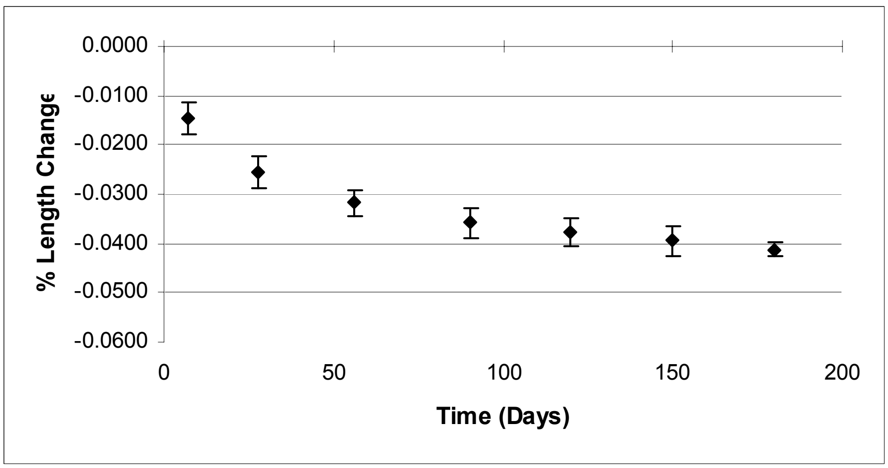


Figure C10: A5-Gravel Percentage Length Change (Test Series 1)

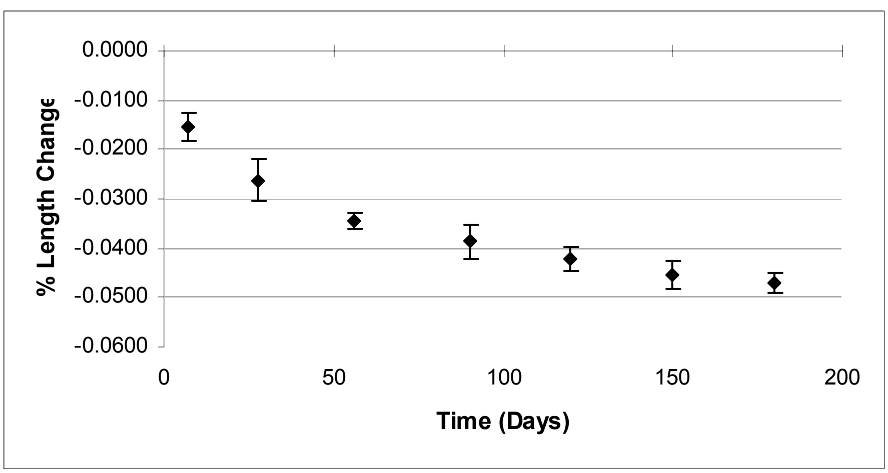


Figure C11: A5-Diabase Percentage Length Change (Test Series 1)

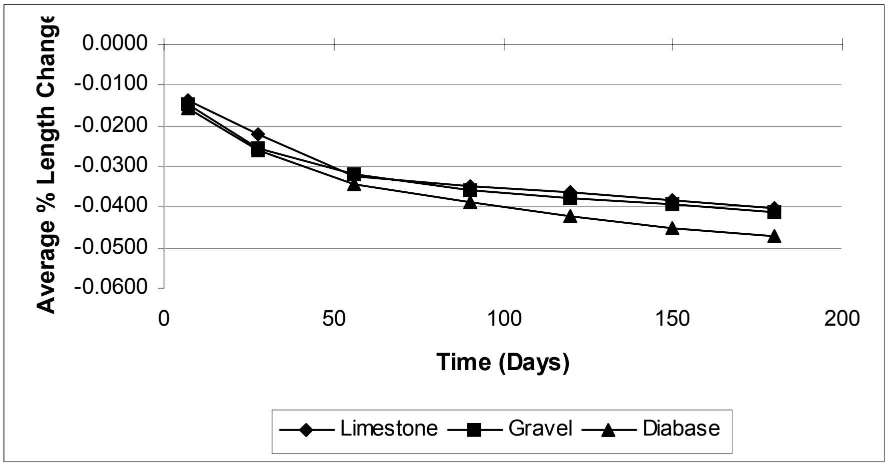


Figure C12: A5 Portland Cement Percentage Length Change (Test Series 1)

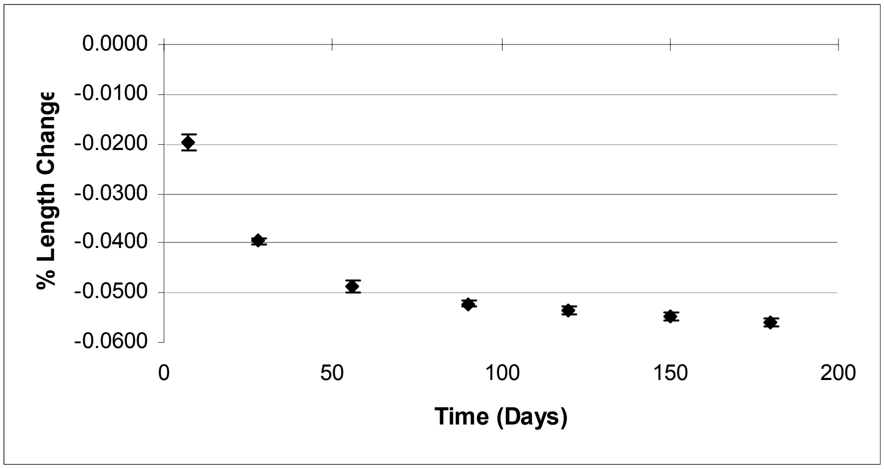


Figure C13: A4-Diabase/Fly Ash Percentage Length Change

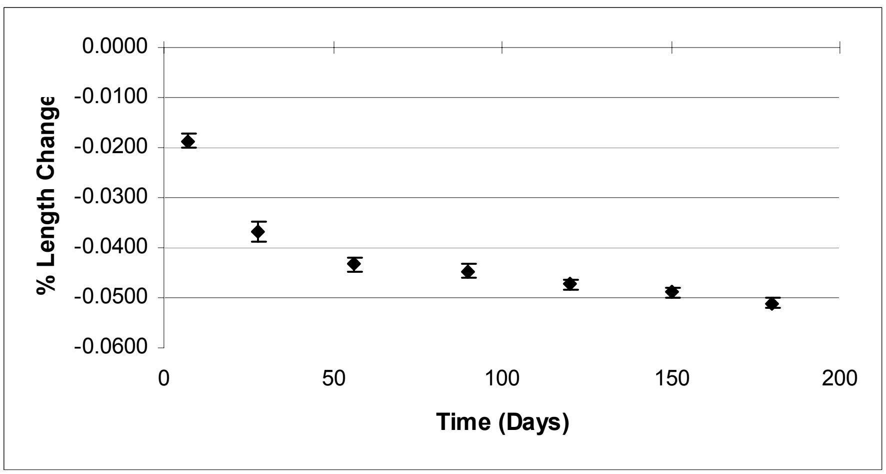


Figure C14: A4-Diabase/Microsilica Percentage Length Change

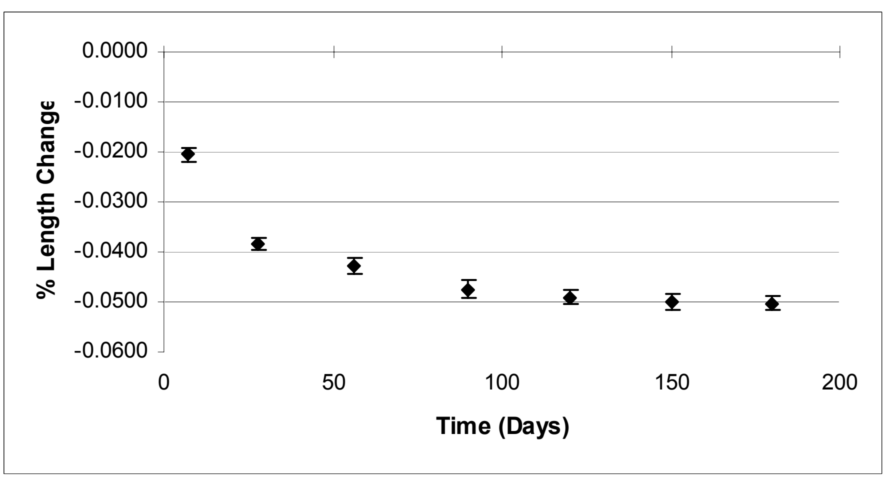


Figure C15: A4-Diabase/Slag Cement Percentage Length Change

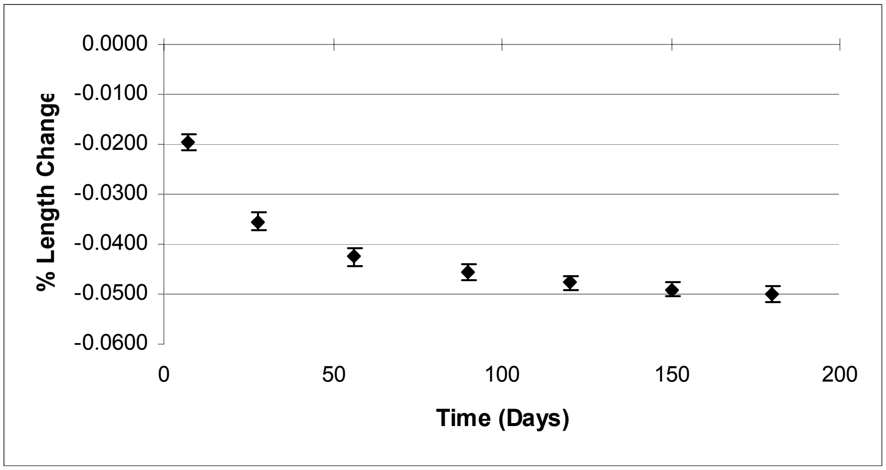


Figure C16: A5-Diabase/Slag Cement Percentage Length Change

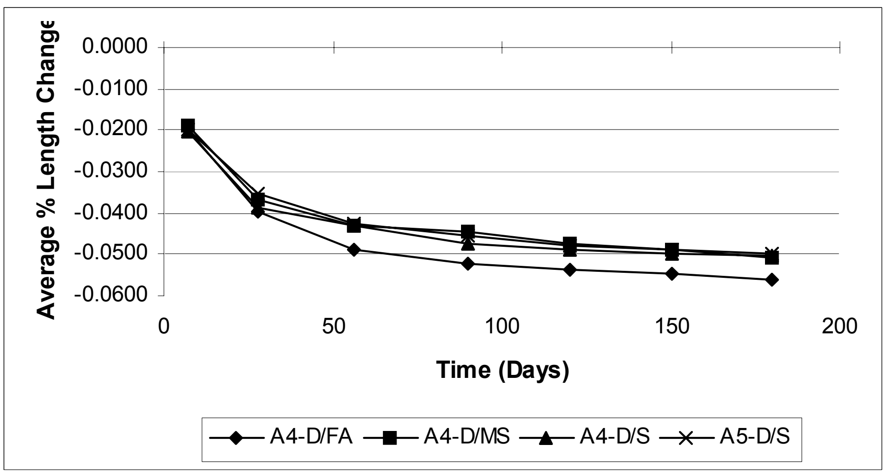


Figure C17: Supplemental Cementitious Materials Percentage Length Change

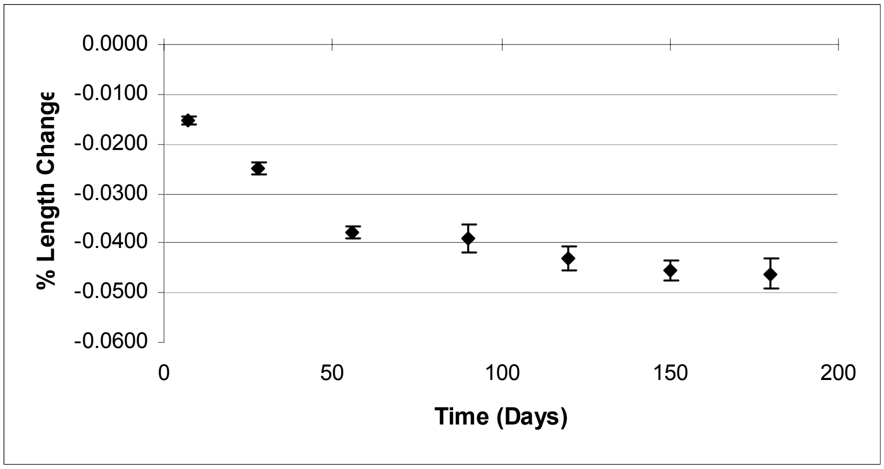


Figure C18: A3 Limestone Percentage Length Change (Test Series 3)

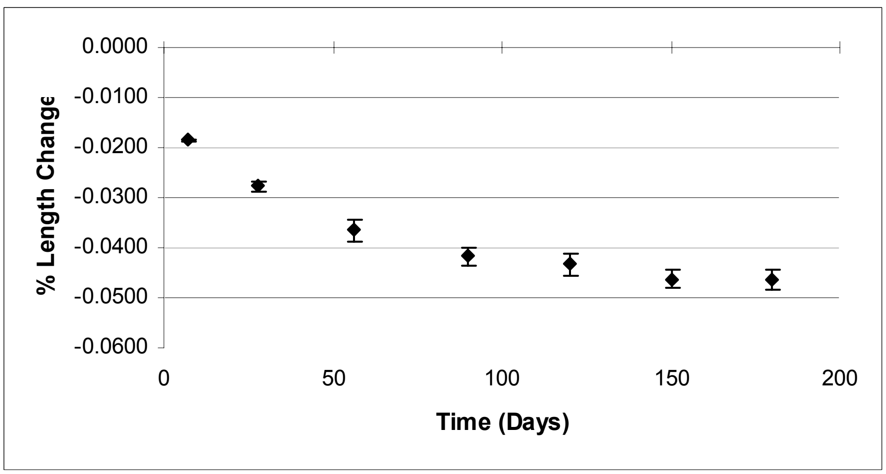


Figure C19: A3 Gravel Percentage Length Change (Test Series 3)

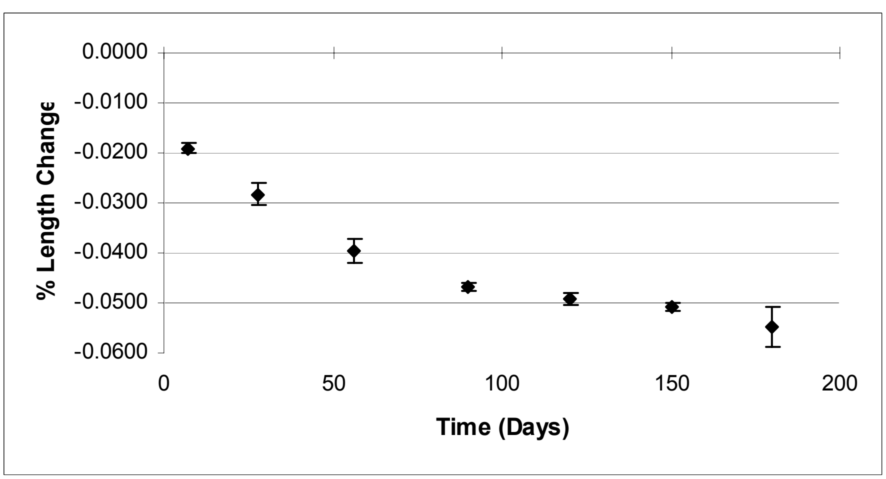


Figure C20: A3 Diabase Percentage Length Change (Test Series 3)

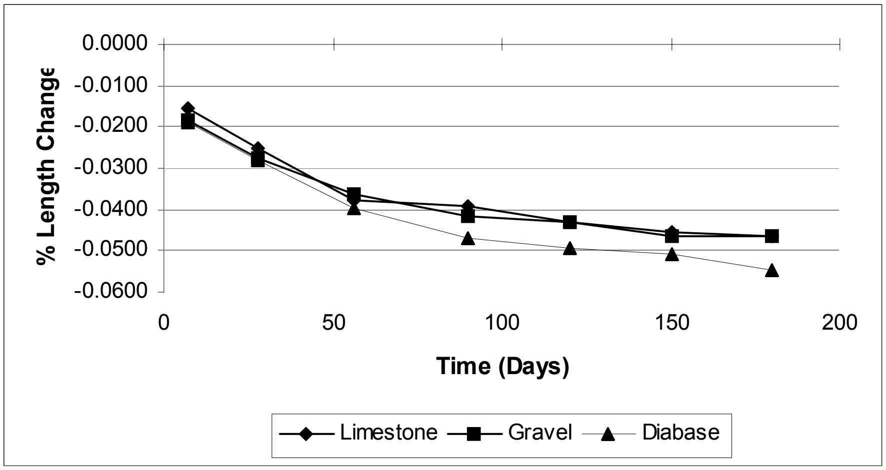


Figure C21: A3 Mixtures Percentage Length Change (Test Series 3)

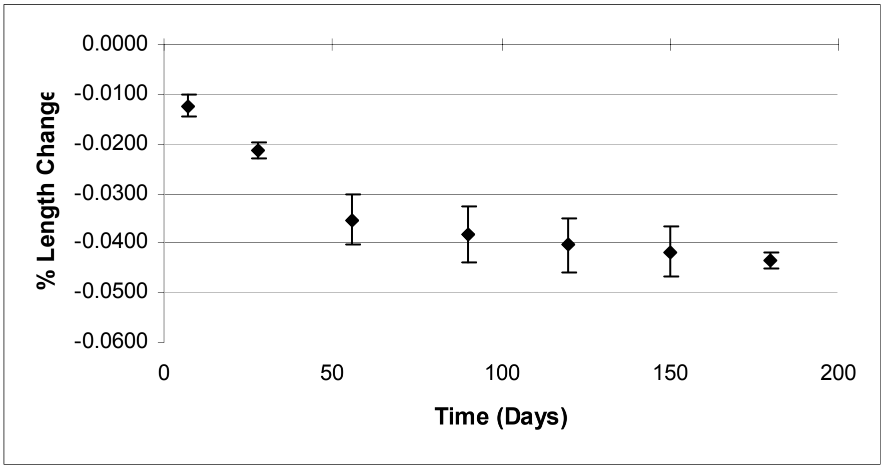


Figure C22: A4 Limestone Percentage Length Change (Test Series 3)

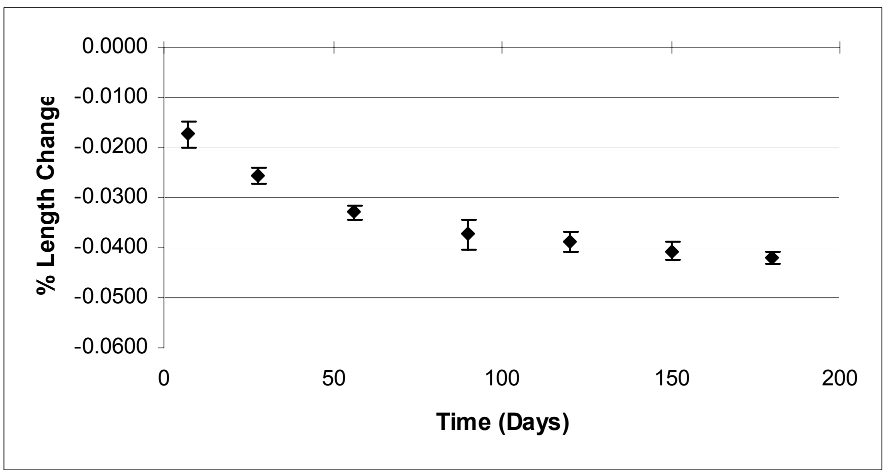


Figure C23: A4 Gravel Percentage Length Change (Test Series 3)

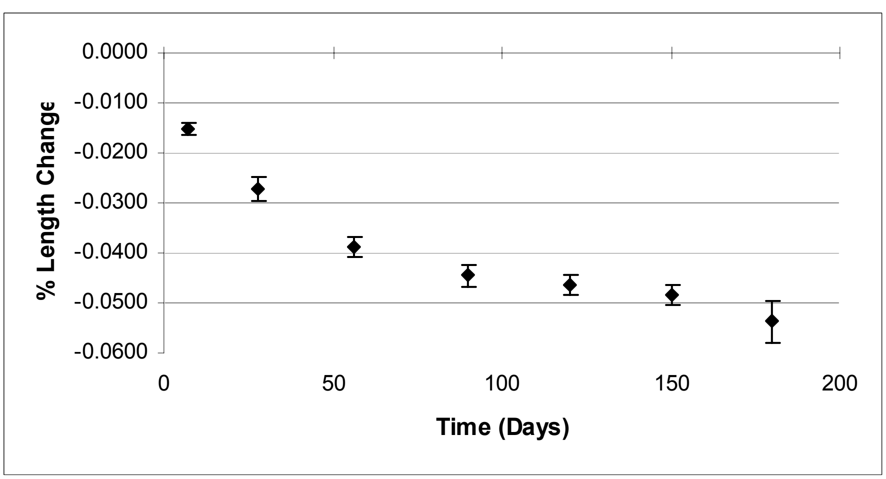


Figure C24: A4 Daibase Percentage Length Change (Test Series 3)

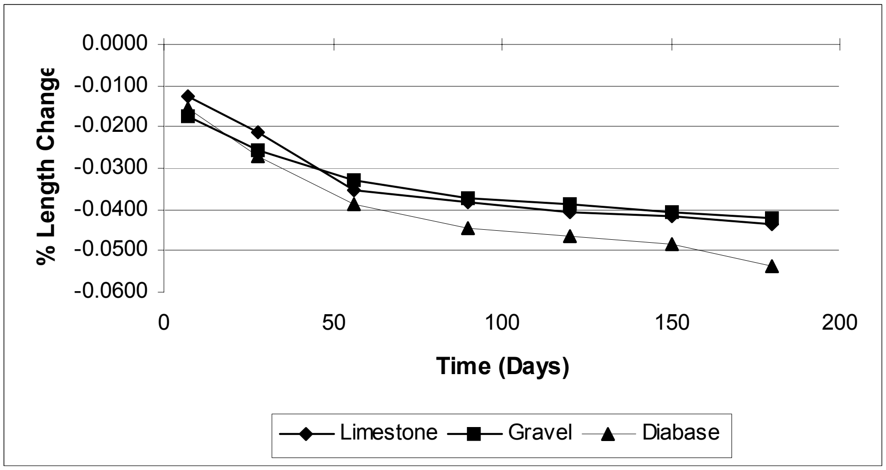


Figure C25: A4 Mixtures Percentage Length Change (Test Series 3)

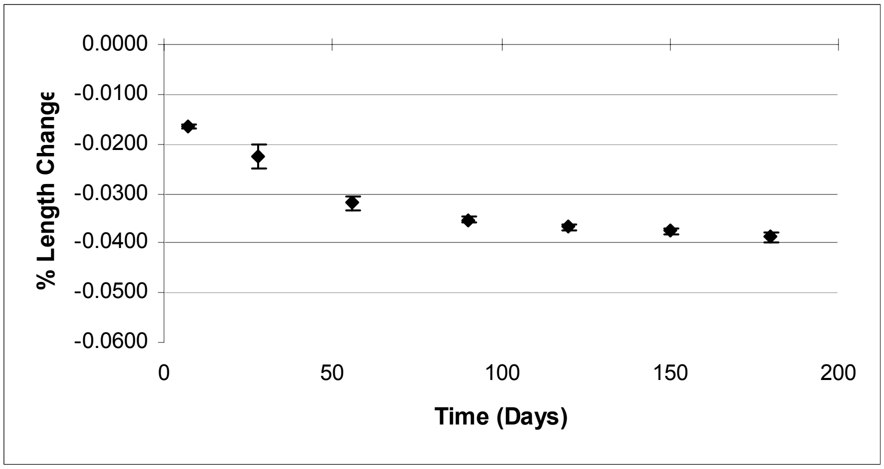


Figure C26: A5 Limestone Percentage Length Change (Test Series 3)

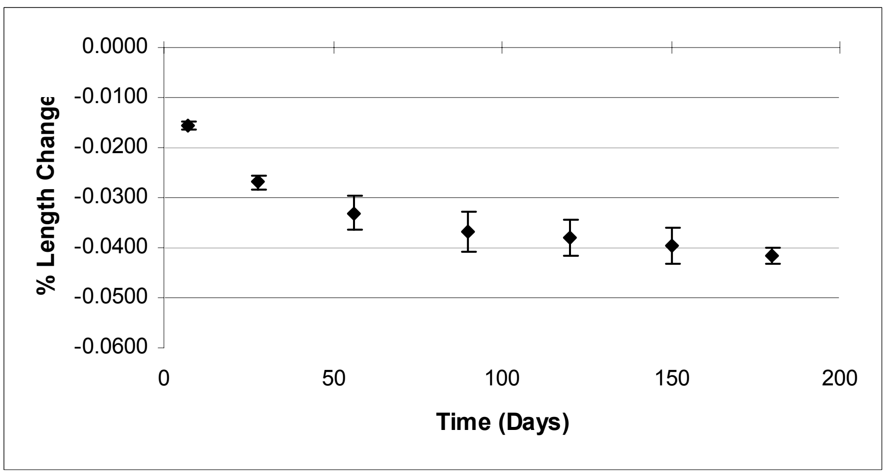


Figure C27: A5 Gravel Percentage Length Change (Test Series 3)

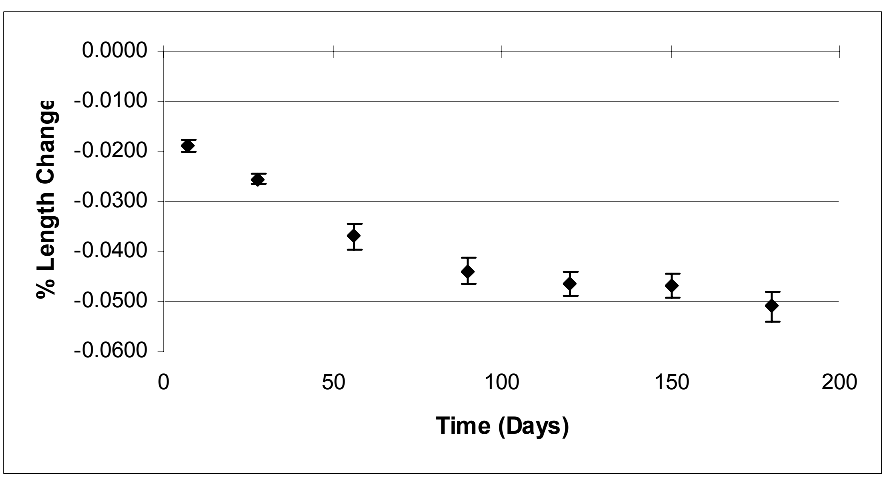


Figure C28: A5 Diabase Percentage Length Change (Test Series 3)

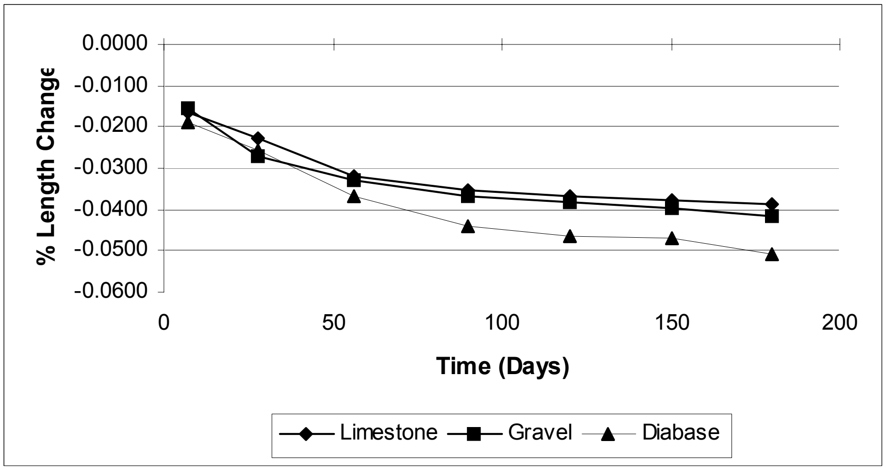


Figure C29: A5 Mixtures Percentage Length Change (Test Series 3)

APPENDIX D

Restrained Shrinkage Mixture Data and Graphs

A3 - Limestone / Portland Cement
Microstrain Data

	Ring 1				Ring 2			
Age	**Gage 1**	**Gage 2**	**Gage 3**	**Gage 4**	**Gage 1**	**Gage 2**	**Gage 3**	**Gage 4**
7	-87	-49	-75	-60	-60	-53	-65	-51
28	-112	-67	-100	-89	-100	-91	-95	-74
56	-205	-183	-180	-137	-183	-156	-150	-121
90	-285	-312	-225	-210	-200	-204	-190	-169
120	-292	-322	-231	-222	-209	-210	-202	-184
150	-121	-76	-190	-184	-217	-219	-215	-191
180	-121	-76	-190	-184	-220	-225	-219	-198

**** Note: Ring 1 Cracked at 125 Days ****

A3 - Limestone / Portland Cement
Ring 1 Statistical Analysis

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	4	-68	16.7	24.6	16.3	-84.1	-51.4
28	4	-92	19.1	20.8	18.7	-110.7	-73.3
56	4	-176	28.4	16.1	27.9	-204.1	-148.4
90	4	-258	48.4	18.8	47.5	-305.5	-210.5
120	4	-267	48.2	18.1	47.2	-314.0	-219.5
150	4	-143	54.4	38.1	53.3	-196.0	-89.5
180	4	-143	54.4	38.1	53.3	-196.0	-89.5

A3 - Limestone / Portland Cement
Ring 2 Statistical Analysis

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	4	-57	6.4	11.3	6.3	-63.6	-50.9
28	4	-90	11.3	12.5	11.1	-101.1	-78.9
56	4	-153	25.4	16.7	24.9	-177.4	-127.6
90	4	-191	15.6	8.2	15.3	-206.1	-175.4
120	4	-201	12.0	6.0	11.8	-213.0	-189.5
150	4	-211	13.1	6.2	12.8	-223.3	-197.7
180	4	-216	12.0	5.5	11.7	-227.2	-203.8

A3 - Limestone / Portland Cement
Statistical Analysis (Both Rings)

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	8	-63	13.0	20.8	9.0	-71.5	-53.5
28	8	-91	14.6	16.0	10.1	-101.1	-80.9
56	8	-164	28.0	17.0	19.4	-183.8	-145.0
90	8	-224	49.0	21.8	34.0	-258.3	-190.4
120	8	-234	47.8	20.4	33.1	-267.1	-200.9
150	8	-177	51.5	29.2	35.7	-212.3	-140.9
180	8	-179	53.3	29.7	36.9	-216.1	-142.2

A3 - Gravel / Portland Cement
Microstrain Data

Age	Ring 1 Gage 1	Ring 1 Gage 2	Ring 1 Gage 3	Ring 1 Gage 4	Ring 2 Gage 1	Ring 2 Gage 2	Ring 2 Gage 3	Ring 2 Gage 4
7	-72	-70	-75	-78	-68	-65	-66	-72
28	-100	-124	-104	-98	-108	-98	-100	-95
56	-162	-144	-115	-112	-129	-125	-126	-105
90	-179	-160	-120	-131	-136	-135	-142	-122
120	-56	-73	-124	-138	-150	-151	-156	-135
150	-56	-73	-124	-138	-170	-175	-174	-152
180	-56	-73	-124	-138	-185	-195	-182	-161

**** Note: Ring 1 Cracked at 117 Days ****

A3 - Gravel / Portland Cement
Ring 1 Statistical Analysis

Age	Sample Size	Mean	Std. Dev	C. O. V. (%)	95% Confidence Limits C. I.	L. L.	U. L.
7	4	-74	3.5	4.7	3.4	-77.2	-70.3
28	4	-107	11.9	11.2	11.7	-118.2	-94.8
56	4	-133	24.0	18.0	23.5	-156.8	-109.7
90	4	-148	26.9	18.3	26.4	-173.9	-121.1
120	4	-98	39.4	40.3	38.6	-136.4	-59.1
150	4	-98	39.4	40.3	38.6	-136.4	-59.1
180	4	-98	39.4	40.3	38.6	-136.4	-59.1

A3 - Gravel / Portland Cement
Ring 2 Statistical Analysis

Age	Sample Size	Mean	Std. Dev	C. O. V. (%)	95% Confidence Limits C. I.	L. L.	U. L.
7	4	-68	3.1	4.6	3.0	-70.8	-64.7
28	4	-100	5.6	5.5	5.4	-105.7	-94.8
56	4	-121	11.0	9.0	10.7	-132.0	-110.5
90	4	-134	8.4	6.3	8.3	-142.0	-125.5
120	4	-148	9.1	6.1	8.9	-156.9	-139.1
150	4	-168	10.7	6.4	10.5	-178.3	-157.2
180	4	-181	14.3	7.9	14.0	-194.8	-166.7

A3 - Gravel / Portland Cement
Statistical Analysis (Both Rings)

Age	Sample Size	Mean	Std. Dev	C. O. V. (%)	95% Confidence Limits C. I.	L. L.	U. L.
7	8	-71	4.4	6.3	3.1	-73.8	-67.7
28	8	-103	9.2	8.9	6.4	-109.8	-97.0
56	8	-127	18.4	14.5	12.8	-140.0	-114.5
90	8	-141	19.9	14.1	13.8	-154.4	-126.8
120	8	-123	37.7	30.7	26.1	-149.0	-96.7
150	8	-133	46.0	34.6	31.9	-164.6	-100.9
180	8	-139	52.2	37.5	36.2	-175.4	-103.1

A3 - Diabase / Portland Cement
Microstrain Data

	Ring 1				Ring 2			
Age	**Gage 1**	**Gage 2**	**Gage 3**	**Gage 4**	**Gage 1**	**Gage 2**	**Gage 3**	**Gage 4**
7	-49	-46	-47	-43	-41	-39	-47	-50
28	-62	-59	-49	-70	-44	-69	-47	-59
56	-109	-106	-73	-94	-76	-98	-70	-97
90	-127	-126	-95	-103	-95	-108	-83	-109
120	-136	-135	-108	-117	-109	-121	-94	-114
150	-147	-141	-111	-125	-117	-128	-105	-128
180	-155	-147	-114	-131	-124	-132	-112	-137

**** Note: No Cracking ****

A3 - Diabase / Portland Cement
Ring 1 Statistical Analysis

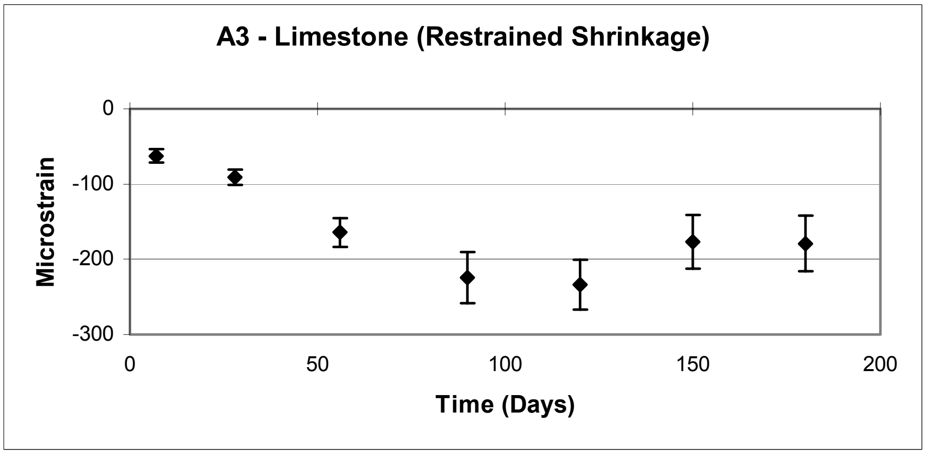
	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	4	-46	2.5	5.4	2.4	-48.7	-43.8
28	4	-60	8.7	14.5	8.5	-68.5	-51.5
56	4	-96	16.3	17.1	16.0	-111.5	-79.5
90	4	-113	16.2	14.4	15.9	-128.6	-96.9
120	4	-124	13.8	11.1	13.5	-137.5	-110.5
150	4	-131	16.2	12.4	15.9	-146.9	-115.1
180	4	-137	18.2	13.3	17.8	-154.5	-119.0

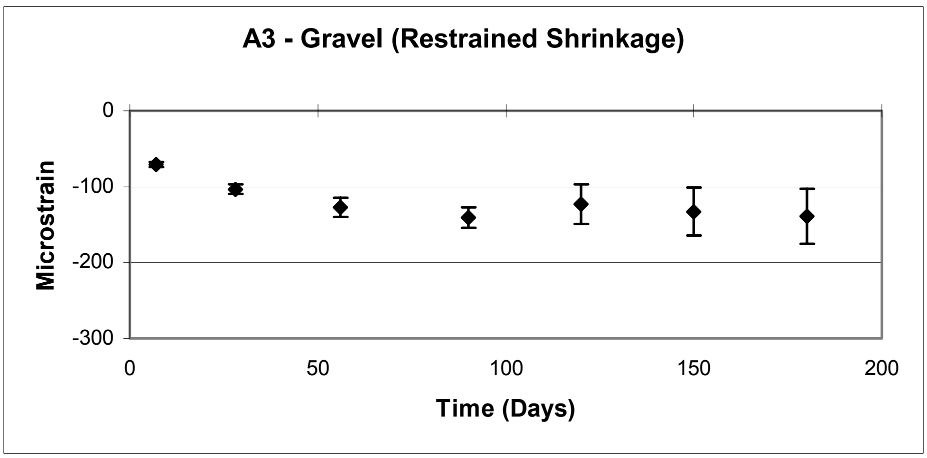
A3 - Diabase / Portland Cement
Ring 2 Statistical Analysis

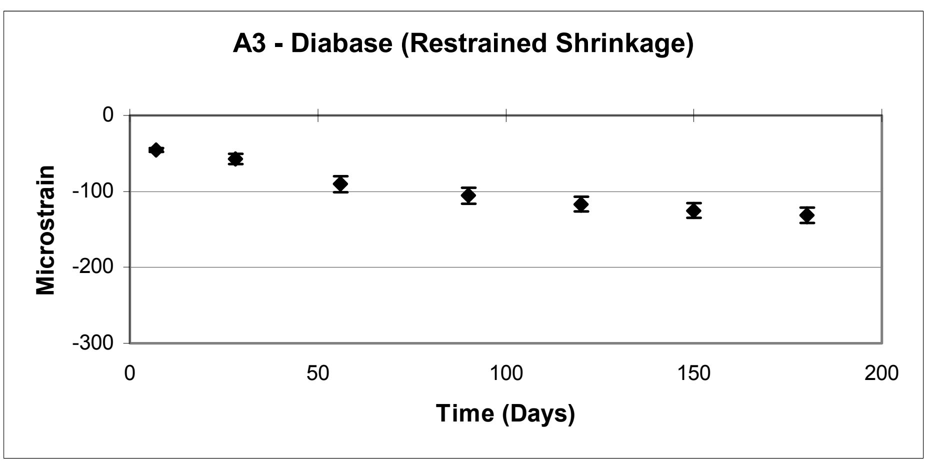
	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	4	-44	5.1	11.6	5.0	-49.3	-39.2
28	4	-55	11.5	21.0	11.3	-66.0	-43.5
56	4	-85	14.4	16.8	14.1	-99.3	-71.2
90	4	-99	12.3	12.4	12.0	-110.8	-86.7
120	4	-110	11.4	10.5	11.2	-120.7	-98.3
150	4	-120	11.0	9.2	10.8	-130.3	-108.7
180	4	-126	10.9	8.6	10.7	-136.9	-115.6

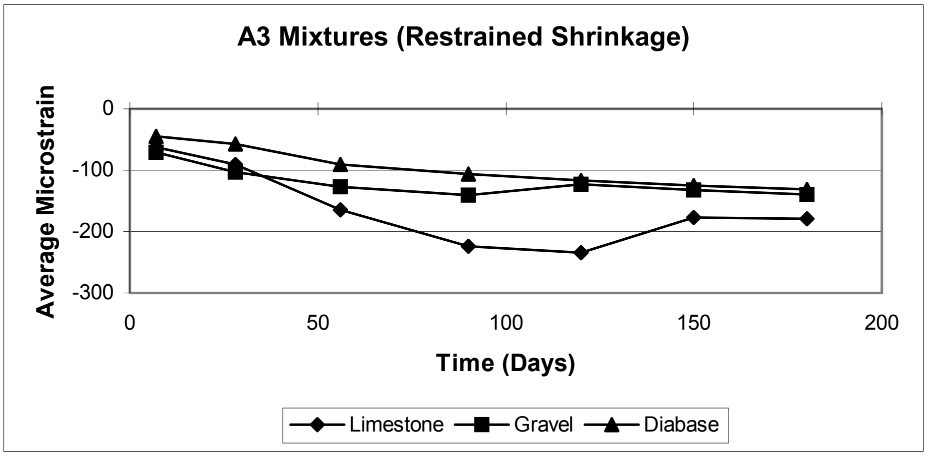
A3 - Diabase / Portland Cement
Statistical Analysis (Both Rings)

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	8	-45	3.9	8.6	2.7	-47.9	-42.6
28	8	-57	9.8	17.2	6.8	-64.2	-50.6
56	8	-90	15.3	16.9	10.6	-100.9	-79.8
90	8	-106	15.3	14.4	10.6	-116.3	-95.2
120	8	-117	14.1	12.0	9.7	-126.5	-107.0
150	8	-125	14.2	11.4	9.9	-135.1	-115.4
180	8	-132	15.0	11.4	10.4	-141.9	-121.1


A3 - Limestone (Restrained Shrinkage)
0
-100
-200
-300
Microstrain
0
50
100
150
200
Time (Days)


A3 - Gravel (Restrained Shrinkage)
0
-100
-200
-300
Microstrain
0
50
100
150
200
Time (Days)


A3 - Diabase (Restrained Shrinkage)
0
-100
-200
-300
Microstrain
0
50
100
150
200
Time (Days)


A3 Mixtures (Restrained Shrinkage)
Average Microstrain
0
-100
-200
-300
0
50
100
150
200
Time (Days)
Limestone
Gravel
Diabase

A4 - Limestone / Portland Cement
Microstrain Data

Age	Ring 1 Gage 1	Ring 1 Gage 2	Ring 1 Gage 3	Ring 1 Gage 4	Ring 2 Gage 1	Ring 2 Gage 2	Ring 2 Gage 3	Ring 2 Gage 4
7	-51	-50	-55	-42	-57	-58	-64	-52
28	-74	-87	-82	-61	-74	-79	-89	-91
56	-114	-129	-120	-104	-137	-125	-141	-147
90	-149	-161	-157	-145	-150	-170	-159	-168
120	-153	-165	-160	-152	-152	-176	-162	-173
150	-159	-167	-163	-157	-154	-179	-165	-175
180	-160	-174	-165	-160	-157	-182	-167	-180

**** Note: No Cracking ****

A4 - Limestone / Portland Cement
Ring 1 Statistical Analysis

Age	Sample Size	Mean	Std. Dev	C. O. V. (%)	95% Confidence Limits C. I.	L. L.	U. L.
7	4	-50	5.4	11.0	5.3	-54.8	-44.2
28	4	-76	11.3	14.9	11.1	-87.1	-64.9
56	4	-117	10.5	9.0	10.3	-127.0	-106.5
90	4	-153	7.3	4.8	7.2	-160.2	-145.8
120	4	-158	6.1	3.9	6.0	-163.5	-151.5
150	4	-162	4.4	2.7	4.3	-165.8	-157.2
180	4	-165	6.6	4.0	6.5	-171.2	-158.3

A4 - Limestone / Portland Cement
Ring 2 Statistical Analysis

Age	Sample Size	Mean	Std. Dev	C. O. V. (%)	95% Confidence Limits C. I.	L. L.	U. L.
7	4	-58	4.9	8.5	4.8	-62.6	-52.9
28	4	-83	8.1	9.7	7.9	-91.2	-75.3
56	4	-138	9.3	6.8	9.1	-146.6	-128.4
90	4	-162	9.2	5.7	9.0	-170.7	-152.8
120	4	-166	11.0	6.6	10.7	-176.5	-155.0
150	4	-168	11.2	6.6	11.0	-179.2	-157.3
180	4	-172	11.7	6.8	11.5	-183.0	-160.0

A4 - Limestone / Portland Cement
Statistical Analysis (Both Rings)

Age	Sample Size	Mean	Std. Dev	C. O. V. (%)	95% Confidence Limits C. I.	L. L.	U. L.
7	8	-54	6.5	12.2	4.5	-58.1	-49.1
28	8	-80	9.9	12.4	6.9	-86.5	-72.8
56	8	-127	14.4	11.3	10.0	-137.1	-117.1
90	8	-157	9.0	5.7	6.2	-163.6	-151.1
120	8	-162	9.3	5.8	6.5	-168.1	-155.2
150	8	-165	8.7	5.3	6.0	-170.9	-158.9
180	8	-168	9.5	5.7	6.6	-174.7	-161.5

A4 - Gravel / Portland Cement
Microstrain Data

	Ring 1				Ring 2			
Age	**Gage 1**	**Gage 2**	**Gage 3**	**Gage 4**	**Gage 1**	**Gage 2**	**Gage 3**	**Gage 4**
7	-66	-60	-54	-66	-55	-52	-49	-45
28	-110	-98	-94	-106	-97	-76	-71	-65
56	-193	-124	-131	-197	-142	-118	-107	-122
90	-221	-160	-174	-227	-178	-133	-132	-179
120	-230	-171	-182	-235	-184	-141	-139	-185
150	-236	-175	-187	-239	-192	-146	-142	-189
180	-240	-181	-194	-245	-201	-149	-145	-194

**** Note: No Cracking ****

A4 - Gravel / Portland Cement
Ring 1 Statistical Analysis

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	4	-62	5.7	9.3	5.6	-67.1	-55.9
28	4	-102	7.3	7.2	7.2	-109.2	-94.8
56	4	-161	39.1	24.3	38.3	-199.6	-122.9
90	4	-196	33.5	17.1	32.8	-228.3	-162.7
120	4	-205	32.7	16.0	32.1	-236.6	-172.4
150	4	-209	33.0	15.8	32.3	-241.6	-176.9
180	4	-215	32.3	15.0	31.6	-246.6	-183.4

A4 - Gravel / Portland Cement
Ring 2 Statistical Analysis

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	4	-50	4.3	8.5	4.2	-54.4	-46.1
28	4	-77	13.9	18.0	13.6	-90.9	-63.6
56	4	-122	14.6	12.0	14.3	-136.6	-107.9
90	4	-156	26.6	17.1	26.0	-181.5	-129.5
120	4	-162	25.7	15.8	25.2	-187.4	-137.1
150	4	-167	26.9	16.1	26.4	-193.6	-140.9
180	4	-172	29.3	17.0	28.8	-201.0	-143.5

A4 - Gravel / Portland Cement
Statistical Analysis (Both Rings)

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	8	-56	7.6	13.6	5.3	-61.2	-50.6
28	8	-90	16.8	18.7	11.6	-101.2	-78.0
56	8	-142	34.4	24.3	23.8	-165.6	-117.9
90	8	-176	35.2	20.1	24.4	-199.9	-151.1
120	8	-183	35.4	19.3	24.5	-207.9	-158.9
150	8	-188	35.8	19.0	24.8	-213.1	-163.4
180	8	-194	36.6	18.9	25.3	-219.0	-168.3

A4 - Diabase / Portland Cement
Microstrain Data

Age	Ring 1 Gage 1	Ring 1 Gage 2	Ring 1 Gage 3	Ring 1 Gage 4	Ring 2 Gage 1	Ring 2 Gage 2	Ring 2 Gage 3	Ring 2 Gage 4
7	-50	-48	-49	-46	-49	-50	-50	-55
28	-111	-115	-117	-90	-85	-111	-93	-161
56	-179	-147	-138	-131	-116	-158	-140	-206
90	-227	-199	-170	-142	-161	-177	-142	-212
120	-231	-205	-185	-151	-167	-185	-151	-220
150	-237	-211	-193	-155	-173	-193	-156	-225
180	-244	-217	-197	-161	-187	-201	-164	-231

**** Note: No Cracking ****

A4 - Diabase / Portland Cement
Ring 1 Statistical Analysis

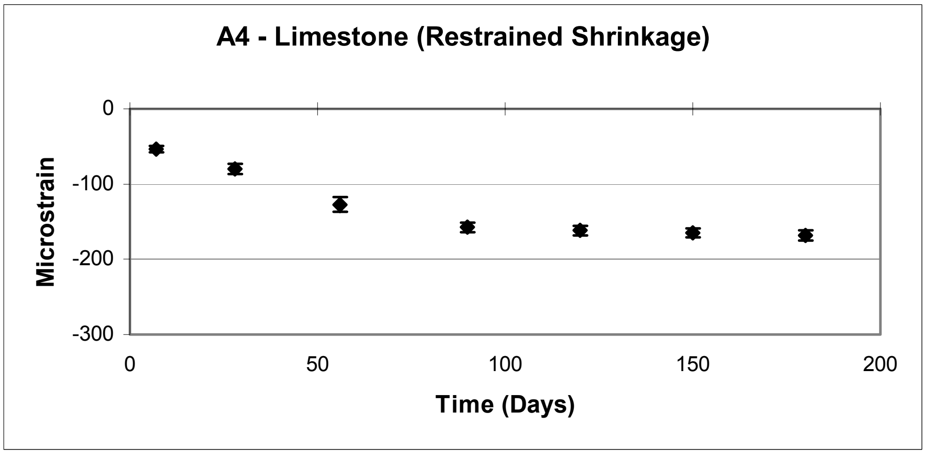
Age	Sample Size	Mean	Std. Dev	C. O. V. (%)	95% Confidence Limits C. I.	L. L.	U. L.
7	4	-48	1.7	3.5	1.7	-49.9	-46.6
28	4	-108	12.4	11.5	12.2	-120.4	-96.1
56	4	-149	21.2	14.3	20.8	-169.5	-128.0
90	4	-185	36.7	19.9	35.9	-220.4	-148.6
120	4	-193	33.7	17.5	33.1	-226.1	-159.9
150	4	-199	34.4	17.3	33.8	-232.8	-165.2
180	4	-205	35.0	17.1	34.3	-239.0	-170.5

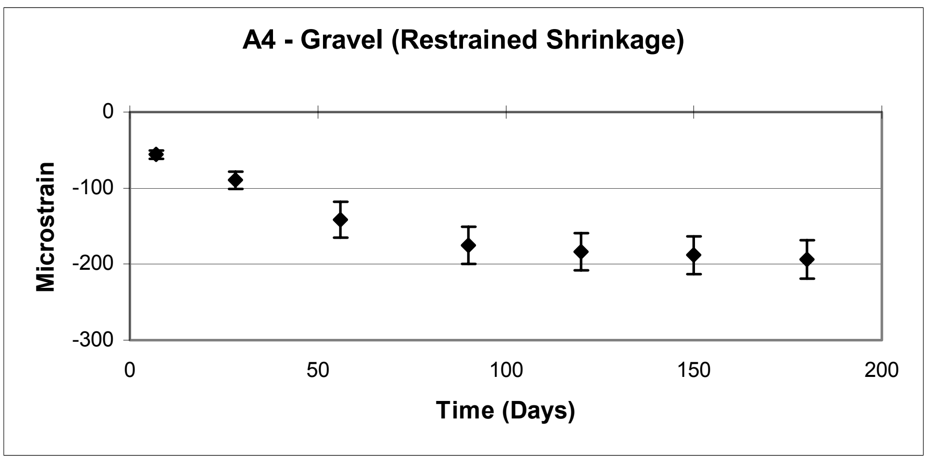
A4 - Diabase / Portland Cement
Ring 2 Statistical Analysis

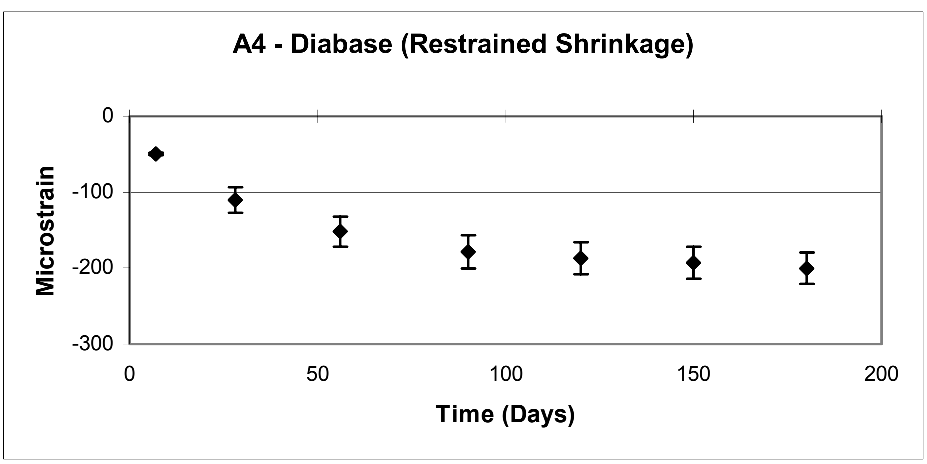
Age	Sample Size	Mean	Std. Dev	C. O. V. (%)	95% Confidence Limits C. I.	L. L.	U. L.
7	4	-51	2.7	5.3	2.7	-53.7	-48.3
28	4	-113	34.1	30.3	33.4	-145.9	-79.1
56	4	-155	38.1	24.6	37.3	-192.3	-117.7
90	4	-173	29.7	17.2	29.1	-202.1	-143.9
120	4	-181	29.6	16.4	29.0	-209.8	-151.7
150	4	-187	29.6	15.9	29.1	-215.8	-157.7
180	4	-196	28.0	14.3	27.5	-223.2	-168.3

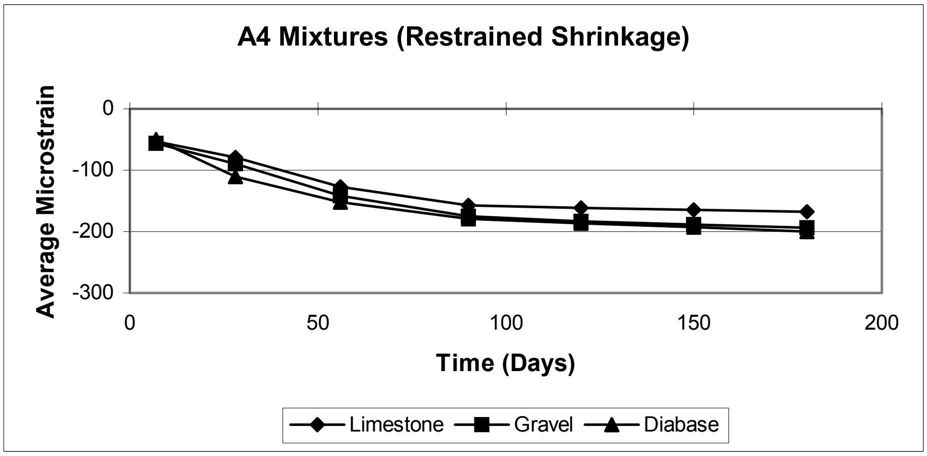
A4 - Diabase / Portland Cement
Statistical Analysis (Both Rings)

Age	Sample Size	Mean	Std. Dev	C. O. V. (%)	95% Confidence Limits C. I.	L. L.	U. L.
7	8	-50	2.6	5.2	1.8	-51.4	-47.9
28	8	-110	23.9	21.6	16.5	-126.9	-93.8
56	8	-152	28.7	18.9	19.9	-171.8	-132.0
90	8	-179	31.5	17.6	21.8	-200.6	-156.9
120	8	-187	30.1	16.1	20.9	-207.7	-166.0
150	8	-193	30.5	15.8	21.1	-214.0	-171.8
180	8	-200	29.7	14.8	20.6	-220.8	-179.7


A4 - Limestone (Restrained Shrinkage)
0
-100
-200
-300
Microstrain
0
50
100
150
200
Time (Days)


A4 - Gravel (Restrained Shrinkage)
0
-100
-200
-300
Microstrain
0
50
100
150
200
Time (Days)


A4 - Diabase (Restrained Shrinkage)
0
-100
-200
-300
Microstrain
0
50
100
150
200
Time (Days)


A4 Mixtures (Restrained Shrinkage)
Average Microstrain
0
-100
-200
-300
0
50
100
150
200
Time (Days)
Limestone
Gravel
Diabase

A5 - Limestone / Portland Cement
Microstrain Data

	Ring 1				Ring 2			
Age	**Gage 1**	**Gage 2**	**Gage 3**	**Gage 4**	**Gage 1**	**Gage 2**	**Gage 3**	**Gage 4**
7	-47	-60	-48	-55	-65	-71	-64	-61
28	-71	-74	-82	-89	-92	-99	-87	-85
56	-129	-77	-86	-134	-129	-141	-131	-120
90	-135	-103	-100	-146	-151	-156	-169	-150
120	-137	-107	-103	-150	-155	-162	-173	-151
150	-138	-110	-107	-153	-158	-167	-177	-153
180	-141	-112	-110	-155	-162	-170	-181	-155

**** Note: No Cracking ****

A5 - Limestone / Portland Cement
Ring 1 Statistical Analysis

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	4	-53	6.1	11.7	6.0	-58.5	-46.5
28	4	-79	8.1	10.3	8.0	-87.0	-71.0
56	4	-107	29.2	27.4	28.6	-135.1	-77.9
90	4	-121	23.0	19.0	22.5	-143.5	-98.5
120	4	-124	22.9	18.4	22.5	-146.7	-101.8
150	4	-127	22.3	17.5	21.8	-148.8	-105.2
180	4	-130	22.1	17.1	21.7	-151.2	-107.8

A5 - Limestone / Portland Cement
Ring 2 Statistical Analysis

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	4	-65	4.2	6.4	4.1	-69.4	-61.1
28	4	-91	6.2	6.9	6.1	-96.9	-84.6
56	4	-130	8.6	6.6	8.4	-138.7	-121.8
90	4	-157	8.7	5.6	8.6	-165.1	-147.9
120	4	-160	9.6	6.0	9.4	-169.7	-150.8
150	4	-164	10.6	6.5	10.4	-174.1	-153.4
180	4	-167	11.2	6.7	10.9	-177.9	-156.1

A5 - Limestone / Portland Cement
Statistical Analysis (Both Rings)

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	8	-59	8.4	14.2	5.8	-64.7	-53.1
28	8	-85	9.2	10.8	6.4	-91.2	-78.5
56	8	-118	23.6	19.9	16.4	-134.7	-102.0
90	8	-139	24.9	17.9	17.2	-156.0	-121.5
120	8	-142	25.2	17.7	17.5	-159.7	-124.8
150	8	-145	25.4	17.5	17.6	-163.0	-127.8
180	8	-148	25.8	17.4	17.9	-166.1	-130.4

A5 - Gravel / Portland Cement
Microstrain Data

Age	Ring 1 Gage 1	Ring 1 Gage 2	Ring 1 Gage 3	Ring 1 Gage 4	Ring 2 Gage 1	Ring 2 Gage 2	Ring 2 Gage 3	Ring 2 Gage 4
7	-60	-59	-68	-63	-64	-53	-56	-61
28	-103	-87	-93	-130	-124	-65	-71	-91
56	-156	-109	-125	-185	-166	-112	-81	-121
90	-215	-194	-185	-281	-179	-148	-126	-141
120	-220	-200	-191	-295	-186	-165	-142	-153
150	-225	-210	-202	-297	-195	-175	-146	-165
180	-97	-102	-160	-120	-203	-181	-158	-174

**** Note: Ring 1 Cracked at 172 Days ****

A5 - Gravel / Portland Cement
Ring 1 Statistical Analysis

Age	Sample Size	Mean	Std. Dev	C. O. V. (%)	95% Confidence Limits C. I.	L. L.	U. L.
7	4	-63	4.0	6.5	4.0	-66.5	-58.5
28	4	-103	19.0	18.4	18.6	-121.9	-84.6
56	4	-144	33.7	23.5	33.0	-176.8	-110.7
90	4	-219	43.4	19.8	42.5	-261.2	-176.3
120	4	-227	47.2	20.9	46.3	-272.8	-180.2
150	4	-234	43.4	18.6	42.5	-276.0	-191.0
180	4	-120	28.6	23.9	28.0	-147.8	-91.7

A5 - Gravel / Portland Cement
Ring 2 Statistical Analysis

Age	Sample Size	Mean	Std. Dev	C. O. V. (%)	95% Confidence Limits C. I.	L. L.	U. L.
7	4	-59	4.9	8.4	4.8	-63.3	-53.7
28	4	-88	26.6	30.3	26.1	-113.8	-61.7
56	4	-120	35.1	29.3	34.4	-154.4	-85.6
90	4	-149	22.3	15.0	21.9	-170.4	-126.6
120	4	-162	18.8	11.7	18.5	-180.0	-143.0
150	4	-170	20.4	12.0	20.0	-190.3	-150.2
180	4	-179	18.7	10.4	18.3	-197.3	-160.7

A5 - Gravel / Portland Cement
Statistical Analysis (Both Rings)

Age	Sample Size	Mean	Std. Dev	C. O. V. (%)	95% Confidence Limits C. I.	L. L.	U. L.
7	8	-61	4.7	7.8	3.3	-63.8	-57.2
28	8	-96	23.0	24.0	15.9	-111.4	-79.6
56	8	-132	34.3	26.0	23.8	-155.7	-108.1
90	8	-184	49.3	26.8	34.2	-217.8	-149.5
120	8	-194	48.1	24.8	33.3	-227.3	-160.7
150	8	-202	46.1	22.9	32.0	-233.8	-169.9
180	8	-149	38.8	26.0	26.9	-176.2	-122.5

A5 - Diabase / Portland Cement
Microstrain Data

	Ring 1				Ring 2			
Age	**Gage 1**	**Gage 2**	**Gage 3**	**Gage 4**	**Gage 1**	**Gage 2**	**Gage 3**	**Gage 4**
7	-44	-47	-52	-52	-33	-60	-53	-75
28	-71	-82	-89	-76	-69	-84	-93	-102
56	-121	-111	-127	-114	-103	-113	-116	-125
90	-192	-181	-187	-154	-137	-144	-154	-166
120	-200	-196	-204	-184	-151	-156	-169	-175
150	-241	-221	-239	-215	-165	-165	-178	-181
180	-141	-135	-144	-105	-171	-178	-198	-188

**** Note: Ring 1 Cracked at 165 Days ****

A5 - Diabase / Portland Cement
Ring 1 Statistical Analysis

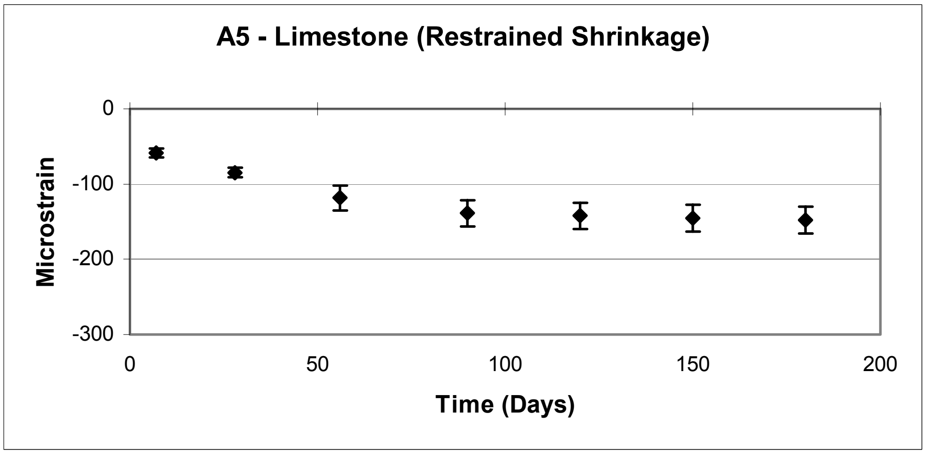
	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	4	-49	3.9	8.1	3.9	-52.6	-44.9
28	4	-80	7.8	9.8	7.6	-87.1	-71.9
56	4	-118	7.2	6.1	7.0	-125.3	-111.2
90	4	-179	16.9	9.5	16.6	-195.1	-161.9
120	4	-196	8.6	4.4	8.5	-204.5	-187.5
150	4	-229	13.0	5.7	12.7	-241.7	-216.3
180	4	-131	17.9	13.6	17.5	-148.8	-113.7

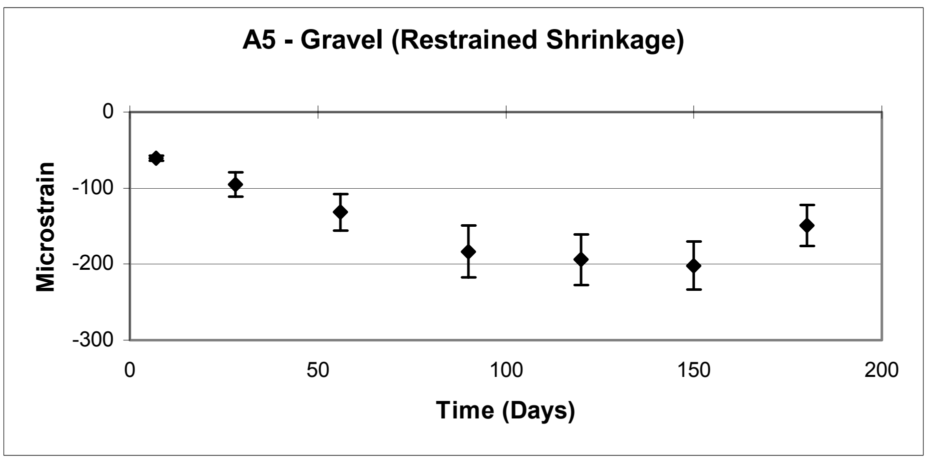
A5 - Diabase / Portland Cement
Ring 2 Statistical Analysis

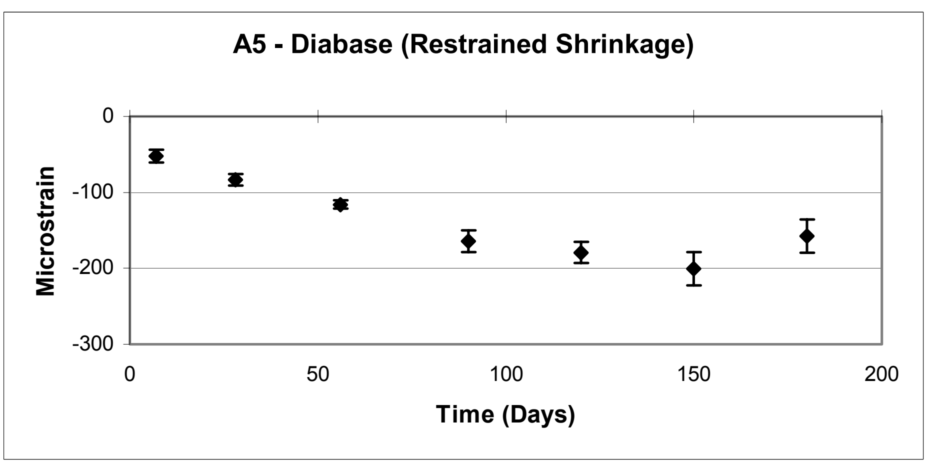
	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	4	-55	17.4	31.6	17.1	-72.3	-38.2
28	4	-87	14.1	16.2	13.8	-100.8	-73.2
56	4	-114	9.1	7.9	8.9	-123.1	-105.4
90	4	-150	12.6	8.4	12.4	-162.6	-137.9
120	4	-163	11.1	6.8	10.9	-173.7	-151.8
150	4	-172	8.5	4.9	8.3	-180.5	-164.0
180	4	-184	11.8	6.4	11.6	-195.3	-172.2

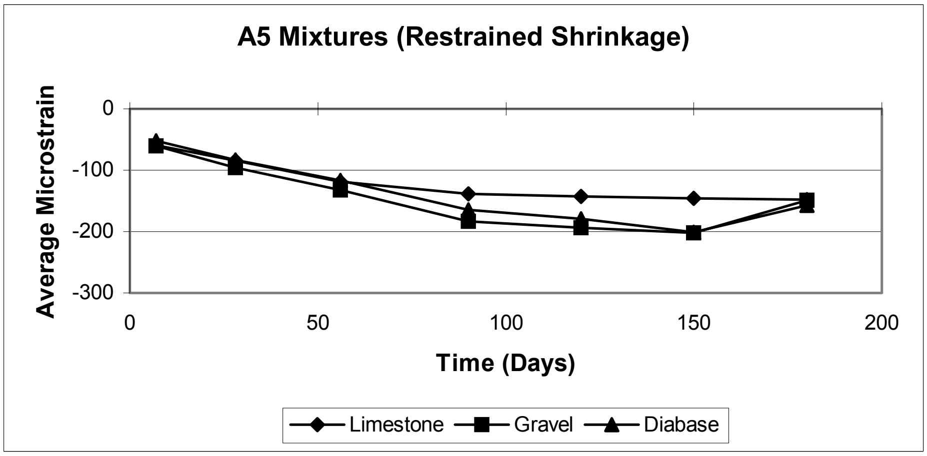
A5 - Diabase / Portland Cement
Statistical Analysis (Both Rings)

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	8	-52	12.2	23.5	8.5	-60.5	-43.5
28	8	-83	11.3	13.5	7.8	-91.1	-75.4
56	8	-116	7.9	6.8	5.5	-121.7	-110.8
90	8	-164	20.5	12.5	14.2	-178.6	-150.2
120	8	-179	20.0	11.2	13.9	-193.3	-165.5
150	8	-201	32.0	15.9	22.2	-222.8	-178.5
180	8	-158	31.4	19.9	21.7	-179.2	-135.8


A5 - Limestone (Restrained Shrinkage)
Microstrain
0
-100
-200
-300
0
50
100
150
200
Time (Days)


A5 - Gravel (Restrained Shrinkage)
Microstrain
0
-100
-200
-300
0
50
100
150
200
Time (Days)


A5 - Diabase (Restrained Shrinkage)
Microstrain
0
-100
-200
-300
0
50
100
150
200
Time (Days)


A5 Mixtures (Restrained Shrinkage)
Average Microstrain
0
-100
-200
-300
0
50
100
150
200
Time (Days)
Limestone
Gravel
Diabase

A4 - Diabase / Fly Ash - Mixture 1
Microstrain Data

	Ring 1				Ring 2			
Age	**Gage 1**	**Gage 2**	**Gage 3**	**Gage 4**	**Gage 1**	**Gage 2**	**Gage 3**	**Gage 4**
7	-60	-64	-57	-63	-59	-58	-56	-61
28	-128	-122	-124	-134	-111	-105	-122	-121
56	-135	-134	-138	-145	-119	-119	-130	-128
90	-175	-174	-181	-182	-156	-163	-170	-167
120	-181	-180	-186	-190	-163	-170	-180	-172
150	-185	-183	-190	-194	-168	-174	-182	-178
180	-190	-186	-196	-200	-172	-179	-190	-183

**** Note: No Cracking ****

A4 - Diabase / Fly Ash - Mixture 1
Ring 1 Statistical Analysis

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	4	-61	3.2	5.2	3.1	-64.1	-57.9
28	4	-127	5.3	4.2	5.2	-132.2	-121.8
56	4	-138	5.0	3.6	4.9	-142.9	-133.1
90	4	-178	4.1	2.3	4.0	-182.0	-174.0
120	4	-184	4.6	2.5	4.6	-188.8	-179.7
150	4	-188	5.0	2.6	4.9	-192.9	-183.1
180	4	-193	6.2	3.2	6.1	-199.1	-186.9

A4 - Diabase / Fly Ash - Mixture 1
Ring 2 Statistical Analysis

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	4	-59	2.1	3.6	2.0	-60.5	-56.5
28	4	-115	8.2	7.1	8.0	-122.8	-106.7
56	4	-124	5.8	4.7	5.7	-129.7	-118.3
90	4	-164	6.1	3.7	5.9	-169.9	-158.1
120	4	-171	7.0	4.1	6.9	-178.1	-164.4
150	4	-176	6.0	3.4	5.9	-181.4	-169.6
180	4	-181	7.5	4.2	7.4	-188.4	-173.6

A4 - Diabase / Fly Ash - Mixture 1
Statistical Analysis (Both Rings)

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	8	-60	2.8	4.7	2.0	-61.7	-57.8
28	8	-121	9.1	7.6	6.3	-127.2	-114.5
56	8	-131	9.0	6.9	6.2	-137.2	-124.8
90	8	-171	8.9	5.2	6.2	-177.2	-164.8
120	8	-178	8.9	5.0	6.1	-183.9	-171.6
150	8	-182	8.4	4.6	5.8	-187.6	-175.9
180	8	-187	9.1	4.8	6.3	-193.3	-180.7

A4 - Diabase / Fly Ash - Mixture 2
Microstrain Data

	Ring 1				Ring 2			
Age	**Gage 1**	**Gage 2**	**Gage 3**	**Gage 4**	**Gage 1**	**Gage 2**	**Gage 3**	**Gage 4**
7	-64	-67	-57	-60	-64	-65	-60	-59
28	-127	-135	-115	-123	-118	-126	-116	-108
56	-140	-148	-126	-134	-131	-143	-130	-128
90	-189	-182	-167	-174	-179	-190	-193	-182
120	-193	-190	-171	-183	-182	-196	-195	-188
150	-195	-198	-175	-189	-187	-201	-196	-191
180	-198	-207	-179	-196	-190	-204	-198	-194

**** Note: No Cracking ****

A4 - Diabase / Fly Ash - Mixture 2
Ring 1 Statistical Analysis

Age	**Sample Size**	**Mean**	**Std. Dev**	**C. O. V. (%)**	**95% Confidence Limits C. I.**	**L. L.**	**U. L.**
7	4	-62	4.4	7.1	4.3	-66.3	-57.7
28	4	-125	8.3	6.7	8.2	-133.2	-116.8
56	4	-137	9.3	6.8	9.1	-146.1	-127.9
90	4	-178	9.6	5.4	9.4	-187.4	-168.6
120	4	-184	9.8	5.3	9.6	-193.8	-174.7
150	4	-189	10.2	5.4	10.0	-199.3	-179.2
180	4	-195	11.7	6.0	11.5	-206.5	-183.5

A4 - Diabase / Fly Ash - Mixture 2
Ring 2 Statistical Analysis

Age	**Sample Size**	**Mean**	**Std. Dev**	**C. O. V. (%)**	**95% Confidence Limits C. I.**	**L. L.**	**U. L.**
7	4	-62	2.9	4.7	2.9	-64.9	-59.1
28	4	-117	7.4	6.3	7.2	-124.2	-109.8
56	4	-133	6.8	5.1	6.6	-139.6	-126.4
90	4	-186	6.6	3.5	6.5	-192.5	-179.5
120	4	-190	6.6	3.4	6.4	-196.7	-183.8
150	4	-194	6.1	3.1	6.0	-199.7	-187.8
180	4	-197	6.0	3.0	5.9	-202.4	-190.6

A4 - Diabase / Fly Ash - Mixture 2
Statistical Analysis (Both Rings)

Age	**Sample Size**	**Mean**	**Std. Dev**	**C. O. V. (%)**	**95% Confidence Limits C. I.**	**L. L.**	**U. L.**
7	8	-62	3.5	5.6	2.4	-64.4	-59.6
28	8	-121	8.5	7.0	5.9	-126.9	-115.1
56	8	-135	7.8	5.8	5.4	-140.4	-129.6
90	8	-182	8.7	4.8	6.0	-188.0	-176.0
120	8	-187	8.3	4.5	5.8	-193.0	-181.5
150	8	-192	8.1	4.3	5.6	-197.1	-185.9
180	8	-196	8.6	4.4	6.0	-201.7	-189.8

A4 - Diabase / Fly Ash - Mixture 3
Microstrain Data

	Ring 1				Ring 2			
Age	**Gage 1**	**Gage 2**	**Gage 3**	**Gage 4**	**Gage 1**	**Gage 2**	**Gage 3**	**Gage 4**
7	-60	-57	-55	-56	-56	-58	-64	-58
28	-113	-113	-99	-107	-114	-120	-130	-120
56	-146	-133	-127	-134	-135	-152	-156	-145
90	-189	-182	-167	-174	-179	-190	-193	-182
120	-192	-187	-175	-179	-182	-192	-197	-189
150	-197	-194	-179	-183	-185	-193	-204	-193
180	-201	-202	-181	-188	-188	-196	-208	-195

**** Note: No Cracking ****

A4 - Diabase / Fly Ash - Mixture 3
Ring 1 Statistical Analysis

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	4	-57	2.2	3.8	2.1	-59.1	-54.9
28	4	-108	6.6	6.1	6.5	-114.5	-101.5
56	4	-135	8.0	5.9	7.8	-142.8	-127.2
90	4	-178	9.6	5.4	9.4	-187.4	-168.6
120	4	-183	7.7	4.2	7.5	-190.8	-175.7
150	4	-188	8.6	4.6	8.4	-196.7	-179.8
180	4	-193	10.2	5.3	10.0	-203.0	-183.0

A4 - Diabase / Fly Ash - Mixture 3
Ring 2 Statistical Analysis

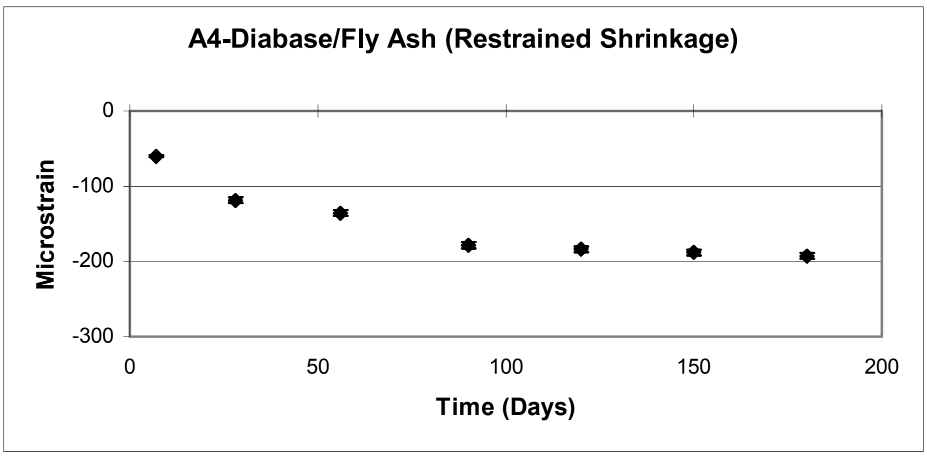
	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	4	-59	3.5	5.9	3.4	-62.4	-55.6
28	4	-121	6.6	5.5	6.5	-127.5	-114.5
56	4	-147	9.2	6.3	9.0	-156.0	-138.0
90	4	-186	6.6	3.5	6.5	-192.5	-179.5
120	4	-190	6.3	3.3	6.1	-196.1	-183.9
150	4	-194	7.8	4.0	7.6	-201.4	-186.1
180	4	-197	8.3	4.2	8.1	-204.9	-188.6

A4 - Diabase / Fly Ash - Mixture 3
Statistical Analysis (Both Rings)

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	8	-58	2.9	5.0	2.0	-60.0	-56.0
28	8	-115	9.3	8.1	6.4	-120.9	-108.1
56	8	-141	10.2	7.3	7.1	-148.1	-133.9
90	8	-182	8.7	4.8	6.0	-188.0	-176.0
120	8	-187	7.4	4.0	5.1	-191.8	-181.5
150	8	-191	8.2	4.3	5.7	-196.7	-185.3
180	8	-195	8.9	4.5	6.1	-201.0	-188.7

A4 - Diabase / Fly Ash
All Rings Satistical Analysis

Age	Sample Size	Mean	Std. Dev	C. O. V. (%)	95% Confidence Limits C. I.	L. L.	U. L.
7	24	-60	3.4	5.6	1.3	-61.3	-58.6
28	24	-119	9.1	7.7	3.6	-122.4	-115.1
56	24	-136	9.6	7.1	3.9	-139.5	-131.8
90	24	-178	9.9	5.6	4.0	-182.3	-174.4
120	24	-184	9.0	4.9	3.6	-187.5	-180.3
150	24	-188	9.1	4.8	3.6	-191.7	-184.4
180	24	-193	9.4	4.9	3.7	-196.3	-188.8



A4 - Diabase / Microsilica - Mixture 1
Microstrain Data

	Ring 1				Ring 2			
Age	**Gage 1**	**Gage 2**	**Gage 3**	**Gage 4**	**Gage 1**	**Gage 2**	**Gage 3**	**Gage 4**
7	-58	-76	-64	-74	-62	-54	-66	-50
28	-86	-88	-90	-105	-103	-95	-104	-85
56	-106	-102	-103	-115	-117	-102	-114	-90
90	-145	-138	-144	-153	-150	-132	-147	-127
120	-162	-151	-157	-165	-162	-145	-161	-138
150	-172	-158	-162	-173	-169	-152	-165	-142
180	-179	-166	-170	-181	-177	-157	-173	-149

**** Note: No Cracking ****

A4 - Diabase / Microsilica - Mixture 1
Ring 1 Statistical Analysis

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	4	-68	8.5	12.5	8.3	-76.3	-59.7
28	4	-92	8.7	9.4	8.5	-100.7	-83.8
56	4	-107	5.9	5.6	5.8	-112.3	-100.7
90	4	-145	6.2	4.3	6.0	-151.0	-139.0
120	4	-159	6.1	3.9	6.0	-164.8	-152.7
150	4	-166	7.4	4.5	7.3	-173.5	-159.0
180	4	-174	7.2	4.1	7.0	-181.0	-167.0

A4 - Diabase / Microsilica - Mixture 1
Ring 2 Statistical Analysis

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	4	-58	7.3	12.6	7.2	-65.2	-50.8
28	4	-97	8.8	9.1	8.6	-105.4	-88.1
56	4	-106	12.3	11.7	12.1	-117.8	-93.7
90	4	-139	11.2	8.1	11.0	-150.0	-128.0
120	4	-152	11.9	7.9	11.7	-163.2	-139.8
150	4	-157	12.4	7.9	12.1	-169.1	-144.9
180	4	-164	13.2	8.1	13.0	-177.0	-151.0

A4 - Diabase / Microsilica - Mixture 1
Statistical Analysis (Both Rings)

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	8	-63	9.1	14.4	6.3	-69.3	-56.7
28	8	-95	8.4	8.9	5.8	-100.3	-88.7
56	8	-106	9.0	8.4	6.2	-112.3	-99.9
90	8	-142	9.0	6.3	6.2	-148.2	-135.8
120	8	-155	9.6	6.2	6.6	-161.8	-148.5
150	8	-162	10.6	6.6	7.4	-169.0	-154.2
180	8	-169	11.2	6.6	7.8	-176.8	-161.2

A4 - Diabase / Microsilica - Mixture 2
Microstrain Data

	Ring 1				Ring 2			
Age	**Gage 1**	**Gage 2**	**Gage 3**	**Gage 4**	**Gage 1**	**Gage 2**	**Gage 3**	**Gage 4**
7	-57	-64	-61	-58	-68	-62	-65	-61
28	-87	-97	-92	-88	-102	-92	-97	-89
56	-98	-113	-108	-101	-123	-113	-117	-107
90	-134	-148	-147	-139	-157	-143	-150	-142
120	-148	-159	-165	-158	-169	-157	-165	-161
150	-162	-171	-172	-165	-183	-171	-173	-172
180	-176	-185	-180	-171	-193	-183	-189	-179

**** Note: No Cracking ****

A4 - Diabase / Microsilica - Mixture 2
Ring 1 Statistical Analysis

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	4	-60	3.2	5.3	3.1	-63.1	-56.9
28	4	-91	4.5	5.0	4.5	-95.5	-86.5
56	4	-105	6.8	6.5	6.6	-111.6	-98.4
90	4	-142	6.7	4.7	6.5	-148.5	-135.5
120	4	-158	7.0	4.5	6.9	-164.4	-150.6
150	4	-168	4.8	2.9	4.7	-172.2	-162.8
180	4	-178	5.9	3.3	5.8	-183.8	-172.2

A4 - Diabase / Microsilica - Mixture 2
Ring 2 Statistical Analysis

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	4	-64	3.2	4.9	3.1	-67.1	-60.9
28	4	-95	5.7	6.0	5.6	-100.6	-89.4
56	4	-115	6.7	5.9	6.6	-121.6	-108.4
90	4	-148	7.0	4.7	6.8	-154.8	-141.2
120	4	-163	5.2	3.2	5.1	-168.1	-157.9
150	4	-175	5.6	3.2	5.4	-180.2	-169.3
180	4	-186	6.2	3.3	6.1	-192.1	-179.9

A4 - Diabase / Microsilica - Mixture 2
Statistical Analysis (Both Rings)

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	8	-62	3.6	5.8	2.5	-64.5	-59.5
28	8	-93	5.2	5.6	3.6	-96.6	-89.4
56	8	-110	8.2	7.5	5.7	-115.7	-104.3
90	8	-145	7.1	4.9	4.9	-149.9	-140.1
120	8	-160	6.4	4.0	4.5	-164.7	-155.8
150	8	-171	6.2	3.6	4.3	-175.4	-166.8
180	8	-182	7.1	3.9	4.9	-186.9	-177.1

A4 - Diabase / Microsilica - Mixture 3
Microstrain Data

	Ring 1				Ring 2			
Age	**Gage 1**	**Gage 2**	**Gage 3**	**Gage 4**	**Gage 1**	**Gage 2**	**Gage 3**	**Gage 4**
7	-58	-60	-55	-63	-54	-59	-51	-56
28	-92	-97	-90	-101	-81	-91	-80	-88
56	-104	-105	-98	-113	-92	-107	-94	-103
90	-133	-140	-133	-146	-124	-145	-128	-139
120	-147	-152	-144	-157	-133	-157	-141	-150
150	-155	-161	-150	-168	-147	-162	-149	-157
180	-169	-170	-155	-174	-153	-173	-155	-163

**** Note: No Cracking ****

A4 - Diabase / Microsilica - Mixture 3
Ring 1 Statistical Analysis

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	4	-59	3.4	5.7	3.3	-62.3	-55.7
28	4	-95	5.0	5.2	4.9	-99.9	-90.1
56	4	-105	6.2	5.9	6.0	-111.0	-99.0
90	4	-138	6.3	4.5	6.1	-144.1	-131.9
120	4	-150	5.7	3.8	5.6	-155.6	-144.4
150	4	-159	7.8	4.9	7.6	-166.1	-150.9
180	4	-167	8.3	5.0	8.1	-175.1	-158.9

A4 - Diabase / Microsilica - Mixture 3
Ring 2 Statistical Analysis

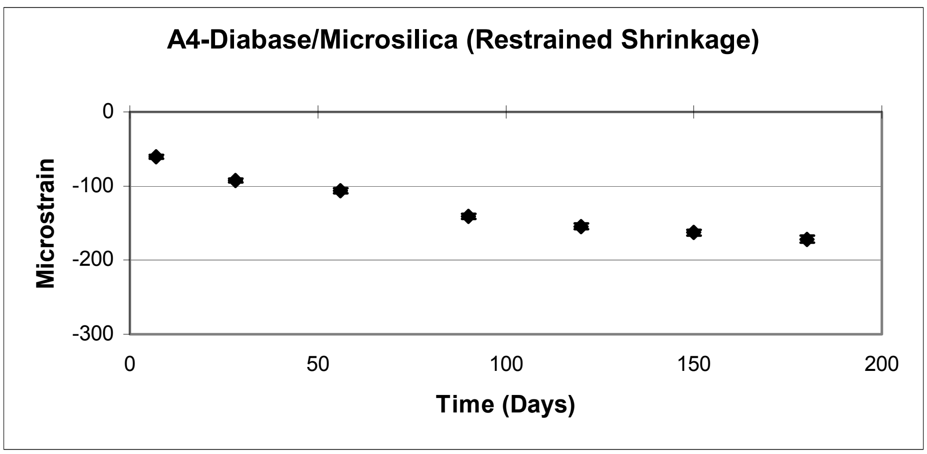
	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	4	-55	3.4	6.1	3.3	-58.3	-51.7
28	4	-85	5.4	6.3	5.2	-90.2	-79.8
56	4	-99	7.2	7.2	7.0	-106.0	-92.0
90	4	-134	9.7	7.2	9.5	-143.5	-124.5
120	4	-145	10.5	7.2	10.3	-155.5	-135.0
150	4	-154	7.0	4.5	6.9	-160.6	-146.9
180	4	-161	9.1	5.6	8.9	-169.9	-152.1

A4 - Diabase / Microsilica - Mixture 3
Statistical Analysis (Both Rings)

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	8	-57	3.8	6.6	2.6	-59.6	-54.4
28	8	-90	7.2	8.0	5.0	-95.0	-85.0
56	8	-102	7.0	6.8	4.8	-106.8	-97.2
90	8	-136	7.9	5.8	5.4	-141.4	-130.6
120	8	-148	8.2	5.6	5.7	-153.3	-141.9
150	8	-156	7.3	4.7	5.1	-161.2	-151.1
180	8	-164	8.7	5.3	6.0	-170.0	-158.0

A4 - Diabase / Microsilica
All Rings Statistical Analysis3

Age	Sample Size	Mean	Std. Dev	C. O. V. (%)	95% Confidence Limits C. I.	L. L.	U. L.
7	24	-61	6.4	10.5	2.5	-63.2	-58.1
28	24	-93	7.0	7.6	2.8	-95.3	-89.7
56	24	-106	8.4	7.9	3.4	-109.4	-102.7
90	24	-141	8.6	6.1	3.4	-144.4	-137.6
120	24	-154	9.4	6.1	3.8	-158.1	-150.6
150	24	-163	10.1	6.2	4.0	-167.0	-158.9
180	24	-172	11.7	6.8	4.7	-176.3	-167.0



A4 - Diabase / Slag Cement - Mixture 1
Microstrain Data

Age	Ring 1 Gage 1	Ring 1 Gage 2	Ring 1 Gage 3	Ring 1 Gage 4	Ring 2 Gage 1	Ring 2 Gage 2	Ring 2 Gage 3	Ring 2 Gage 4
7	-59	-51	-56	-52	-57	-54	-57	-59
28	-111	-90	-87	-61	-93	-93	-97	-103
56	-131	-108	-102	-66	-107	-111	-115	-120
90	-146	-129	-125	-88	-125	-134	-136	-141
120	-152	-138	-135	-100	-136	-142	-142	-152
150	-156	-147	-142	-109	-143	-146	-148	-159
180	-162	-154	-151	-113	-151	-154	-159	-164

**** Note: No Cracking ****

A4 - Diabase / Slag Cement - Mixture 1
Ring 1 Statistical Analysis

Age	Sample Size	Mean	Std. Dev	C. O. V. (%)	95% Confidence Limits C. I.	L. L.	U. L.
7	4	-55	3.7	6.8	3.6	-58.1	-50.9
28	4	-87	20.5	23.5	20.1	-107.3	-67.2
56	4	-102	26.9	26.4	26.4	-128.1	-75.4
90	4	-122	24.4	20.0	23.9	-145.9	-98.1
120	4	-131	22.1	16.8	21.7	-152.9	-109.6
150	4	-139	20.5	14.8	20.1	-158.6	-118.4
180	4	-145	21.8	15.1	21.4	-166.4	-123.6

A4 - Diabase / Slag Cement - Mixture 1
Ring 2 Statistical Analysis

Age	Sample Size	Mean	Std. Dev	C. O. V. (%)	95% Confidence Limits C. I.	L. L.	U. L.
7	4	-57	2.1	3.6	2.0	-58.8	-54.7
28	4	-97	4.7	4.9	4.6	-101.1	-91.9
56	4	-113	5.6	4.9	5.4	-118.7	-107.8
90	4	-134	6.7	5.0	6.5	-140.5	-127.5
120	4	-143	6.6	4.6	6.5	-149.5	-136.5
150	4	-149	7.0	4.7	6.8	-155.8	-142.2
180	4	-157	5.7	3.6	5.6	-162.6	-151.4

A4 - Diabase / Slag Cement - Mixture 1
Statistical Analysis (Both Rings)

Age	Sample Size	Mean	Std. Dev	C. O. V. (%)	95% Confidence Limits C. I.	L. L.	U. L.
7	8	-56	3.0	5.4	2.1	-57.7	-53.5
28	8	-92	14.6	15.9	10.1	-102.0	-81.7
56	8	-108	19.0	17.7	13.2	-120.7	-94.3
90	8	-128	17.8	13.9	12.3	-140.3	-115.7
120	8	-137	16.4	11.9	11.3	-148.5	-125.8
150	8	-144	15.2	10.6	10.6	-154.3	-133.2
180	8	-151	16.1	10.7	11.2	-162.2	-139.8

A4 - Diabase / Slag Cement - Mixture 2
Microstrain Data

	Ring 1				Ring 2			
Age	**Gage 1**	**Gage 2**	**Gage 3**	**Gage 4**	**Gage 1**	**Gage 2**	**Gage 3**	**Gage 4**
7	-47	-48	-50	-41	-56	-40	-56	-46
28	-79	-80	-86	-71	-92	-46	-101	-78
56	-90	-96	-98	-82	-101	-57	-109	-95
90	-118	-125	-128	-113	-125	-94	-132	-212
120	-125	-133	-135	-120	-133	-100	-141	-130
150	-132	-137	-142	-128	-140	-105	-150	-137
180	-137	-143	-149	-135	-147	-110	-157	-142

**** Note: No Cracking ****

A4 - Diabase / Slag Cement - Mixture 2
Ring 1 Statistical Analysis

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	4	-47	3.9	8.3	3.8	-50.3	-42.7
28	4	-79	6.2	7.8	6.0	-85.0	-73.0
56	4	-92	7.2	7.9	7.0	-98.5	-84.5
90	4	-121	6.8	5.6	6.6	-127.6	-114.4
120	4	-128	7.0	5.5	6.9	-135.1	-121.4
150	4	-135	6.1	4.5	6.0	-140.7	-128.8
180	4	-141	6.3	4.5	6.2	-147.2	-134.8

A4 - Diabase / Slag Cement - Mixture 2
Ring 2 Statistical Analysis

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	4	-50	7.9	15.9	7.7	-57.2	-41.8
28	4	-79	24.1	30.4	23.6	-102.9	-55.6
56	4	-91	23.1	25.5	22.6	-113.1	-67.9
90	4	-141	50.3	35.7	49.3	-190.0	-91.5
120	4	-126	17.9	14.2	17.6	-143.6	-108.4
150	4	-133	19.5	14.6	19.1	-152.1	-113.9
180	4	-139	20.3	14.6	19.9	-158.9	-119.1

A4 - Diabase / Slag Cement - Mixture 2
Statistical Analysis (Both Rings)

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	8	-48	6.0	12.5	4.1	-52.1	-43.9
28	8	-79	16.3	20.6	11.3	-90.4	-67.8
56	8	-91	15.8	17.4	11.0	-102.0	-80.0
90	8	-131	34.9	26.6	24.2	-155.0	-106.7
120	8	-127	12.7	10.0	8.8	-135.9	-118.3
150	8	-134	13.4	10.0	9.3	-143.2	-124.6
180	8	-140	14.0	10.0	9.7	-149.7	-130.3

A4 - Diabase / Slag Cement - Mixture 3
Microstrain Data

	Ring 1				Ring 2			
Age	**Gage 1**	**Gage 2**	**Gage 3**	**Gage 4**	**Gage 1**	**Gage 2**	**Gage 3**	**Gage 4**
7	-44	-54	-44	-50	-58	-51	-55	-52
28	-66	-80	-69	-73	-89	-76	-83	-80
56	-77	-97	-78	-88	-99	-84	-93	-88
90	-106	-127	-108	-119	-129	-111	-123	-113
120	-111	-132	-117	-124	-131	-121	-131	-119
150	-117	-138	-125	-130	-139	-128	-135	-127
180	-121	-142	-131	-134	-146	-130	-141	-135

**** Note: No Cracking ****

A4 - Diabase / Slag Cement - Mixture 3
Ring 1 Statistical Analysis

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	4	-48	4.9	10.2	4.8	-52.8	-43.2
28	4	-72	6.1	8.4	5.9	-77.9	-66.1
56	4	-85	9.4	11.1	9.2	-94.2	-75.8
90	4	-115	9.8	8.5	9.6	-124.6	-105.4
120	4	-121	9.1	7.5	8.9	-129.9	-112.1
150	4	-128	8.8	6.9	8.6	-136.1	-118.9
180	4	-132	8.7	6.6	8.5	-140.5	-123.5

A4 - Diabase / Slag Cement - Mixture 3
Ring 2 Statistical Analysis

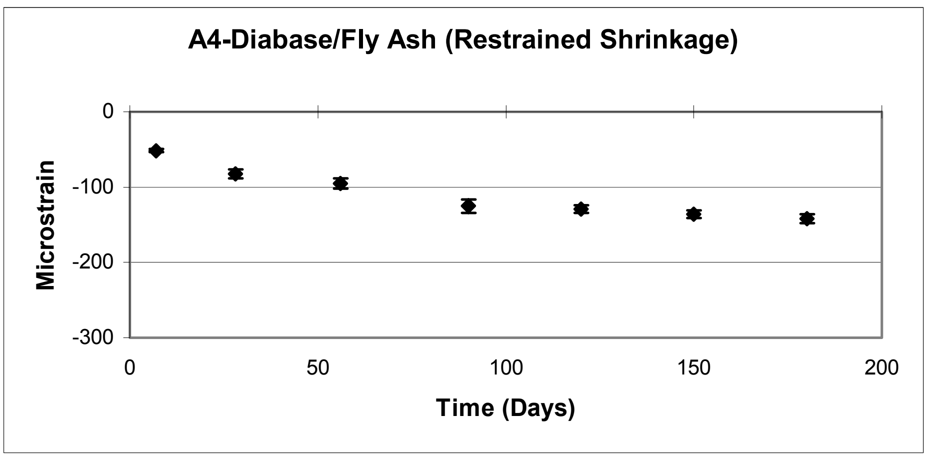
	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	4	-54	3.2	5.9	3.1	-57.1	-50.9
28	4	-82	5.5	6.7	5.4	-87.4	-76.6
56	4	-91	6.5	7.1	6.4	-97.4	-84.6
90	4	-119	8.5	7.1	8.3	-127.3	-110.7
120	4	-126	6.4	5.1	6.3	-131.8	-119.2
150	4	-132	5.7	4.3	5.6	-137.9	-126.6
180	4	-138	7.0	5.1	6.8	-144.8	-131.2

A4 - Diabase / Slag Cement - Mixture 3
Statistical Analysis (Both Rings)

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	8	-51	5.0	9.8	3.5	-54.5	-47.5
28	8	-77	7.6	9.8	5.2	-82.2	-71.8
56	8	-88	8.1	9.3	5.6	-93.6	-82.4
90	8	-117	8.8	7.5	6.1	-123.1	-110.9
120	8	-123	7.6	6.2	5.3	-128.6	-117.9
150	8	-130	7.3	5.6	5.1	-135.0	-124.8
180	8	-135	8.0	5.9	5.5	-140.5	-129.5

A4 - Diabase / Slag Cement
All Rings Statistical Analysis

Age	Sample Size	Mean	Std. Dev	C. O. V. (%)	95% Confidence Limits C. I.	L. L.	U. L.
7	24	-52	5.6	10.9	2.2	-53.8	-49.3
28	24	-83	14.4	17.5	5.8	-88.4	-76.9
56	24	-96	16.8	17.6	6.7	-102.2	-88.8
90	24	-125	22.9	18.3	9.2	-134.5	-116.1
120	24	-129	13.6	10.5	5.4	-134.6	-123.7
150	24	-136	13.3	9.8	5.3	-141.2	-130.5
180	24	-142	14.3	10.1	5.7	-147.7	-136.3



A5 - Diabase / Slag Cement - Mixture 1
Microstrain Data

	Ring 1				Ring 2			
Age	**Gage 1**	**Gage 2**	**Gage 3**	**Gage 4**	**Gage 1**	**Gage 2**	**Gage 3**	**Gage 4**
7	-67	-64	-64	-55	-49	-62	-42	-58
28	-108	-87	-109	-74	-93	-114	-88	-106
56	-123	-102	-127	-116	-110	-124	-98	-114
90	-137	-112	-139	-128	-116	-133	-112	-123
120	-152	-122	-153	-140	-121	-145	-129	-135
150	-164	-129	-161	-149	-135	-152	-135	-146
180	-170	-139	-172	-155	-144	-164	-148	-156

**** Note: No Cracking ****

A5 - Diabase / Slag Cement - Mixture 1
Ring 1 Statistical Analysis

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	4	-63	5.2	8.3	5.1	-67.6	-57.4
28	4	-95	17.0	18.0	16.7	-111.2	-77.8
56	4	-117	11.0	9.4	10.8	-127.8	-106.2
90	4	-129	12.3	9.5	12.1	-141.1	-116.9
120	4	-142	14.4	10.2	14.1	-155.9	-127.6
150	4	-151	15.9	10.5	15.6	-166.3	-135.2
180	4	-159	15.3	9.6	15.0	-174.0	-144.0

A5 - Diabase / Slag Cement - Mixture 1
Ring 2 Statistical Analysis

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	4	-53	9.0	17.1	8.8	-61.6	-43.9
28	4	-100	11.9	11.9	11.7	-111.9	-88.6
56	4	-112	10.8	9.6	10.5	-122.0	-101.0
90	4	-121	9.2	7.6	9.0	-130.0	-112.0
120	4	-133	10.1	7.6	9.9	-142.4	-122.6
150	4	-142	8.4	5.9	8.3	-150.3	-133.7
180	4	-153	8.9	5.8	8.7	-161.7	-144.3

A5 - Diabase / Slag Cement - Mixture 1
Statistical Analysis (Both Rings)

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	8	-58	8.6	14.9	5.9	-63.6	-51.7
28	8	-97	13.9	14.3	9.7	-107.0	-87.7
56	8	-114	10.5	9.2	7.3	-121.5	-107.0
90	8	-125	10.9	8.7	7.6	-132.6	-117.4
120	8	-137	12.6	9.2	8.7	-145.8	-128.4
150	8	-146	12.7	8.7	8.8	-155.2	-137.6
180	8	-156	12.0	7.7	8.3	-164.3	-147.7

A5 - Diabase / Slag Cement - Mixture 2
Microstrain Data

	Ring 1				Ring 2			
Age	**Gage 1**	**Gage 2**	**Gage 3**	**Gage 4**	**Gage 1**	**Gage 2**	**Gage 3**	**Gage 4**
7	-49	-54	-40	-58	-57	-54	-58	-63
28	-98	-92	-100	-94	-99	-88	-118	-140
56	-110	-102	-104	-109	-102	-101	-121	-144
90	-120	-108	-113	-119	-114	-115	-138	-149
120	-135	-127	-122	-131	-133	-122	-152	-159
150	-147	-136	-141	-149	-139	-135	-168	-172
180	-161	-142	-153	-160	-146	-140	-175	-187

**** Note: No Cracking ****

A5 - Diabase / Slag Cement - Mixture 2
Ring 1 Statistical Analysis

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	4	-50	7.8	15.4	7.6	-57.9	-42.6
28	4	-96	3.7	3.8	3.6	-99.6	-92.4
56	4	-106	3.9	3.6	3.8	-110.0	-102.5
90	4	-115	5.6	4.9	5.5	-120.5	-109.5
120	4	-129	5.6	4.3	5.4	-134.2	-123.3
150	4	-143	5.9	4.1	5.8	-149.0	-137.5
180	4	-154	8.8	5.7	8.6	-162.6	-145.4

A5 - Diabase / Slag Cement - Mixture 2
Ring 2 Statistical Analysis

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	4	-58	3.7	6.5	3.7	-61.7	-54.3
28	4	-111	22.8	20.5	22.4	-133.6	-88.9
56	4	-117	20.2	17.3	19.8	-136.8	-97.2
90	4	-129	17.3	13.4	17.0	-146.0	-112.0
120	4	-142	17.0	12.0	16.7	-158.2	-124.8
150	4	-154	19.2	12.5	18.8	-172.3	-134.7
180	4	-162	22.6	14.0	22.2	-184.2	-139.8

A5 - Diabase / Slag Cement - Mixture 2
Statistical Analysis (Both Rings)

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	8	-54	7.0	12.9	4.8	-59.0	-49.3
28	8	-104	17.2	16.6	11.9	-115.5	-91.7
56	8	-112	14.6	13.1	10.2	-121.8	-101.5
90	8	-122	14.1	11.5	9.8	-131.8	-112.2
120	8	-135	13.6	10.0	9.4	-144.5	-125.7
150	8	-148	14.2	9.6	9.9	-158.2	-138.5
180	8	-158	16.4	10.4	11.4	-169.4	-146.6

A5 - Diabase / Slag Cement - Mixture 3
Microstrain Data

	Ring 1				Ring 2			
Age	**Gage 1**	**Gage 2**	**Gage 3**	**Gage 4**	**Gage 1**	**Gage 2**	**Gage 3**	**Gage 4**
7	-53	-62	-57	-60	-65	-60	-66	-57
28	-96	-112	-98	-110	-116	-101	-121	-102
56	-106	-124	-103	-119	-123	-108	-127	-110
90	-120	-140	-113	-135	-136	-120	-141	-119
120	-131	-152	-125	-147	-152	-131	-148	-133
150	-137	-159	-133	-152	-160	-137	-165	-139
180	-147	-166	-142	-165	-166	-145	-176	-149

**** Note: No Cracking ****

A5 - Diabase / Slag Cement - Mixture 3
Ring 1 Statistical Analysis

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	4	-58	3.9	6.8	3.8	-61.8	-54.2
28	4	-104	8.2	7.9	8.0	-112.0	-96.0
56	4	-113	10.1	8.9	9.9	-122.9	-103.1
90	4	-127	12.6	9.9	12.4	-139.4	-114.6
120	4	-139	12.8	9.2	12.6	-151.3	-126.2
150	4	-145	12.3	8.5	12.0	-157.3	-133.2
180	4	-155	12.3	7.9	12.1	-167.1	-142.9

A5 - Diabase / Slag Cement - Mixture 3
Ring 2 Statistical Analysis

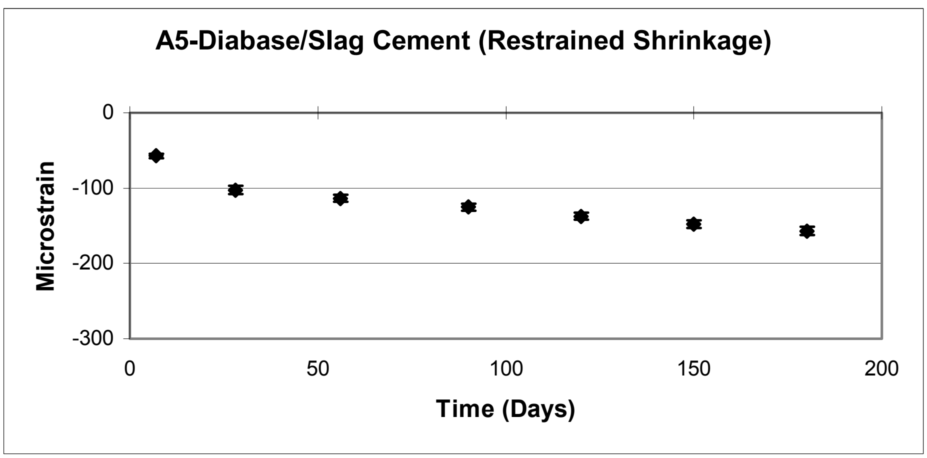
	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	4	-62	4.2	6.8	4.2	-66.2	-57.8
28	4	-110	10.0	9.1	9.8	-119.8	-100.2
56	4	-117	9.4	8.0	9.2	-126.2	-107.8
90	4	-129	11.2	8.7	10.9	-139.9	-118.1
120	4	-141	10.6	7.5	10.3	-151.3	-130.7
150	4	-150	14.3	9.5	14.0	-164.3	-136.2
180	4	-159	14.5	9.1	14.2	-173.2	-144.8

A5 - Diabase / Slag Cement - Mixture 3
Statistical Analysis (Both Rings)

	Sample			C. O. V.	95% Confidence Limits		
Age	**Size**	**Mean**	**Std. Dev**	**(%)**	**C. I.**	**L. L.**	**U. L.**
7	8	-60	4.3	7.2	3.0	-63.0	-57.0
28	8	-107	9.1	8.5	6.3	-113.3	-100.7
56	8	-115	9.3	8.1	6.4	-121.4	-108.6
90	8	-128	11.1	8.7	7.7	-135.7	-120.3
120	8	-140	10.9	7.8	7.6	-147.5	-132.3
150	8	-148	12.6	8.6	8.8	-156.5	-139.0
180	8	-157	12.6	8.1	8.8	-165.8	-148.2

A5 - Diabase / Slag Cement
All Rings Statistical Analysis

Age	Sample Size	Mean	Std. Dev	C. O. V. (%)	95% Confidence Limits C. I.	L. L.	U. L.
7	24	-57	7.0	12.2	2.8	-60.1	-54.4
28	24	-103	13.8	13.4	5.5	-108.2	-97.1
56	24	-114	11.3	9.9	4.5	-118.1	-109.1
90	24	-125	11.8	9.5	4.7	-129.7	-120.3
120	24	-137	12.0	8.7	4.8	-142.2	-132.6
150	24	-148	12.6	8.6	5.1	-152.6	-142.4
180	24	-157	13.3	8.4	5.3	-162.3	-151.7



APPENDIX E

Analysis of Variance

Comparison of A3 Portland Cement Concrete Mixtures

A3 Mixtures @ 7 Days			
Comparison	**F-value**	**p-value**	**Hypothesis**
Limestone vs. Gravel	124.32	0.000	Different
Limestone vs. Diabase	58.75	0.000	Different
Gravel vs. Diabase	1.70	0.215	Same

A3 Mixtures @ 28 Days			
Comparison	**F-value**	**p-value**	**Hypothesis**
Limestone vs. Gravel	12.08	0.004	Different
Limestone vs. Diabase	5.71	0.032	Different
Gravel vs. Diabase	0.21	0.652	Same

A3 Mixtures @ 56 Days			
Comparison	**F-value**	**p-value**	**Hypothesis**
Limestone vs. Gravel	0.01	0.921	Same
Limestone vs. Diabase	1.65	0.224	Same
Gravel vs. Diabase	1.06	0.322	Same

A3 Mixtures @ 90 Days			
Comparison	**F-value**	**p-value**	**Hypothesis**
Limestone vs. Gravel	2.17	0.166	Same
Limestone vs. Diabase	20.60	0.001	Different
Gravel vs. Diabase	18.02	0.001	Different

A3 Mixtures @ 120 Days			
Comparison	**F-value**	**p-value**	**Hypothesis**
Limestone vs. Gravel	0.14	0.711	Same
Limestone vs. Diabase	19.69	0.001	Different
Gravel vs. Diabase	21.85	0.001	Different

A3 Mixtures @ 150 Days			
Comparison	**F-value**	**p-value**	**Hypothesis**
Limestone vs. Gravel	0.88	0.364	Same
Limestone vs. Diabase	19.23	0.001	Different
Gravel vs. Diabase	22.94	0.000	Different

Comparison of A4 Portland Cement Concrete Mixtures

A4 Mixtures @ 7 Days			
Comparison	**F-value**	**p-value**	**Hypothesis**
Limestone vs. Gravel	19.98	0.001	Different
Limestone vs. Diabase	10.57	0.005	Different
Gravel vs. Diabase	3.66	0.008	Same

A4 Mixtures @ 28 Days			
Comparison	**F-value**	**p-value**	**Hypothesis**
Limestone vs. Gravel	12.70	0.003	Different
Limestone vs. Diabase	14.83	0.001	Different
Gravel vs. Diabase	0.78	0.392	Same

A4 Mixtures @ 56 Days			
Comparison	**F-value**	**p-value**	**Hypothesis**
Limestone vs. Gravel	0.78	0.394	Same
Limestone vs. Diabase	1.79	0.203	Same
Gravel vs. Diabase	20.31	0.001	Different

A4 Mixtures @ 90 Days			
Comparison	**F-value**	**p-value**	**Hypothesis**
Limestone vs. Gravel	0.11	0.744	Same
Limestone vs. Diabase	3.60	0.084	Same
Gravel vs. Diabase	11.35	0.005	Different

A4 Mixtures @ 120 Days			
Comparison	**F-value**	**p-value**	**Hypothesis**
Limestone vs. Gravel	0.30	0.596	Same
Limestone vs. Diabase	3.46	0.090	Same
Gravel vs. Diabase	26.26	0.000	Different

A4 Mixtures @ 150 Days			
Comparison	**F-value**	**p-value**	**Hypothesis**
Limestone vs. Gravel	0.16	0.697	Same
Limestone vs. Diabase	4.82	0.050	Same
Gravel vs. Diabase	32.07	0.000	Different

Comparison of A5 Portland Cement Concrete Mixtures

A5 Mixtures @ 7 Days			
Comparison	**F-value**	**p-value**	**Hypothesis**
Limestone vs. Gravel	4.08	0.063	Same
Limestone vs. Diabase	19.17	0.001	Different
Gravel vs. Diabase	23.45	0.000	Different

A5 Mixtures @ 28 Days			
Comparison	**F-value**	**p-value**	**Hypothesis**
Limestone vs. Gravel	9.81	0.010	Different
Limestone vs. Diabase	5.78	0.033	Different
Gravel vs. Diabase	3.03	0.106	Same

A5 Mixtures @ 56 Days			
Comparison	**F-value**	**p-value**	**Hypothesis**
Limestone vs. Gravel	0.37	0.552	Same
Limestone vs. Diabase	11.89	0.005	Different
Gravel vs. Diabase	3.25	0.096	Same

A5 Mixtures @ 90 Days			
Comparison	**F-value**	**p-value**	**Hypothesis**
Limestone vs. Gravel	0.57	0.461	Same
Limestone vs. Diabase	46.58	0.000	Different
Gravel vs. Diabase	8.12	0.014	Different

A5 Mixtures @ 120 Days			
Comparison	**F-value**	**p-value**	**Hypothesis**
Limestone vs. Gravel	0.53	0.479	Same
Limestone vs. Diabase	63.21	0.000	Different
Gravel vs. Diabase	12.77	0.003	Different

A5 Mixtures @ 150 Days			
Comparison	**F-value**	**p-value**	**Hypothesis**
Limestone vs. Gravel	1.10	0.312	Same
Limestone vs. Diabase	62.39	0.000	Different
Gravel vs. Diabase	10.58	0.006	Different

Comparison of Supplemental Cementitious Material Mixtures

Pozzolan Mixtures @ 7 Days			
Comparison	**F-value**	**p-value**	**Hypothesis**
Fly Ash vs. Microsilica	0.55	0.464	Same
Fly Ash vs. A4 Slag	0.72	0.403	Same
Fly Ash vs. A5 Slag	0.03	0.854	Same
Microsilica vs. A4 Slag	2.67	0.111	Same
Microsilica vs. A5 Slag	0.67	0.418	Same
A4 Slag vs. A5 Slag	0.29	0.591	Same

Pozzolan Mixtures @ 28 Days			
Comparison	**F-value**	**p-value**	**Hypothesis**
Fly Ash vs. Microsilica	7.62	0.009	Different
Fly Ash vs. A4 Slag	0.70	0.409	Same
Fly Ash vs. A5 Slag	10.56	0.003	Different
Microsilica vs. A4 Slag	2.59	0.117	Same
Microsilica vs. A5 Slag	0.96	0.334	Same
A4 Slag vs. A5 Slag	5.36	0.027	Different

Pozzolan Mixtures @ 56 Days			
Comparison	**F-value**	**p-value**	**Hypothesis**
Fly Ash vs. Microsilica	22.85	0.000	Different
Fly Ash vs. A4 Slag	13.31	0.001	Different
Fly Ash vs. A5 Slag	18.22	0.000	Different
Microsilica vs. A4 Slag	0.09	0.765	Same
Microsilica vs. A5 Slag	0.38	0.542	Same
A4 Slag vs. A5 Slag	0.65	0.427	Same

Pozzolan Mixtures @ 90 Days			
Comparison	**F-value**	**p-value**	**Hypothesis**
Fly Ash vs. Microsilica	31.29	0.000	Different
Fly Ash vs. A4 Slag	5.33	0.027	Different
Fly Ash vs. A5 Slag	16.53	0.000	Different
Microsilica vs. A4 Slag	3.84	0.057	Same
Microsilica vs. A5 Slag	0.06	0.815	Same
A4 Slag vs. A5 Slag	2.18	0.149	Same

Pozzolan Mixtures @ 120 Days			
Comparison	**F-value**	**p-value**	**Hypothesis**
Fly Ash vs. Microsilica	24.86	0.000	Different
Fly Ash vs. A4 Slag	6.11	0.019	Different
Fly Ash vs. A5 Slag	13.67	0.001	Different
Microsilica vs. A4 Slag	1.76	0.194	Same
Microsilica vs. A5 Slag	0.00	0.985	Same
A4 Slag vs. A5 Slag	1.19	0.284	Same

Pozzolan Mixtures @ 150 Days			
Comparison	**F-value**	**p-value**	**Hypothesis**
Fly Ash vs. Microsilica	18.96	0.000	Different
Fly Ash vs. A4 Slag	7.30	0.011	Different
Fly Ash vs. A5 Slag	12.50	0.001	Different
Microsilica vs. A4 Slag	0.50	0.486	Same
Microsilica vs. A5 Slag	0.02	0.876	Same
A4 Slag vs. A5 Slag	0.55	0.465	Same

Pozzolan Mixtures @ 180 Days			
Comparison	**F-value**	**p-value**	**Hypothesis**
Fly Ash vs. Microsilica	15.86	0.000	Different
Fly Ash vs. A4 Slag	7.61	0.009	Different
Fly Ash vs. A5 Slag	11.43	0.002	Different
Microsilica vs. A4 Slag	0.17	0.685	Same
Microsilica vs. A5 Slag	0.05	0.820	Same
A4 Slag vs. A5 Slag	0.31	0.583	Same

Comparison of Fly Ash to Microsilica and Slag Cement

Fly Ash vs. Microsilica and Slag Cement Combined				
Comparison	**Age**	**F-value**	**p-value**	**Hypothesis**
FA vs MS/Slag Combined	7	0.01	0.932	Same
FA vs MS/Slag Combined	28	3.61	0.063	Same
FA vs MS/Slag Combined	56	21.05	0.000	Different
FA vs MS/Slag Combined	90	15.35	0.000	Different
FA vs MS/Slag Combined	120	14.60	0.000	Different
FA vs MS/Slag Combined	150	13.77	0.001	Different
FA vs MS/Slag Combined	150	12.94	0.001	Different

Comparison of A4 PCC and SCM Mixtures

A4 Pozzolan and Portland Cement Comparison @ 7 Days			
Comparison	**F-value**	**p-value**	**Hypothesis**
Fly Ash vs. PC	12.72	0.002	Different
Microsilica vs. PC	10.63	0.003	Different
Slag vs. PC	18.73	0.000	Different

A4 Pozzolan and Portland Cement Comparison @ 28 Days			
Comparison	**F-value**	**p-value**	**Hypothesis**
Fly Ash vs. PC	124.19	0.000	Different
Microsilica vs. PC	44.30	0.000	Different
Slag vs. PC	63.75	0.000	Different

A4 Pozzolan and Portland Cement Comparison @ 56 Days			
Comparison	**F-value**	**p-value**	**Hypothesis**
Fly Ash vs. PC	63.09	0.000	Different
Microsilica vs. PC	11.77	0.002	Different
Slag vs. PC	8.69	0.007	Different

A4 Pozzolan and Portland Cement Comparison @ 90 Days			
Comparison	**F-value**	**p-value**	**Hypothesis**
Fly Ash vs. PC	27.66	0.000	Different
Microsilica vs. PC	0.66	0.426	Same
Slag vs. PC	3.57	0.072	Same

A4 Pozzolan and Portland Cement Comparison @ 120 Days			
Comparison	**F-value**	**p-value**	**Hypothesis**
Fly Ash vs. PC	28.61	0.000	Different
Microsilica vs. PC	1.77	0.197	Same
Slag vs. PC	3.29	0.083	Same

A4 Pozzolan and Portland Cement Comparison @ 150 Days			
Comparison	**F-value**	**p-value**	**Hypothesis**
Fly Ash vs. PC	25.53	0.000	Different
Microsilica vs. PC	1.45	0.242	Same
Slag vs. PC	1.86	0.186	Same

Comparison of A5 PCC and SCM Mixtures

A5-Diabase/Slag Cement vs. A5-Diabase/Portland Cement				
Comparison	**Age**	**F-value**	**p-value**	**Hypothesis**
Slag vs. Portland Cement	7	0.40	0.535	Same
Slag vs. Portland Cement	28	30.42	0.000	Different
Slag vs. Portland Cement	56	7.60	0.011	Different
Slag vs. Portland Cement	90	1.34	0.259	Same
Slag vs. Portland Cement	120	1.12	0.300	Same
Slag vs. Portland Cement	150	2.27	0.146	Same

APPENDIX F

Compressive Strength and Modulus of Elasticity

Table F1: A3-Limestone Compressive Strength and Modulus of Elasticity (Test Series 1)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	34.3	4980	27.9	4.05
28	40.5	5870	29.1	4.22
56	42.4	6150	30.3	4.39
90	46.2	6700	31.4	4.56

Table F2: A3-Gravel Compressive Strength and Modulus of Elasticity (Test Series 1)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	36.9	5350	28.3	4.11
28	41.0	5940	29.6	4.29
56	44.9	6510	30.8	4.47
90	47.4	6880	32.1	4.65

Table F3: A3-Diabase Compressive Strength and Modulus of Elasticity (Test Series 1)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	34.9	5060	27.2	3.94
28	38.7	5620	28.6	4.15
56	40.6	5890	29.5	4.28
90	44.6	6470	30.3	4.39

Table F4: A4-Limestone Compressive Strength and Modulus of Elasticity (Test Series 1)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	35.4	5140	27.4	3.97
28	42.4	6150	28.9	4.19
56	46.1	6690	31.2	4.52
90	47.2	6840	33.2	4.81

Table F5: A4-Gravel Compressive Strength and Modulus of Elasticity (Test Series 1)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	37.4	5430	28.6	4.15
28	43.6	6320	29.8	4.32
56	47.8	6940	32.9	4.77
90	49.5	7180	34.5	5.01

Table F6: A4-Diabase Compressive Strength and Modulus of Elasticity (Test Series 1)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	34.4	4990	25.6	3.71
28	41.4	6000	27.9	4.05
56	45.2	6560	30.4	4.41
90	46.3	6720	32.9	4.77

Table F7: A5-Limestone Compressive Strength and Modulus of Elasticity (Test Series 1)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	50.7	7350	33.6	4.87
28	53.7	7790	35.6	5.17
56	55.2	8010	36.7	5.32
90	58.1	8420	39.2	5.69

Table F8: A5-Gravel Compressive Strength and Modulus of Elasticity (Test Series 1)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	45.6	6620	32.6	4.73
28	50.1	7270	35.2	5.10
56	53.2	7720	36.5	5.30
90	55.9	8110	37.3	5.41

Table F9: A5-Diabase Compressive Strength and Modulus of Elasticity (Test Series 1)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	42.9	6220	31.7	4.60
28	48.3	7000	33.9	4.92
56	51.0	7390	35.6	5.17
90	53.7	7790	36.4	5.28

Table F10: A4-Diabase/Fly Ash-Mixture 1 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	47.4	6880	30.8	4.47
28	52.8	7660	35.0	5.07
56	54.1	7840	36.6	5.31
90	57.6	8350	40.4	5.86

Table F11: A4-Diabase/Fly Ash-Mixture 2 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	48.4	7020	31.5	4.57
28	53.9	7820	35.6	5.17
56	55.2	8000	37.3	5.41
90	58.7	8510	41.2	5.98

Table F12: A4-Diabase/Fly Ash- Average Compressive Strength and Modulus of Elasticity

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	47.9	6950	31.2	4.52
28	53.4	7740	35.3	5.12
56	54.6	7920	36.7	5.33
90	58.1	8430	40.7	5.90

Table 13G: A4-Diabase/Fly Ash-All Mixtures (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	47.9	6950	31.2	4.52
28	53.4	7740	35.3	5.12
56	54.6	7920	36.9	5.35
90	58.1	8430	40.8	5.91

Table F14: A4-Diabase/Microsilica-Mixture 1 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	MPa	psi	GPa	x10^6 psi
7	48.7	7070	31.2	4.52
28	54.3	7880	36.7	5.33
56	58.6	8500	39.0	5.65
90	61.9	8980	43.4	6.30

Table F15: A4-Diabase/Microsilica-Mixture 2 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	MPa	psi	GPa	x10^6 psi
7	46.4	6730	30.1	4.36
28	51.7	7500	34.6	5.02
56	55.8	8090	38.1	5.53
90	59.0	8550	41.3	5.99

Table F16: A4-Diabase/Microsilica-Mixture 3 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	MPa	psi	GPa	x10^6 psi
7	46.9	6800	30.1	4.36
28	52.3	7580	35.1	5.09
56	56.3	8170	38.5	5.58
90	59.5	8630	41.7	6.05

Table 17G: A4-Diabase/Microsilica- Average Compressive Strength and Modulus of Elasticity

	Compressive Strength		Modulus of Elasticity	
Age	MPa	psi	GPa	x10^6 psi
7	47.3	6870	30.4	4.41
28	52.8	7650	35.5	5.15
56	56.9	8250	38.5	5.59
90	60.1	8720	42.1	6.11

Table F18: A4-Diabase/Slag Cement-Mixture 1 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	50.5	7320	33.6	4.88
28	54.8	7950	37.6	5.45
56	58.6	8500	40.0	5.80
90	61.4	8910	42.5	6.17

Table F19: A4-Diabase/Slag Cement-Mixture 2 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	50.3	7300	33.1	4.80
28	54.2	7860	37.0	5.36
56	58.4	8470	39.2	5.69
90	61.1	8860	42.1	6.11

Table F20: A4-Diabase/Slag Cement-Mixture 3 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	49.7	7210	33.1	4.80
28	54.0	7830	36.5	5.30
56	57.8	8380	38.7	5.62
90	60.5	8780	42.3	6.13

Table 21G: A4-Diabase/Slag Cement- Average Compressive Strength and Modulus of Elasticity

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	50.2	7280	33.3	4.83
28	54.3	7880	37.0	5.37
56	58.3	8450	39.3	5.70
90	61.0	8850	42.3	6.14

Figure F22: A5-Diabase/Slag Cement-Mixture 1 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	50.4	7310	32.4	4.70
28	54.1	7850	37.2	5.39
56	57.8	8390	39.1	5.67
90	61.1	8860	43.4	6.30

Figure F23: A5-Diabase/Slag Cement-Mixture 2 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	51.9	7530	33.4	4.84
28	55.8	8090	38.3	5.56
56	59.7	8660	40.2	5.83
90	62.7	9090	44.7	6.49

Figure F24: A5-Diabase/Slag Cement-Mixture 3 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	51.7	7500	33.6	4.88
28	55.9	8110	38.7	5.62
56	60.1	8710	40.8	5.92
90	63.1	9150	45.6	6.62

Figure 25G: A5-Diabase/Slag Cement-Average Compressive Strength and Modulus of Elasticity

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	51.3	7450	33.1	4.81
28	55.3	8020	38.1	5.52
56	59.2	8590	40.0	5.81
90	62.3	9030	44.6	6.47

Table F26: A3-Limestone-Series 3-Mixture 1 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	31.7	4600	26.1	3.78
28	38.0	5510	28.1	4.07
56	40.2	5830	29.4	4.27
90	44.1	6390	30.5	4.42

Table F27: A3-Limestone-Series 3-Mixture 2 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	34.7	5030	28.5	4.13
28	41.4	6010	30.6	4.44
56	43.9	6370	32.2	4.67
90	48.1	6980	33.3	4.83

Table F28: A3-Limestone-Series 3-Mixture 3 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	30.8	4470	25.3	3.67
28	36.8	5340	27.2	3.94
56	39.0	5650	28.5	4.14
90	42.7	6190	29.5	4.28

Table 29G: A3-Limestone-Series 3 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	32.4	4700	26.6	3.86
28	38.7	5620	28.6	4.15
56	41.0	5950	30.1	4.36
90	45.0	6520	31.1	4.51

Table F30: A3-Gravel-Series 3-Mixture 1 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	36.8	5340	27.5	3.99
28	41.0	5940	29.2	4.23
56	44.5	6450	30.3	4.39
90	46.9	6800	31.2	4.52

Table F31: A3-Gravel-Series 3-Mixture 2 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	36.4	5280	27.2	3.95
28	40.5	5880	28.8	4.18
56	44.1	6390	29.9	4.34
90	47.2	6850	30.9	4.48

Table F32: A3-Gravel-Series 3-Mixture 3 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	38.3	5550	28.6	4.15
28	42.6	6180	30.3	4.40
56	46.3	6710	31.4	4.56
90	48.8	7080	32.5	4.71

Table 33G: A3-Gravel-Series 3 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	37.2	5390	27.8	4.03
28	41.4	6000	29.4	4.27
56	44.9	6520	30.5	4.43
90	47.6	6910	31.5	4.57

Table F34: A3-Diabase-Series 3-Mixture 1 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	37.2	5390	28.1	4.07
28	42.1	6110	29.6	4.29
56	45.9	6650	31.0	4.50
90	48.0	6960	31.9	4.62

Table F35: A3-Diabase-Series 3-Mixture 2 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	37.6	5460	28.4	4.12
28	42.6	6180	29.9	4.34
56	46.4	6730	31.4	4.55
90	48.5	7040	32.2	4.67

Table F36: A3-Diabase-Series 3-Mixture 3 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	37.3	5410	28.1	4.08
28	42.3	6130	29.6	4.30
56	46.0	6670	31.1	4.51
90	48.1	6980	31.9	4.62

Table 37G: A3-Diabase-Series 3 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	37.4	5420	28.2	4.09
28	42.3	6140	29.7	4.31
56	46.1	6680	31.2	4.52
90	48.2	6990	32.0	4.64

Table F38: A4-Limestone-Series 3-Mixture 1 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	37.3	5410	28.3	4.10
28	44.2	6410	30.5	4.42
56	48.1	6980	33.1	4.80
90	49.0	7110	34.6	5.02

Table F39: A4-Limestone-Series 3-Mixture 2 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	36.9	5350	28.0	4.06
28	43.7	6340	30.1	4.37
56	47.6	6910	32.8	4.76
90	48.5	7040	34.3	4.97

Table F40: A4-Limestone-Series 3-Mixture 3 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	35.4	5140	26.9	3.90
28	42.0	6090	29.0	4.20
56	45.7	6630	31.5	4.57
90	46.6	6760	32.9	4.77

Table 41G: A4-Limestone-Series 3 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	36.5	5300	27.7	4.02
28	43.3	6280	29.9	4.33
56	47.2	6840	32.5	4.71
90	48.1	6970	33.9	4.92

Table F42: A4-Gravel-Series 3-Mixture 1 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	38.0	5510	28.6	4.15
28	44.3	6420	30.6	4.44
56	49.9	7240	34.2	4.96
90	50.7	7350	35.0	5.07

Table F43: A4-Gravel-Series 3-Mixture 2 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	38.3	5560	28.8	4.18
28	44.5	6460	31.0	4.50
56	50.4	7310	34.5	5.00
90	51.2	7430	35.5	5.15

Table F44: A4-Gravel-Series 3-Mixture 3 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	38.8	5630	29.2	4.23
28	45.2	6550	31.2	4.52
56	50.9	7380	34.9	5.06
90	51.6	7490	35.6	5.17

Table F45: A4-Gravel-Series 3 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	38.4	5570	28.9	4.19
28	44.7	6480	30.9	4.49
56	50.4	7310	34.5	5.01
90	51.2	7420	35.4	5.13

Table F46: A4-Diabase-Series 3-Mixture 1 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	38.6	5600	29.1	4.22
28	45.5	6600	31.5	4.57
56	49.8	7230	34.5	5.01
90	51.0	7400	35.9	5.20

Table F47: A4-Diabase-Series 3-Mixture 2 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	37.2	5390	28.0	4.06
28	43.8	6350	30.3	4.40
56	47.9	6950	33.2	4.81
90	49.0	7110	34.5	5.00

Table F48: A4-Diabase-Series 3-Mixture 3 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	36.7	5330	27.6	4.01
28	43.3	6280	29.9	4.34
56	47.4	6880	32.8	4.75
90	48.5	7030	33.9	4.92

Table F49: A4-Diabase-Series 3 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	37.5	5440	28.2	4.10
28	44.2	6410	30.6	4.44
56	48.4	7020	33.5	4.86
90	49.5	7180	34.7	5.04

Table F50: A5-Limestone-Series 3-Mixture 1 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	47.8	6940	32.3	4.69
28	52.0	7540	34.1	4.95
56	54.1	7850	36.1	5.24
90	56.9	8250	38.2	5.54

Table F51: A5-Limestone-Series 3-Mixture 2 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	51.7	7500	35.0	5.08
28	56.2	8150	36.9	5.35
56	58.5	8490	39.1	5.67
90	61.5	8920	41.3	5.99

Table F52: A5-Limestone-Series 3-Mixture 3 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	46.9	6800	31.7	4.60
28	50.9	7380	33.4	4.85
56	53.0	7690	35.4	5.14
90	55.7	8080	37.4	5.42

Table F53: A5-Limestone-Series 3 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	48.8	7080	33.0	4.79
28	53.0	7690	34.8	5.05
56	55.2	8010	36.9	5.35
90	58.0	8420	39.0	5.65

Table F54: A5-Gravel-Series 3-Mixture 1 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	44.8	6500	31.5	4.57
28	48.9	7090	33.5	4.86
56	51.8	7510	35.4	5.14
90	55.8	8090	36.4	5.28

Table F55: A5-Gravel-Series 3-Mixture 2 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	36.9	5350	30.2	4.38
28	47.0	6810	32.2	4.67
56	49.8	7220	34.1	4.94
90	53.6	7770	35.0	5.07

Table F56: A5-Gravel-Series 3-Mixture 3 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	45.3	6570	31.8	4.61
28	49.4	7160	33.9	4.91
56	52.3	7590	35.9	5.20
90	56.3	8170	36.7	5.33

Table F57: A5-Gravel-Series 3 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	42.3	6140	31.2	4.52
28	48.4	7020	33.2	4.81
56	51.3	7440	35.1	5.09
90	55.2	8010	36.0	5.23

Table F58: A5-Diabase-Series 3-Mixture 1 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	42.7	6200	30.9	4.48
28	48.5	7030	32.6	4.73
56	50.3	7300	33.9	4.91
90	53.3	7730	36.0	5.22

Table F59: A5-Diabase-Series 3-Mixture 2 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	40.7	5900	29.4	4.26
28	46.1	6680	31.4	4.55
56	47.8	6930	31.9	4.63
90	50.7	7360	34.1	4.94

Table F60: A5-Diabase-Series 3-Mixture 3 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	41.2	5970	29.9	4.33
28	46.5	6750	31.5	4.57
56	48.3	7010	32.4	4.70
90	51.3	7440	34.7	5.04

Table F61: A5-Diabase-Series 3 (Compressive Strength and Modulus of Elasticity)

	Compressive Strength		Modulus of Elasticity	
Age	**MPa**	**psi**	**GPa**	**x10^6 psi**
7	41.5	6020	30.0	4.36
28	47.0	6820	31.8	4.62
56	48.8	7080	32.7	4.75
90	51.8	7510	34.9	5.07

VITA

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