EFFECT OF MATERIALS AND CURING PERIOD ON SHRINKAGE OF CONCRETE

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ABSTRACT

The ASTM C157 free shrinkage test is used to evaluate the effects of mix proportioning parameters and curing on concrete shrinkage with the goal of providing recommendations that will reduce concrete shrinkage in bridge decks. Specimens are dried up to 365 days at 23 ± 2^{o} C (73 ± 3^{o} F) and 50 ± 4 percent relative humidity. Parameters include aggregate content; cement fineness; water-cement ratio; curing period; partial cement replacement by slag, Class C fly ash, or silica fume; superplasticizer dosage; the use of a shrinkage reducing admixture; and aggregate type.

The results indicate that increasing the aggregate content (decreasing the paste content) of a concrete mix decreases shrinkage and that water-cement ratio has little effect in and of itself. For a given aggregate content and water-cement ratio, concretes made with Type I/II cement shrink more than concretes made with Type II coarse-ground cement. Concrete containing a 30 percent cement replacement (by volume) of either Class C fly ash or granulated ground blast-furnace slag exhibit higher shrinkage than concrete with only Type I/II cement when cured for three days. Limestone coarse aggregate produces concrete with higher shrinkage than concrete made with quartzite coarse aggregate. Increased curing periods lead to a decrease in shrinkage for concretes made with either Type I/II or Type II coarse-ground cement. No consistent effect of dosage rate on shrinkage was observed for concretes made with the superplasticizers tested. The use of a shrinkage reducing admixture at a dosage rate of 2 percent by weight of cement reduced the shrinkage of concrete nearly

32 percent after 365 days. The shrinkage reducing admixture, however, produced concrete that at times exhibited an unstable air content.

Keywords: aggregates, cement fineness, concrete, cracking, curing, fly ash, paste content, shrinkage, silica fume, slag, superplasticizers, free shrinkage, shrinkage-reducing admixture

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CHAPTER 1: INTRODUCTION

1.1 GENERAL

The durability of concrete bridge decks is of prime importance. A study performed by the Portland Cement Association, completed in 1970, showed that a number of factors contribute to deck deterioration, mix proportions, bridge design, and construction practices. A main contributing factor is cracking. Cracks allow water and deicing chemicals to reach reinforcing steel, increasing corrosion and accelerating freeze-thaw damage. Cracks that extend through the full thickness of a deck may allow chlorides to corrode the supporting girders as well.

A study by Lindquist, Darwin and Browning (2005) used Fick's Second Law of Diffusion to analyze chloride ingress on the bridge decks. Chloride samples were taken on and away from cracks at five equally spaced intervals to a depth of 95 mm (3.75 in.) into the deck.

The study found that chloride contents taken away from cracks at a depth of 76.2 mm (3.0 in.) (the design cover for the top reinforcing steel) were well below the most conservative estimate of the critical corrosion threshold for conventional reinforcing steel, [0.60 kg/m^3 (1 lb/yd^3)] for all bridge deck types through the first 12 years of deck life. Regardless of bridge type, however, the critical chloride threshold can be reached at cracks as little as nine months, and by 24 months, the chloride content exceeds this value in a majority of the decks. A 2002 Federal Highway Administration study estimated that the direct costs associated with corrosion of highway bridges totaled $8.3 billion, with the indirect direct costs reaching as much as ten times that value (Yunovich et al. 2002). These observations provides strong motivation to reduce the amount of cracking in bridge decks.

The major cause of cracking in concrete bridge decks is drying shrinkage. Shrinkage cracks occur when restrained volume contraction causes tensile stresses to exceed the tensile strength of the concrete. The decrease of shrinkage cracking is affected by both concrete materials properties and construction practices.

1.2 FACTORS EFFECTING CRACKING ON BRIDGE DECKS

This section describes the studies that were used in determine the parameters to investigate in this study.

1.2.1 Krauss and Rogalla (1996)

Krauss and Rogalla (1996) studied factors pertaining to concrete materials, design details, and construction practices that influence the occurrence of early transverse cracking in bridge decks. The authors noted that early transverse cracking contributed to corrosion of reinforcing steel and damage to components under the deck, thus reducing the overall life of bridges. The study had five components. First, an extensive literature review; second, a survey of all state departments of transportation (DOTs) and several transportation agencies outside of the United States; third, laboratory testing of different concrete mixes using restrained ring specimens; fourth, a field study with extensive instrumentation of and a monitoring system installed on the Portland-Columbia bridge between Pennsylvania and New

Jersey; and fifth, an analytical study used finite element analysis techniques to study factors leading to cracking on 18,000 bridge system scenarios. With the results, Krauss and Rogalla ranked factors or combinations of factors contributing to and proposed guidelines/recommendations to prevent or reduce transverse cracking in new bridge decks.

Krauss and Rogalla found that longitudinal tensile stresses in the concrete deck cause transverse cracking. The stresses are most commonly caused by concrete shrinkage and changing concrete temperature. The following were used to evaluate the cracking tendency of different concretes: restrained shrinkage tests with a concrete rings 75 mm (3 in.) wide, 150 mm (6 in.) tall, around a 19 mm (3/4 in.) thick steel tube, along with free shrinkage tests (ASTM C127) and compressive tests (ASTM C192).

The authors reported that two major factors affecting drying shrinkage are paste volume and quantity of water within the mix. Other factors affecting drying shrinkage are aggregate type and gradation, cement type, and environmental conditions, such as temperature and humidity. They suggested that, to reduce drying shrinkage, it is important to reduce the paste volume and total amount of water in the mix, maximize the amount of aggregate, use aggregates with low shrinkage properties, and use Type II cement or shrinkage compensating cements and avoid Type III cement. The authors also stated that increasing the curing time of the concrete may not reduce the long-term shrinkage but may reduce the shrinkage rate. Concrete strength was also determined to be a contributing factor to cracking tendency of concrete, particularly high early strength concretes. Concretes with higher compressive strengths have a higher modulus of elasticity, which results in a reduction in creep. The authors suggested that concretes with low early moduli of elasticity, low early strength, and high early creep will reduce cracking.

1.2.2 Babaei and Purvis (1996)

Babaei and Purvis (1996) performed a three phase study for Pennsylvania Department of Transpiration (PennDOT) investigating concrete durability problems on bridge decks and prevention methods for premature bridge deck cracking. The first phase examined existing bridge decks in Pennsylvania with the intent to identify types of cracking, the significance of and causes of cracking, and methods to minimize cracking on the bridge decks. This was done using "walk-by" surveys of 111 bridges and in-depth surveys of the 12 decks included in the walk-by surveys. The second phase consisted of field tests and observations on a total of eight bridge deck construction projects to identify design and construction procedures that contribute to cracking. The third phase used 76 × 76 × 254 mm (3 × 3 × 10 in.) laboratory shrinkage specimens to verify and modify findings of the first two phases.

During the first phase of the study, it was concluded that transverse cracking was the most prevalent type of cracking on the bridge decks and was most likely due to shrinkage in hardened concrete and restraint provide by longitudinal beams. After examining concrete cores, it was determined that cracks intersected coarse aggregate particles indicating that the cracks occurred in the hardened concrete as opposed to the plastic concrete. Thus, the cause of cracking was most likely drying and thermal shrinkage, as opposed to cracks caused by plastic shrinkage or settlement. Of the 111 bridges surveyed, 51 were prestressed concrete I-beam bridges, 41 were prestressed concrete spread box-beam bridges, and 19 were steel beam bridges. Overall, the steel beam bridges had the most cracking. Also, simply supported bridges had better performance in terms of transverse cracking than continuous bridges because of additional cracking over the supports in the negative moment region due to flexural stresses. This contrasts to the observations of Lindquist et al. (2005) who observed no strong correlation between the region of the bending moment and crack density. Of the transverse cracking observed, almost all followed the line of the top transverse reinforcement, regardless of the type of superstructure, and those cracks extended to the level of the top transverse bars and beyond.

During their field studies, Babaei and Purvis found that long-term shrinkage, thermal shrinkage plus drying shrinkage, was capable of developing transverse cracking on a bridge deck within one year after construction, emphasizing the importance of limiting early-age shrinkage. The latter observation agrees with the findings of Lindquist et al. (2005). After surveying the eight bridges in phase two of the study, Babaei and Purvis found that to limit the transverse crack spacing to a minimum of 9 m (30 ft), the long-term drying shrinkage in free shrinkage specimens for concrete planned for use in the deck must be kept below 700 με (equivalent to 400 με after 28 days of drying) and the thermal shrinkage should be limited to a maximum of 150 με, corresponding to a maximum concrete/deck differential temperature of 12° C (22° F) during the first 24 hours after placement of the concrete.

Babaei and Purvis cataloged a number of factors that can affect shrinkage, including concrete water content, the cement content, cement source, fly ash replacement, aggregate type, and construction practices. After reviewing the in-depth surveys, they concluded that increased water content equated to more evaporation after curing and consequently more drying shrinkage. They equated an increase in water content of 15 kg/m^3 (25 lb/yd^3) to an increase in drying shrinkage of 75 με.

Babaei and Purvis found that cement content, type, source, and fly ash replacement can impact both thermal and drying shrinkage. Three Type I cements from different sources and one Type II cement were studied in the laboratory. They found that drying and thermal shrinkage can vary significantly between concretes made using cements from different sources. When comparing two cements from the same source, they found that replacing Type I with Type II cement resulted in a 25 percent decrease in drying shrinkage. In terms of thermal shrinkage, Type II cement generated a lower heat of hydration than Type I cement, and therefore, its use could have a positive impact on overall shrinkage. Information from this study, however, was not sufficient to quantify the effects of the type of cement on thermal and drying shrinkage. The test for the effect of fly ash replacement on shrinkage was also very limited but a 15 percent replacement Type I cement with fly ash resulted in a 75 percent increase in drying shrinkage (895 με compared to 510 με) at four months of drying. They could not generalize their results from the data.

Overall, Babaei and Purvis recommended limiting both the cement and the water content as much as possible. They suggested reducing the water content through a reduction in cement content (at a constant water-cement ratio) or using a water reducing admixture. From the results of the laboratory and field studies, they recommended cement contents between 376 to 446 kg/m^3 (634 to 752 lb/yd^3) to provide a concrete strength of 31 MPa (4500 psi). Based on the work of Lindquist et al. (2005), the recommended cement contents are quite high.

Aggregate type was also found to have a significant impact on shrinkage. Typically, concretes containing aggregates with a lower modulus of elasticity produce more shrinkage because of the aggregate's diminished restraining ability. Aggregates with higher absorptions and lower specific gravities typically have a lower modulus of elasticity and, thus, are more susceptible to shrinkage (Neville 1996). Babaei and Purvis found that aggregate type played an important role in the performance of the 12 bridge decks in terms of transverse cracking.

They classified aggregates as having a high absorption and low specific gravity as "soft" and aggregates having a low absorption and high specific gravity as "hard". They found that soft aggregates produce concretes with a higher drying shrinkage than hard aggregates and that soft fine aggregates do not contribute as much to the drying shrinkage of concrete as soft coarse aggregates. They suggested that coarse aggregate absorption be limited to 0.5 percent and fine aggregate absorption be limited to 1.5 percent. They did point out, however, that there may be exceptions in which an aggregate with high absorption can produce concrete with relatively low shrinkage.

Babaei and Purvis found that thermal shrinkage could cause cracking in hot or cold weather deck placements. This was due to a temperature difference between the girders and the concrete. They estimated that 228 $\mu\varepsilon$ of thermal shrinkage is needed to initiate cracking.

In the field, concrete temperatures were monitored at the bridge deck up to 8.5 hours after casting. They found the difference between the peak concrete temperature and the ambient temperature ranged from 0 to 17^{o} C (0 to 31^{o} F). They estimated that a difference in temperature would contribute to thermal shrinkage at an average rate of 9.9 $\mu\varepsilon$ per degree C (5.5 $\mu\varepsilon$ per degree F).

In hot weather construction, they recommended using retarders to reduce the rise in temperature of the concrete, particularly when the ambient temperature exceeds 24^{o} C (75^{o} F). They also recommend that concrete should be covered with wet burlap no later than 30 minutes after finishing and that the burlap should be kept wet continuously to minimize heat build-up. They suggested that during hot weather, concrete should be placed at night to minimize the heat build up that occurs due to the combined effects of ambient heat and cement hydration.

In cold weather, the area under the girders should be heated to reduce the deck/beam temperature differential. During curing, the surface insulation should be controlled so that the concrete surface temperature is between 13 and 24^{o} C (55 and 75^{o} F) and the area underneath the deck should be enclosed and heated so that the air temperature underneath the deck is kept as close as possible to the concrete temperature. After curing, the concrete should be allowed to cool slowly to come into equilibrium with the ambient temperature. This should be done by slowly removing the sources of heat. The maximum temperature drop during the first 24 hours after curing should be limited to 14°C (25°F). The temperature differential between the deck and the girders, however, should never exceed 12°C (22°F), as stated before.

1.2.3 Lindquist, Darwin, and Browning (2005)

A study performed by Lindquist, Darwin, and Browning (2005) explored 27 variables affecting crack density, delaminated area, and chloride ingress on bridge decks. These parameters included bridge age, construction practices, material properties, site conditions, bridge design, and traffic volume. Data were analyzed from field studies performed on 59 steel girder bridges in conjunction with 76 surveys performed over a 10-year period, including work by Schmidt and Darwin (1995) and Miller and Darwin (2000). These studies were limited to steel girder bridges based on earlier observations that these bridges exhibit the greatest amount of deck cracking (Portland Cement Association 1970). Of 59 bridges, which were constructed between 1984 and 2002, 13 had monolithic bridge decks, 16 had conventional overlays bridge decks, and 30 had silica fume overlay decks.

Crack density surveys

Crack densities were used to determine the relative degree of cracking for different bridges. After a deck was surveyed, a crack map was drawn and digitally scanned. The image was then analyzed to determine the crack density in m/m^2. As the results from the three studies were analyzed, it was found that crack density increased with the age of the bridge deck, so the crack densities were corrected for age based on average rates of increase. A key observation by Lindquist et al. (2005) was that the properties of the subdeck rather than those of the overlay played the major role in the performance of bridge decks with overlays. Thus, in the discussion that follows, overlay deck properties refer to those of the subdeck only.

Overall, the combined volume of water and cement, the cement paste constituent of concrete, was demonstrated to have a strong influence on crack density. Cement paste is the component of concrete that undergoes shrinkage. For monolithic and overlay bridges, a sharp increase in crack density was observed for decks with paste contents over 27 percent by volume, leading to a recommendation to use paste content below 27 percent to reduce bridge deck cracking.

Lindquist et al. (2005) observed that, for overlay bridge subdecks, all of which had water-cement ratios between 0.40 and 0.45, crack density decreased with an increase in water-cement ratio. This observation was attributed to the lower modulus of elasticity and higher levels of creep associated with concretes with higher water-cement ratios. For monolithic bridge decks, all which had water-cement ratios of 0.42 or 0.44, a small increase in crack density was observed for an increase in water-cement ratio, but the increase was not statistically significant.

Concrete slump had a statistically insignificant effect on crack density for conventional overlay decks, with a slight increase in crack density with increased slump. In contrast, crack density clearly increased for monolithic bridge decks with increasing slump. The effect of higher slump concrete and its contribution to subsidence cracking was demonstrated by Dakhil, Cady, and Carrier (1975). Lindquist et al. (2005) recommended that monolithic decks and overlay subdecks be placed at the lowest slump that would allow proper placement and consolidation.

Lindquist et al. (2005) also observed that crack density was nearly constant for air contents less than 5.5 percent, but dropped as the air content increased from 5.5 to 6.5 percent for monolithic and overlay decks.

Site conditions during placement were observed to be critical in bridge deck cracking. High air temperatures, can increase the evaporation rate, contributing to plastic shrinkage cracking and contributing to total deck cracking. This was observed to be true for both conventional overlay and monolithic decks for which crack densities increased as the maximum air temperature increased. The range in air temperature can also be a problem in terms of thermal shrinkage. Lindquist et al. (2005) found that for monolithic placements, an increase in temperature range on the day of placement, corresponded to an increase in crack density. Although, they found the trend was not statistically significant, it did match findings by Eppers, French, and Hajjar (1998) who observed an increased level of cracking when the daily air temperature range exceeded 10^{o} C (18^{o} F).

Lindquist et al. (2005) observed that monolithic decks cracked less than overlay decks. Silica fume overlays were observed to provide no advantage over conventional overlays in terms of decreased crack density or improved chloride resistance, and conventional overlays were recommended for use only for resurfacing applications because, not only did they exhibit more severe cracking than monolithic decks, but uncracked concrete provided adequate protection from chlorides for reinforcement. They recommended that, rather than using overlays, the prime focus should be placed on minimizing cracking. Finally, they observed for all bridge deck types that a large percentage of the total crack density was established early in the life of the bridge and that the key to reducing total cracking is to reduce early age cracking.

1.3 TYPES OF SHRINKAGE

Cracking in concrete bridge decks can be attributed to various types of concrete shrinkage including plastic, autogenous, thermal, and drying shrinkage.

Plastic shrinkage occurs in plastic concrete and is caused by rapid moisture loss of the concrete. In fresh concrete, water fills the voids between cement particles. Water can be removed from the surface of plastic concrete by external influences such as evaporation, or suction of the water by the subbase or formwork material. When moisture is removed faster than it can be replaced by bleed water, menisci form, exerting negative capillary pressure on the cement skeleton. This pressure causes the volume of the paste to contract (Mindess, Young, and Darwin, 2003). Restraint from the concrete below the drying surface causes tensile stresses to form and cracks form in the plastic concrete. A combination of high wind velocity, low relative humidity, high air temperature, and high concrete temperature attribute to an increase in plastic shrinkage. To avoid plastic shrinkage, evaporation rates should not exceed 0.5kg/m^2/h (0.1 lb/ft^2/h) (Mindess, Young, Darwin 2003).

Temperature differences in concrete can result in differential volume changes and, thus, cause tensile stresses to occur. This differential volume change is known as thermal shrinkage, and when the tensile stresses in the concrete exceed the tensile capacity of the concrete, cracking occurs. Differential temperatures in concrete can occur if portions of the concrete lose heat of hydration at different rates, or if weather conditions cool or heat a portion of the concrete (ACI Committee 224 2007).

When no additional water is available during curing of the concrete, moisture is lost because it is consumed by hydration thus shrinkage occurs. This process is known as self-desiccation and causes autogenous shrinkage. It predominantly occurs in concrete with low water-cement ratios (< 0.30). Because autogenous shrinkage is relatively small in concrete with water-cement ratios greater than 0.30, autogenous shrinkage is usually included as part of drying shrinkage.

Autogenous shrinkage can also occur due to chemical shrinkage. Concretes that have a finer pore structure will be more susceptible to autogenous shrinkage. Pozzolanic reactions with mineral admixtures, such as silica fume, or faster setting cements with higher amounts of C_3A can lead to a finer pore structure. Mix proportioning is one method used to address autogenous shrinkage (Holt and Leivo 2004).

Drying shrinkage is the volume reduction caused by the loss of water from the network of capillary pores within hardened concrete. When concrete is subject to restraint from another part of the structure or the subgrade, tensile stresses can develop. If these tensile stresses exceed the tensile strength of the concrete, cracks form. Non-uniform or differential shrinkage within the concrete can also provide restraint that can lead to drying shrinkage cracking, as well.

The three mechanisms that cause drying shrinkage are capillary stress, disjoining pressure, and surface free energy. This occurs at relative humidities between 45 and 95 percent. At relative humidities below 45 percent, menisci are no longer sand, thus, capillary stresses and disjoining pressure do not exist (Mindess, Young, and Darwin 2003). The meniscus between cement particles forms a curved surface causing the water to be in hydrostatic tension and the surrounding solid material to be in hydrostatic compression. This hydrostatic compression can cause cement particles to rearrange, forcing some pores to become smaller, thus causing a reduction in the volume of the cement paste. Disjoining pressure is also only significant down to about 45 percent relative humidity, and it increases with increasing relative humidity. It is the pressure caused by absorbed water confined within the small spaces of the capillary pores. In this narrow space, the water exerts pressure on the adjacent solid surfaces. Upon drying, when the absorbed water is lost, the disjoining pressure is reduced and the cement particles are drawn closer together resulting in shrinkage. Below 45 percent relative humidity, when capillary stress and disjoining pressure are no longer applicable, shrinkage is caused by changes in surface energy. The last few molecular layers of water on the surrounding solid material is the most strongly absorbed. This water has a high surface tension (surface free energy), exerting a compressive force on the cement particles. This causes a net reduction in the volume (Mindess, Young, and Darwin 2003). Drying shrinkage is a major contributor to cracking of concrete on bridge decks and will be the main focus of this study.

1.4 FACTORS AFFECTING DRYING SHRINKAGE

There are many factors that affect drying shrinkage of concrete. The factors studied in this report include: water content, aggregate content and type, cement fineness, the use of a shrinkage reducing admixture, different curing periods, the use of mineral admixtures, and the use of superplasticizers.

1.4.1 Water Content

The portion of concrete that experiences the most volume change is the portion that consists of water and cementitious material, commonly known as cement paste. Carlson (1938) demonstrated this by comparing solid specimens of neat cement and concrete made with porous, non-absorbent rubber particles. He found that each shrank equally, and concluded that cement paste, if unrestrained by aggregate, would shrink 5 to 15 times more than ordinary concrete. Carlson also stated that water content is probably the most important single factor affecting shrinkage in concrete.

Picket (1956) studied mortars with different water cement ratios (0.35 and 0.50) and different aggregate contents ranging from 0 to 65 percent aggregate content by volume. Mortars with different types of aggregate (pulverized silica, Ottawa sand, and graded Elgin sand) were used. Shrinkage specimens with dimensions of 22 × 25 × 286 mm (7/8 × 1 × 11¼ in.) were cured for 7 days and then dried for 224 days. While the primary purpose of the study was to determine the effect of aggregate content on concrete shrinkage, he also observed an effect of water-cement ratio as well. Picket did not report the mix proportions for each mix, so it is not known if the increased water-cement ratio was achieved by increasing the water content or decreasing the cement or if the paste contents of the mixes changed or remained constant. A constant slump was not maintained for the concrete mixes.

For mortar made with 50 percent Ottawa sand and a water-cement ratio of 0.50, the shrinkage after 224 days was 1700 με, while the shrinkage of a similar concrete with a water-cement ratio of 0.35 and 53 percent Ottawa sand was only 940 με. Similar results were observed with the Elgin sand aggregate used in concretes with an aggregate content of 50 percent. Shrinkage after 224 days for mortar with a water-cement ratio of 0.50 and 50 percent aggregate content was 1650 με, while shrinkage for mortar with a water-cement ratio of 0.35 and 53 percent aggregate was 1080 με. Picket (1956) stated that, at a constant aggregate content, shrinkage was approximately proportional to the water-cement ratio and shrinkage should increase with increase in water-cement ratio. Picket hypothesized that, because of hydrostatic tension in the concrete gel structure, large spaces between particles will become larger and small spaces will become smaller. He concluded that the original spacing between gel particles depends on the water-cement ratio and that more shrinkage is possible with greater spacing. Concretes with higher water-cement ratios have a more open structure, and concretes with lower water-cement ratios do not have many large capillaries and therefore have less capacity to shrink. It is important to note, however, that the aggregate content and thus the paste content was not held constant when comparing concretes with the two water-cement ratios. This difference in paste content between the concretes of different water-cement ratios could be a factor contributing to the difference in shrinkage.

Hindy et al. (1994) studied concretes with water-cementitious (*w/cm*) ratios of 0.22 and 0.28 to compare the effect of water-cementitious ratio on shrinkage. The concrete with a *w/cm* ratio of 0.22 contained a natural granite sand as fine aggregate and a limestone coarse aggregate with a blended cement containing 7 to 8 percent (by mass) of silica fume. The concrete with the *w/cm* ratio of 0.28 contained the same aggregates, but the cement was not blended with silica fume. Both concretes contained a superplasticizer to obtain an 8 in. (200 mm) slump. To obtain the lower *w/cm* mix, the cement content was increased and the water was decreased compared to the original mix. The 0.28 *w/cm* mix contained 29.7 percent paste, while the 0.22 *w/cm* mix contained 28.1 percent paste. After 28 days of drying, he found that the 0.28 *w/cm* and the 0.22 *w/cm* mixes exhibited shrinkage of 392 and 362 με, respectively. Similarly, after 365 days of drying, the 0.28 and 0.22 *w/cm* mixes exhibited shrinkage of 702 and 630 με, respectively. Hindy et al. stated that the increase in *w/cm* increased the shrinkage by providing more space for free water diffusion and reducing the rigidity of the solid matrix that resists shrinkage. The authors also pointed out other factors that could be affecting the reduced shrinkage between the two mixes other than the *w/cm*. He pointed out that silica fume densifies the hydrated paste, thus slowing shrinkage. The lower *w/cm* mix contained silica fume; thus, the decrease in shrinkage cannot be contributed completely to the decrease in *w/cm* ratio. Another factor not mentioned by Hindy et al., but still a major contributing factor to decreasing shrinkage was the overall decrease in the paste content of the lower *w/cm* ratio mix compared to the original mix.

1.4.2 Aggregates

Aggregate serves to restrain drying shrinkage, so increasing the aggregate content will lead to a decrease in concrete shrinkage because it allows for a mixture with less paste. It has been shown by many authors that in an increase in aggregate size and/or and increase in aggregate content, both resulting in an increase in aggregate volume, provides restraint for the concrete and reduces shrinkage (Carlson 1938, Picket 1956, Powers 1959, Rao 2001).

The modulus of elasticity of the aggregate helps determine the degree of restraint it will provide against shrinkage (Neville 1996). Aggregates with high absorption, and thus high porosity, are usually associated with a low modulus of elasticity (Carlson 1938), which will result in less restraint against shrinkage in concrete. Carlson (1938) studied concretes with a water-cement ratio of 0.40 and mix proportions of 1:2.5 by weight containing only one size of aggregate, 4.75 to 9.5 mm (3/16 to 3/8 in.), to evaluate the effect of aggregate type alone on shrinkage. Using a sample of mixed gravel that had 1 percent absorption and a specific gravity (SG) of 2.74, Carlson observed a shrinkage after one year of 560 με. From this mixed gravel sample, Carlson hand picked pebbles of different aggregate types. The aggregate pebbles studied for shrinkage were slate (1.3 percent absorption, SG of 2.75), granite (0.8 percent absorption, SG of 2.67), and quartz (0.3 percent absorption, SG of 2.66). Tests of concrete containing slate, granite, and quartz produced shrinkage values after 1 year of 680, 470, and 320 με, respectively. Carlson also tested concrete containing sandstone from West Virginia and crushed limestone from California. He concluded that the compressibility of the aggregate is the most important single property of aggregate affecting concrete shrinkage.

Carlson (1938) also evaluated the effect of aggregate size on shrinkage using two different types of aggregate, crushed dolomite and mixed sand with gravel. The water-cement ratio was held constant (0.65). The slump was held constant at 75 mm (3 in.) by increasing the cement content. The concrete was cured for 7 days, and the 6 month shrinkage was reported. The gradation of the aggregates was compared by using an "ideal" gradation, which was achieved by remixing aggregates of each size. Gravel and sand concretes with aggregate maximum sizes of 19, 9.5, and 4.75 mm (3/4, 3/8, and 3/16 in.) produced six-month shrinkage values of 800, 925, and 1100 με, respectively. This resulted in 40 percent lower shrinkage by increasing the maximum aggregate size from 4.75 to 19 mm (3/16 to 3/4 in.). Clearly, increasing the maximum size aggregate produced a lower shrinkage for the gravel and sand concretes. For the crushed dolomite concrete, maximum size aggregates of 19, 9.5, and 4.75 mm, (3/4, 3/8, and 3/16 in.), produced six month shrinkage values of 700, 775, and 1000 με, respectively. This resulted in 50 percent lower shrinkage by increasing the maximum aggregate size from 4.75 to 19 mm (3/16 to 3/4 in.). Carlson concluded that using a larger sized aggregate, a lower water content can be used. As stated earlier, Carlson held the slump constant by modifying both the water and the cement contents, and subsequently the paste content. Concretes with smaller maximum sized aggregate requires more paste for the same slump than concrete with a larger aggregate.

Picket (1956) derived a theoretical formula to calculate the effect of aggregate content on mortar shrinkage during drying. He studied mortars to test his equation using mortar with different water-cement ratios (0.35 and 0.50) and different aggregate contents, ranging from 0 to 65 percent. Mortars with different types of aggregate (pulverized silica, Ottawa sand, and graded Elgin sand) were also tested to determine the effect of the type of aggregate on concrete shrinkage. Material properties for each aggregate were not reported. Shrinkage specimens with dimensions of 22 × 25 × 286 mm (7/8 × 1 × 11¼ in.) were cured for 7 days and then dried for 224 days. For mortar with a water-cement ratio of 0.50 containing silica aggregate contents of 5, 15, 30, and 50 percent, respective shrinkage values at 224 days of 4000, 3600, 2200, and 2000 με were produced, representing an overall shrinkage reduction of 50 percent. Ottawa sand and Elgin sand also yielded less shrinkage as aggregate contents were increased (68 percent and 69 percent decreases in shrinkage, respectively). For mortar with a water-cement ratio of 0.50 containing

Elgin sand aggregate contents of 5, 15, 30, and 50 percent, respective shrinkage values at 224 days of 5350, 3720, 2700, and 1650 $\mu\varepsilon$ were produced. For mortar with a water-cement ratio of 0.50 containing Ottawa sand aggregate contents of 5, 15, 30, and 50 percent, respective shrinkage values at 224 days of 5450, 4500, 2850, and 1700 $\mu\varepsilon$ were produced. Mortar with a water-cement ratio of 0.35 produced similar results; that is, increased aggregate content resulted in lower shrinkage mortar. When comparing the effect of aggregate type at the same water-cement (0.50) and aggregate content (30 percent), Ottawa sand produced the most shrinkage (2850 $\mu\varepsilon$) followed by the Elgin sand mixes (2700 $\mu\varepsilon$) and a pulverized silica sand mix that had the least shrinkage (2200 $\mu\varepsilon$). This effect of aggregate type on shrinkage was observed for other aggregate contents and for the other water-cement ratios tested. This was attributed to by Picket to differences in the restraining properties of aggregates. Pickett used this test program to verify an equation derived to estimate the effect of aggregate on drying shrinkage.

$$S = S_O(1-g)^{\alpha} \qquad (1.1)$$

where S is the shrinkage, S_o is the shrinkage that would occur if no aggregates were present, g is the volume of aggregate per unit volume of mix, and α is a constant dependant on the type of aggregate. The results of the test program verified Pickett's equation.

Rao (2001) studied the effect of silica fume and aggregate size on mortar shrinkage. Two series of mortar specimens with dimensions of 25 × 25 × 250 mm (1 × 1 × 10 in.) were water cured for 7 days. Series I contained natural river sand (SG

2.68) that passed the 1.18 mm (No. 16) sieve and was retaining on the 0.60 mm (No. 30) sieve. In Series II, he used the same natural river sand but used fractions falling in the ranges of 2.36-1.18, 1.18-0.60 and 0.60-0.30 mm (No. 8-No.16, No. 16-No.30, No.30-No. 50) at a ratio of 1:1:1. The Series I mortar mixes had silica fume replacements of cement (by weight) of 0, 5, 10, 15, 17.5, 20, 22.5, 25, 27.5, and 30 percent with a cementitious material to sand ratio of 1:3 and a water-cementitious material ratio of 0.50. The Series II mortar mixes also had a water-cementitious ratio of 0.50, and a cementitious material to sand ratio of 1:3, but the silica fume replacements were limited to 0, 10, 15, and 20 percent by weight. Comparing Series I [1.18 mm (No. 16.) maximum size aggregate] to Series II [2.36 mm (No. 8) maximum size aggregate] with 0 percent silica fume replacement at 28 days of drying, the mortar shrinkage values were 110 and 75.7 $\mu\varepsilon$, respectively. After 730 days of drying, the shrinkage values of 6300 and 1900 $\mu\varepsilon$ for Series I and II, respectively. Similar observations were also obtained when comparing mortars for each series with 10, 15, and 20 percent silica fume replacements at 730 days. For the series with 10 percent silica fume replacement at 730 days, the shrinkage values were 7100 and 3780 $\mu\varepsilon$ for Series I and II, respectively. For series with 15 percent silica fume replacement at 730 days, the shrinkage values of 7240 and 4600 $\mu\varepsilon$ for Series I and II, respectively. For the series with 20 percent silica fume replacement at 730 days, the shrinkage values were 6990 and 2270 $\mu\varepsilon$ for Series I and II, respectively. At 730 days of drying, the mortars with the smaller aggregate size (Series I) experienced shrinkage values from 1.5 to 3 times higher than what was observed from the mortars with the larger aggregate (Series II) depending on the amount of silica fume replacement. Rao attributed this to the restraining affect of aggregate. Rao's results, while very distinct in his study, are contrary to any theoretical understanding of shrinkage (total quantity of aggregate rather than aggregate size should control shrinkage) and may be due to other causes, such as mineralogical differences in the aggregate particles as a function of size or errors in moisture corrections when the mortar was batched. His work has not been replicated by others.

1.4.3 Cement Fineness

Cement fineness can also be a factor in concrete shrinkage. Finer cement is one cause of a finer pore structure. A finer pore structure can cause the meniscus that forms within the pores upon drying, to have a greater radius of curvature leading to greater surface tension. This can lead to more shrinkage (Holt and Leivo 2004).

Some authors also feel that because of their higher surface area, finer cement particles lead to a higher heat of hydration, thus producing an increased quantity of hydration product.

Powers (1959) pointed out that the coarsest particles of cement do not completely hydrate and become dense bodies encased by gel even after years of curing. These unhydrated particles provide restraint, much like aggregate, and he concluded that coarsely ground cement produced paste with less shrinkage than finer ground cements. Powers stated that the minimum cement particle size is not known, but suggested that particles retained on the 200 sieve do not become hydrated.

Powers also pointed out that pastes made with cements with the same fineness but different chemical compositions, shrinkage will be dependant on the gypsum content. Cements deficient in gypsum can cause an increase in shrinkage of up to 50 percent. Bennett and Loat (1970) agreed with Powers, that unhydrated cement particles in concrete act as aggregate to resist shrinkage.

There is some debate, however, as to whether this increase in shrinkage in neat cement made with finer cement will translate into an equivalent percentage increase in shrinkage in concrete over a long period of time (Neville 1996).

Bennett and Loat (1970) addressed this point when they studied concretes with cements with three degrees of fineness 0.277, 0.490, and 0.742 m^2/g at water-cement ratios of 0.30, 0.375, 0.450, and 0.525. The aggregates consisted of 19-mm (3/4-in.) maximum size crushed quartzite gravel and pit sand. Concretes with aggregate-to-cement ratios of 3, 4, and 5 were tested. Batch weights were not reported by the author, however. When the water-cement ratio was increased at a constant aggregate-cement ratio, the paste content of the mix was also increased. Shrinkage specimens with dimensions of 102 × 102 × 483 mm (4 × 4 × 19 in.) were cast, with some specimens cured for 1 day and others cured for 28 days. For specimens cured for 1 day with an aggregate-cement ratio of 3 and a water-cement ratio of 0.45, increasing the cement fineness of the concrete increased the long-term shrinkage, with concretes with cement finenesses of 0.277, 0.490, 0.742 m^2/g produced shrinkage at 500 days of 520, 680, and 690 $\mu\varepsilon$, respectively. Similar results were observed at the other water-cement ratios. Shrinkage values were only reported at

500 days, but the authors pointed out that although the two finer cements produced concretes with little difference in shrinkage at 500 days, the early shrinkage (24 hrs) was greater for the finer cement. The authors attributed this to a more rapid rate of hydration for the finer cement. Workability decreased when finer cement was used, leading to a higher water demand to achieve the same workability. When comparing concretes with equal workability, shrinkage increased.

1.4.4 Shrinkage Reducing Admixtures

Many researchers have observed improved shrinkage resistance in concrete that contains a shrinkage reducing admixture (SRA). Shrinkage reducing admixtures work by reducing the surface tension of the mix water, which in turn reduces the stress in the capillary pores. Manufacturers indicate that 28-day concrete shrinkage can be reduced by 50 to 80 percent and that ultimate shrinkage can be reduced by 25 to 50 percent (Balogh 1996).

Shah, Karaguler, and Sarigaphuti (1992) studied three types of shrinkage reducing admixtures (designated as SRA1, SRA2, and SRA3) to determine their effectiveness in reducing drying shrinkage. SRA1 was a commercial admixture containing an alkoxylated alcohol, SRA2 was an experimental alcohol based material, and SRA3 was an alkoxylated alcohol-based oligomer. The authors evaluated the three SRAs at contents of 1, 2, and 4 percent by weight of cement. Shrinkage specimens with dimensions of 100 × 100 × 285 mm (4 × 4 × 11¼ in.) were cast and cured for 4 hours. Curing for 4 hours was chosen to start measuring shrinkage as early as possible. Concrete proportions by weight were 1:2:2:0.5 (Type I cement:sand:coarse aggregate:water). Coarse aggregate consisted of a 9-mm (5/16-in.) pea gravel, and fine aggregate was natural river sand with a maximum size of 3 mm (1/8 in.).

At 2 percent SRA content by weight of cement, all three SRA's produced concrete with 20 to 40 percent lower shrinkage than the control mix. At 42 days, concretes containing SRAs 1, 2, and 3 had shrinkage of 310, 330, and 410 $\mu\varepsilon$, respectively, while the control mix had a shrinkage of 510 $\mu\varepsilon$. Results for other SRA contents were not reported, but the authors noted that similar results were also observed at 1 and 4 percent SRA content and that as SRA content increased, shrinkage at 42 days was observed to decrease for all three types of SRA.

Folliard and Berke (1997) also observed similar results with SRA. One type of SRA was studied, a blend of propylene glycol derivatives, in conjunction with its use with concrete containing silica fume. Four concrete mixes were compared, concrete control mixes containing no silica fume and 7.5 percent silica fume were compared to similar mixes containing 1.5 percent SRA (by mass of binder). Superplastizer was used to maintain a target slump of 150 to 200 mm (6 to 8 in.). The mix water was reduced to account for the superplasticizer, silica fume slurry liquid, and the SRA to maintain a constant water-cementitious ratio of 0.35 and a paste content of 32.5 percent. The concrete mixes consisted of Type I cement, natural sand (Fineness Modulus = 2.65), and Size 67 crushed quartz diorite meeting ASTM C33. The superplasticizer was a naphthalene sulfonate formaldehyde (ASTM C494 Type

A/F). Shrinkage specimens had dimensions of 75 × 75 × 285 mm (3 × 3 × 11¼ in.). Specimens were demolded after 24 hrs and then stored at 20° C (68° F) and 50 percent relative humidity.

After 28 days, the shrinkage was reduced by 35 to 53 percent for the mixes containing an SRA. The concrete mixes not containing silica fume shrank 490 με without the SRA and 320 με with the SRA, a 35 percent reduction, and the mixes containing silica fume shrank 510 με without the SRA and 240 με with the SRA, a 53 percent reduction. After 120 days, the SRA resulted in a larger absolute but smaller percentage reduction in shrinkage in each case: the concrete mixes not containing silica fume shrank 700 με without the SRA and 500 με with the SRA, a 29 percent reduction, and the mixes containing silica fume shrank 770 με without the SRA and 440 με with the SRA, a 43 percent reduction.

Among other authors who have noted the benefits of SRAs are Karagular and Shah (1990), Shah, Balogh (1996), Weiss, and Yang (1998), Weiss and Shah (2002), See, Attiogbe, and Miltenberger (2003), and Holt and Leivo (2004).

1.4.5 Curing Period

Studies have found that proper curing of concrete is essential to decreased cracking on bridge decks, which can improve the overall performance of a bridge deck (Lindquist, Darwin, Browning 2005). However, the effect of the length of the curing period as a factor to decrease overall shrinkage of concrete has been debatable. Some authors feel that prolonged moist curing delays the advent of shrinkage but ultimately has little effect on the magnitude of shrinkage (Neville 1996). Powers (1959) theorized that prolonged moist curing in cement paste should theoretically increase drying shrinkage because more of the cement particles are allowed to hydrate, thus decreasing the portion of the cement particles that have a restraining effect against shrinkage. Powers stated that prolonged curing also increases the strength and modulus of elasticity and reduces the rate of creep, thus making the concrete more susceptible to cracking around aggregate particles when restrained. This internal cracking, however, could relieve stress around particles and overall shrinkage might be diminished. He concluded that the length of curing ultimately has little effect on shrinkage.

Carlson (1938) studied the effect of curing time on shrinkage of neat cement paste and mortar. The cement was coarse by today's standards. Cement pastes with a water-cement ratio of 0.40 that were moist cured for 2 days and 28 days exhibited 90-day shrinkage of 3500 and 2210 $\mu\varepsilon$, respectively. For mortar, with the same water-cement ratio, containing 75 percent cement and 25 percent dolomite fines by weight, the shrinkage values at 90 days for specimens cured for 2 and 28 days were 3120 and 2580 $\mu\varepsilon$, respectively. The addition of 25 percent fines lessened the effect gained by extended curing. For mortar with a water-cement ratio of 0.40, containing 50 percent cement and 50 percent dolomite fines, the shrinkage values at 90 days for specimens cured for 2 and 28 days were 2860 and 2880 $\mu\varepsilon$, respectively, showing no effect of prolonged curing.

Carlson also studied a neat paste cement made with modified portland cement containing 6 percent C_3A. At a water-cement ratio of 0.60, the 90-day shrinkage of specimens cured for 2 and 28 days was 2200 $\mu\varepsilon$ for both. Then Carlson studied the neat paste with the same cement but with a water-cement ratio of 0.30, and the 90-day shrinkage values of specimens cured for 2 and 28 days were 1490 and 1380 $\mu\varepsilon$, respectively, thus, showing that the effect of moist curing varied for cement pastes with different water-cement ratios and that the addition of aggregate was not the only factor affecting shrinkage. Carlson stated that the effect of prolonged curing could have two contradictory effects, and whichever was dominate would determine if the prolonged curing would increase or decrease shrinkage. The first effect is that prolonged moist curing would harden the cement paste and thus improve its restraining effect against shrinkage. The second effect is that prolonged moist curing would produce more hydrated cement and this gelatinous material is the portion of the paste that shrinks, thus producing more shrinkage.

Carlson also believed an important factor in explaining shrinkage is internal cracking of the paste between aggregate particles, which allows shrinkage to occur without fully reducing the overall length of specimens and, thus, leads to lower values of shrinkage. This cracking between aggregate particles could be very fine and not visible, or it could be visible upon close inspection. Carlson concluded that if this type of internal cracking occurred at an early age, it would lead to low overall shrinkage and that extended moist curing would have little effect on the shrinkage of concrete.

Bennett and Loat (1970) studied concretes of varying cement fineness for curing periods of 1 and 28 days (discussed previously in Section 1.4.3 on fineness). Concretes cured for 28 days experienced swelling. The concrete made with the coarsest cement experienced the most swelling (140 με), while the concrete made with the finest cement experienced almost no swelling. Concretes cured for 28 days had increased shrinkage at 500 days as the fineness of the cement used in the concrete increased. The authors concluded that, for the finer cements, the mixing water quickly combined with the cement and the replacement of free water from the outside was rapid enough to produce swelling. For concretes made with the coarsest cement (0.277 m^2/g), curing did not appear to have an effect after 500 days because specimens cured for 1 day and specimens cured for 28 days both had shrinkage of 520 με. The impact of curing was more pronounced as the cement fineness increased. For concrete, the middle cement fineness (0.490 m^2/g) specimens cured for 1 day experienced a shrinkage of 680 με at 500 days, while specimens cured for 28 days experienced shrinkage of 610 με at the same age. For the finest cements (0.742 m^2/g), the specimens cured for 1 and 28 days experienced shrinkage strains at 500 days of 690 and 580 με, respectively.

1.4.6 Mineral Admixtures

Mineral admixtures such as ground granulated blast furnace slag and the pozzolans fly ash and silica fume are often used in high-performance concrete to increase strength and durability, decrease permeability, and in some cases to reduce costs by replacing cement. Their effect on drying shrinkage, however, is not clear. Mokarem et. al. (2005) state that the addition of pozzolans generally increases pore refinement, thus creating smaller pores. Drying shrinkage is associated with the water held in the smaller pores, which can lead to increased shrinkage. There are other reports that show that mineral admixtures have little to no affect on shrinkage of concrete.

Fly Ash

According to ACI Committee 232 (2003), if the fly ash replacement causes an overall increase in the paste volume, drying shrinkage may increase slightly if the water content remains constant. Because fly ash particles are generally more spherical than cement particles, however, they increase workability, and the water content may, thus, be reduced for a given workability. If this reduction in water is accounted for, drying shrinkage should not be affected for concrete with up to 20 percent fly ash by weight compared to plain concrete. If the added workability is not used (ie., keeping the water cementitious material ratio constant), however, Neville (1996) reports that including fly ash can increase shrinkage of concrete by up to 20 percent.

Atis (2003) studied the effects of high-volume replacement of cement by Class F fly ash on the shrinkage of concrete. Concrete mixtures with a constant slump and weight of cementitious material were compared. Mixtures were evaluated for shrinkage over a six month period and included a control mix with no fly ash, mixes with 50 and 70 percent fly ash replacements by weight. The test specimens were 50 × 50 × 200 mm (2 × 2 × 7 7/8 in.) and demolded at 1 day and then stored at 20° C (68° F) and 65 percent relative humidity. Atis found that, after six months, the 70 percent fly ash replacement mix had on average 36 percent less shrinkage than the control mix and the 50 percent fly ash replacement mix had on average 30 percent less shrinkage than the control mix. At six months, the shrinkage values of the 70 and 50 percent fly ash replacement mixes were 263 and 294 $\mu\varepsilon$, respectively, while the control mix shrinkage value was 385 $\mu\varepsilon$. Since the slump was held constant, each mix had a different water-cementitious material ratio and, thus, different water and total cement paste contents. The 70 percent fly ash replacement mix had the lowest water-cementitious material ratio, 0.29 and a paste content of 26.3 percent, followed by the 50 percent fly ash replacement mix with *w/cm* = 0.30 and a paste content of 26.7 percent, and the control mix with *w/cm* = 0.32 and a paste content of 28.7 percent. Atis attributed the decrease in shrinkage to the decreased water and paste contents and lower amounts of hydrated paste in the replacement mixes. Unhydrated cementitious material may act as aggregate, restraining shrinkage. It should be noted that the specimens were only cured for 24 hours and fly ash needs a much longer curing period to combine chemically with the calcium hydroxide in the hydrating cement paste.

Gopalan and Haque (1987) studied the effect of 0, 20, 35, and 50 percent Class F fly ash replacement by volume of cement on concrete shrinkage at water-cementitious material ratios of 0.33, 0.44, and 0.47. The aggregates were crushed gravel with a 20-mm (3/4-in.) maximum size and river sand. The mixes were designed for a constant slump using a calcium lignosulfonate based water-reducing admixture and vinsol resin as the air entraining agent. The test specimens were 75 × 75 × 285 mm (3 × 3 × 11¼ in.) and were cured for 7 days. Overall, they found the shrinkage of the mixes containing fly ash to be slightly higher than that of the control mixes. They concluded that since the overall shrinkage of the concrete containing the fly ash was only marginally higher than the control mix, fly ash has little affect on shrinkage.

Slag

According to ACI Committee 233 (2003), there are conflicting results on how the use of slag in concrete affects the drying shrinkage. Hogan and Meusel (1981) found that slag replacements of 40, 50, and 65 percent (by weight) produced higher shrinkage by as much as 63 percent after 64 weeks. No curing period was reported. They stated that the increased shrinkage may be due to the greater volume of paste in the concrete when slag is substituted on an equal mass basis. Hogan and Meusel surmised that shrinkage could be reduced through the addition of gypsum along with the slag. Neville (1996) reports that including slag in concrete can increase shrinkage by up to 60 percent, particularly at a constant water-cement ratio.

Khatri, Sirivivatnanon, and Gross (1995) studied concrete mixtures with a constant slump, a binder content of 430 kg/m^3 (725 lb/yd^3), and water-cementitious material ratio of 0.35 with different levels of slag replacement. Some mixtures also contained silica fume. Test specimens were 75 × 75 × 285 mm (3 × 3 × 11¼ in.) and cured for 7 days. The coarse aggregate was crushed river gravel with a maximum size of 20 mm (3/4 in.) and the fine aggregate was a blend of coarse river sand and fine dune sand. A water reducing admixture and a superplasticizer were used to maintain a slump of close to 120 mm (4.5 in.). When comparing concrete containing no slag and concrete containing a slag replacement of 65 percent by weight, the presence of slag increased the early-age (less than 28 days) and long-term shrinkage (greater than 56 days) of the concrete. At 20 days, the mix containing no slag and the mix containing 65 percent slag had shrinkage values of 450 and 600 με, respectively. At 400 days the mix containing no slag and the mix containing 65 percent slag had shrinkage values of 825 and 1025 με, respectively. When comparing concrete containing no slag and concrete containing 10 percent silica fume, 31.5 percent slag, and 58.5 percent cement, the concrete containing no mineral admixtures had lower long-term and early-age shrinkage. At 20 days, the mix containing no slag and the mix containing 10 percent silica fume, 31.5 percent slag, and 58.5 percent cement had shrinkage values of 450 and 675 με, respectively. At 400 days, the mix containing no slag and the mix containing 10 percent silica fume, 31.5 percent slag, and 58.5 percent cement had shrinkage values of 825 and 925 με, respectively. They also studied concrete mixes containing 10 percent silica fume, 58.5 percent slag, and 31.5 percent cement with the similar results as before, the concrete containing no mineral admixtures had lower early and long term shrinkage. At 20 days the mix containing no slag and the mix containing 10 percent silica fume, 58.5 percent slag, and 31.5 percent cement had shrinkage values of 450 and 670 με, respectively. At 400 days the mix containing no slag and the mix containing 10 percent silica fume, 58.5

percent slag, and 31.5 percent cement had shrinkage values of 825 and 1000 $\mu\varepsilon$, respectively. Overall, Khatri et al. found that the mixes containing slag have higher shrinkage than concrete without slag at all ages and that increases in slag content result in increased drying shrinkage. Slag has a lower specific gravity than to cement; thus a greater volume of slag will be used to replace the same mass of cement resulting in a higher paste content. This higher paste content could be one factor contributing to the observed increase in shrinkage of the slag concretes observed.

Li, Wee, and Wong (2002) evaluated concrete mixtures with a constant water-cementitious material ratio, 0.30, to determine the effect of slag on concrete shrinkage. They compared concrete with a 65 percent slag replacement by weight with a control mix containing no mineral admixtures. They found that the mixture with the slag had slightly higher early-age shrinkage than the control mix. After about 60 days, however, the difference in shrinkage for the two mixes was negligible. Since the slag replacement was by weight, the slag mix had a higher paste content (32.1 percent) than the control mix (31 percent). As mentioned by other authors, this could have been the reason for the slight different in shrinkage.

Silica Fume

ACI Committee 234 (2006) reports that the quantity of silica fume and the duration of curing prior to drying are important factors in the drying shrinkage of concrete containing silica fume. In individual studies, authors have observed effects of silica fume on the shrinkage of concrete. Sellevold and Nilsen (1987) found little effect on shrinkage for silica fume replacements of up to 10 percent by weight for both long-term and early-age shrinkage. Carette and Malhotra (1983) studied concrete with silica fume replacements of 0 to 30 percent by weight. Their first series held the slump constant at 75 mm (6.88 in.) while increasing the water content, as needed. The control mix had a water-cement ratio of 0.64. With silica fume replacements, the water-cementitious ratio ranged from 0.65 for a 5 percent replacement to 0.84 for a 30 percent replacement. Water demand and, thus, the water-cementitious material ratio increased linearly with increasing quantities of silica fume. As seen in other data, one would expect the mixtures with the higher water contents to exhibit higher shrinkage; Carette and Malhotra, however, found practically no difference in drying shrinkage. They theorized that the additional water needed for the constant slump was bound chemically and was, thus, not located in the gel or capillary pores. Their second series tested similar concrete mixtures, except the slump was held constant using a superplasticizer instead of the increasing the water content. Again, they found that the addition of silica fume, at any replacement, did not appear to have a significant affect on shrinkage. Overall, they found little to no effect of the percent replacement on short or long-term shrinkage.

Rao (2001) studied two series of mortars (previously described in Section 1.4.2 on aggregate) to observe the effect of silica fume replacement and aggregate size on mortar shrinkage. The mortar specimens, with dimensions of 25 × 25 × 250 mm (1 × 1 × 10 in.), were water cured for 7 days. He found that silica fume had a higher impact on shrinkage during the first 28 days of drying than after longer periods (greater than 730 days). The Series I [1.18 mm (No. 16) maximum-size aggregate] mortar mixes had a water-cementitious material ratio of 0.50, a cementitious material to sand ratio of 1:3, and silica fume replacements of cement (by weight) of 0, 5, 10, 15, 17.5, 20, 22.5, 25, 27.5, and 30 percent. The Series II [2.36 mm (No. 8) maximum-size aggregate] mortar mixes also had a water-cementitious ratio of 0.50, and a cementitious material to sand ratio of 1:3, but the silica fume replacements were limited to 0, 10, 15, and 20 percent by weight. At 28 days, both Series I and II at 28 days exhibited in increased shrinkage with increases in silica fume content. Shrinkage in Series I ranged from 110 $\mu\varepsilon$ for 0 percent silica fume replacement to 830 $\mu\varepsilon$ for 30 percent silica fume replacement after 28 days of drying. Shrinkage in Series II ranged from 75.7 $\mu\varepsilon$ for 0 percent silica fume replacement to 907 $\mu\varepsilon$ for 20 percent silica fume replacement. Series I also exhibited an increase in shrinkage for increases silica fume content at 400 days and 600 days of drying. At 400 days of drying, 0 percent silica fume replacement yielded a shrinkage of 2100 $\mu\varepsilon$, while 30 percent silica fume replacement yielded 2890 $\mu\varepsilon$. At 600 days of drying, 0 percent silica fume replacement yielded a shrinkage of 5370 $\mu\varepsilon$, while 30 percent silica fume replacement yielded a shrinkage of 6240 $\mu\varepsilon$. After 1095 days of drying for mortars in Series I, no specific pattern was observed. The mortar with the highest shrinkage was the 20 percent silica fume replacement at 8590 $\mu\varepsilon$, while the lowest was the control mix with 7640 $\mu\varepsilon$. Rao stated that the most important factor contributing to increased early-age (28-day) shrinkage was the increased content of calcium silicate hydrate and the chemical shrinkage due to the pozzolanic reaction and pore size refinement due to the silica fume, which was complete at an early-age. He also stated that the refinement of the pore size could contribute to autogenous or self-desiccation shrinkage at this early age. Rao concluded that ultimate drying shrinkage (past 365 days) was not necessarily a function of silica fume replacement and the most noticeable affects took place in the first 28 days. It is important to note that the silica fume replacement was calculated as a percentage of the weight of cement. Silica fume has a lower specific gravity compared to cement; thus a greater volume of silica fume will be used to replace the same mass of cement and can result in a higher paste content.

Khatri, Sirivivatnanon, and Gross (1995) studied concrete mixtures with a constant slump, a binder content of 430 kg/m^3 (725 lb/yd^3), and water-cementitious material ratio of 0.35 with varying silica fume replacements. Test specimens were 75 × 75 × 285 mm (3 × 3 × 11¼ in.) and cured for 7 days. Khatri et al. found that concrete with a 10 percent silica fume replacement by weight and a water-cementitious ratio of 0.35 had increased early-age (less than 28 days) shrinkage but slightly decreased long-term (greater than 56 days) shrinkage compared to concrete with a similar binder content and water-cement ratio but without mineral admixtures. At 400 days, the mix containing no silica fume and the mix containing 10 percent silica fume had shrinkage values of 825 and 750 $\mu\varepsilon$, respectively. The authors attributed the decrease in shrinkage of the mixes containing silica fume to the fact that silica fume does not change the total pore volume of the cement paste but increases the percentage of fine pores. This finer pore structure could reduce the loss of water and thus reduce the drying shrinkage. This is contrary to observations by other authors.

Whiting, Detwiler, and Lagergren (2000) studied concretes with silica fume replacements of Type I/II cement ranging from 0 to 12 percent by weight and with water-cementitious ratios ranging from 0.35 to 0.45. Specimens were cured for either 3 or 7 days. They concluded that silica fume has little effect on the long-term shrinkage of concrete, but that silica fume can increase early-age shrinkage with increasing silica fume replacement for a given water-cementitious material ratio. They also noted that concretes with very high or very low water-cementitious material ratios show an increased sensitivity to silica fume replacement. They pointed out that the concretes observed to have greater shrinkage also had a higher paste content and that greater shrinkage was observed for the specimens with the shorter curing period (3 versus 7 days).

Li, Wee, and Wong (2002) compared concrete mixtures with a water-cementitious material ratio of 0.30. Mixtures contained either a 10 percent silica fume replacement by weight of cement or no silica fume. Specimens had dimensions of 100 × 100 × 400 mm (4 × 4 × 15 ¾ in.) and were cured for 3 days. They found that concrete containing silica fume had noticeably lower early-age and long-term (greater than 60 days) shrinkage than the control mix without silica fume. Since the silica replacement was made by weight, the silica fume mix had a slightly higher paste content (32 percent) than the control mix (31 percent). They noted that even though the concretes containing silica fume had lower drying shrinkage, they had greater autogenous shrinkage than concrete made with cement alone. They noted that the combined effects of drying and autogenous shrinkage could cause higher overall shrinkage in silica fume mixes and mixes with blended silica fume and ground granulated furnace slag, particularly at low water-cementitious ratios. Brooks (1999) arrived at similar conclusions, noting that autogenous shrinkage was far more significant in silica fume concrete than in plain concrete where autogenous shrinkage is generally insignificant.

Alsayed (1998) studied the effect of the addition of silica fume to concrete on its shrinkage characteristics. Specimens had dimensions of 76 × 76 × 286 mm (3 × 3 × 11 ¼ in.) and were cured for 7 days. The concrete mixes had a water-cementitious material ratio of 0.30. Mix 1 was a control mix containing cement, an ASTM C494 Type F naphthalene superplasticizer, and had a slump of 175 mm (7 in.). Mix 2 contained 10 percent silica fume, an ASTM C494 Type F naphthalene superplasticizer, and had a slump of 40 mm (1 ½ in.). Mix 3 contained 10 percent silica fume, an ASTM C494 Type B/D polymer water reducer, and had a slump of 40 mm (1 ½ in.). It is important to note that the silica fume (10 percent of the cement weight) was in *addition* to the cement and was not a cement replacement, thus producing higher paste content. One would expect that concrete with a higher paste content would produce more concrete shrinkage, but Alsayed observed the opposite.

1.4.7 Superplasticizers

Johnston et. al (1979) studied four different types of superplasticizer, melamine formaldehyde condensate, sufoaryl alklene, sulfonate polymer, and polymerized naphthalene condensate and their effects on concrete shrinkage and other behavior. They used two control mixes, Mix A proportioned with 32 percent paste to achieve a slump of 100 mm (4 in.) and Mix B proportioned with 23.7 percent paste to produce zero slump by decreasing the water content but keeping the same water-cement ratio (0.50). Additional test mixes were similar to the zero slump mix, except they contained enough superplasticizer to achieve a 100 mm (4 in.) slump. The shrinkage specimens were 100 × 300 mm (4 × 12 in.) cylinders with shrinkage measurements taken with a demounmechanical extensometer. Specimens were cured for 56 days. All four superplasticizers increased bleeding, and all but the melamine formaldehyde condensate superplasticizer increased the setting time of the concrete by about 20 percent.

With values of 620 $\mu\varepsilon$ and 635 $\mu\varepsilon$, respectively, the concrete containing sulfonate polymer and the polymerized naphthalene produced 9 to 11 percent higher shrinkage at 91 days, than control Mix B, which had a shrinkage of 570 $\mu\varepsilon$. The other two superplasticizers, melamine formaldehyde and the sufoaryl alklene, produced lower shrinkage at 91 days compared to control Mix B, with values of 545 and 560 $\mu\varepsilon$, respectively. The author pointed out that, although some admixtures produced concretes with more shrinkage than control Mix B, none of the mixes produced more shrinkage than control Mix A (32 percent paste), which had a shrinkage value of 640 $\mu\varepsilon$ at 91 days. The comparison between control Mix B and the mixes with superplastizer are most beneficial because they compare concretes with a paste content of 23.7 percent.

Brooks (1999) analyzed 96 sets of test data collected by other authors that evaluated the shrinkage behavior of concrete containing two types of plasticizer, lignosulphonate and carboxylic acid, and three different types of superplasticizer, sulphonated naphthalene formaldehyde condensate, sulphonated melamine condensate, and copolymer. He found no significant difference in shrinkage among concretes as a function of the type of admixture but, overall, a general increase in shrinkage of 20 percent for concretes containing compared to control mixes without the admixtures.

Findings by Faroug et al. (1999) and Holt and Leivo (2004) matched observations made in the current study. Faroug et al. (1999) studied the effect of superplasticizer on the workability of concrete and found that at large water-cement ratios (0.50 or more), superplasticizers can become ineffective and can cause segregation in the concrete mix. Holt and Leivo (2004) observed that overdosing concrete with superplasticizer can often retard the set of concrete.

1.5 OBJECTIVE AND SCOPE

This report describes an experimental study that uses the ASTM C157 free shrinkage test to evaluate the effects of mix proportioning parameters and curing on concrete shrinkage with the goal of providing recommendations that will result in a reduction of concrete shrinkage in bridge decks. The study parameters include aggregate content, cement fineness, water-cement ratio, curing period, partial cement replacement by ground granulated blast furnace slag, Class C fly ash, or silica fume, superplasticizer dosage, the use of a shrinkage reducing admixture, and aggregate type.

The study consists of seven programs. Program I involves the evaluation of non-air-entrained concrete mixes with aggregate contents of 60, 70, and 80 percent by volume with water-cement ratios of 0.40, 0.45, and 0.50. These proportions are used with Type II coarse-ground and Type I/II cements for a total of 18 concrete mixes.

Program II evaluates non-air-entrained concrete with partial cement replacements by slag, Class C fly ash, and silica fume. The mixtures have an aggregate content of 70 percent, a water-cementitious material ratio of 0.45, and contain Type I/II cement. The mineral admixtures replace cement on a volume basis at rates of 30 percent slag, 30 percent Class C fly ash, and 10 percent silica fume. A concrete mix with the same proportions, but without mineral admixtures, serves as a control.

Program III evaluates the effect of different aggregate types, limestone and quartz, on concrete shrinkage. Four mixes are compared, two with limestone and two with quartz, all using Type I/II cement, a water-cement ratios of 0.45, and aggregate contents of approximately 70 percent. Of the four mixes evaluated, half are non-air-entrained and half are air-entrained.

Program IV evaluates the effect of curing period on concrete shrinkage. Non-air-entrained batches with Type II coarse-ground and Type I/II cements, 70 percent aggregate, and a 0.45 water-cement ratio are cured for either 3, 7, 14, or 28 days. Three air-entrained batches with similar proportions are cured for 3, 7, and 14 days.

Program V evaluates superplasticizers used at rates that vary within the manufacturers' recommended dosage range. Type I/II cement is used along with 70 percent aggregate and a water-cement ratio of 0.45

Program VI and VII consist of concrete mixes designed specifically for use in bridge decks. Mixes include those that have been used by the Missouri Department of Transportation (MoDOT) and Kansas Department of Transpiration (KDOT). Others include mixes with shrinkage reducing admixtures, Type II coarse-ground cement and quantities of cement.

For all mixes cast in Programs VI and VII and the air-entrained mixes in Programs III and IV, the desired slump is between 25 and 75 mm (1 and 3 in.), and the concrete temperature at casting is at or below 21° C (70° F). The target air content is 7 to 9 percent, with the exception of the MoDOT and KDOT mixes, which are cast with air contents meeting the individual DOT specifications.

CHAPTER 2: EXPERIMENTAL PROGRAM

2.1 GENERAL

This chapter describes the experimental work performed in this study, including the equipment, materials and procedures. The study covers the effects of: aggregate content, water cement ratio, cement type, aggregate type, mineral admixtures, chemical admixtures, and curing time on the free shrinkage of concrete. Actual bridge deck mixes are also evaluated. This study includes seven test programs. Test matrices are listed in Tables 2.1 through 2.7, aggregate gradations are listed in Tables 2.8 through 2.14, and the mix proportions for each batch are listed in Tables 2.15 through 2.21.

2.2 FREE SHRINKAGE TEST

Free shrinkage prisms were cast in cold-rolled steel molds (Figure 2.1) from Humboldt Manufacturing Co. (Model H-3254), as specified in ASTM C157. These molds produced specimens that were 76 × 76 × 286 mm (3 × 3 × 11¼ in.), as shown in Figure 2.2. Gage studs were cast in each end of the prisms, giving a gage length of 254 mm (10 in.). The gage studs, from Humboldt Manufacturing Co. (Model H-3260), were made of 316 stainless steel. They were knurled at one end and threaded at the other. Including studs, the outside to outside length of the specimens was 295 mm (11 5/8 in.).

Shrinkage readings were made using a mechanical dial gage length comparator from Humboldt Manufacturing Co. (Model H-3250). The total range of the length comparator was 0.400 in. (10 mm) with 0.0001-in. (0.00254-mm) divisions.

2.3 MATERIALS

Two types of portland cement were used in this study, Type I/II and a coarse-ground Type II. Five types of coarse aggregates were used including, two types of limestone and three types of quartzite. Two fine aggregates were used, sand and pea gravel. The mineral admixtures included Class C fly ash, blast furnace slag, and silica fume, and the chemical admixtures included two air entraining agents, three superplasticizers, and a shrinkage reducing admixture.

2.3.1 Cement

The Type I/II cement was produced by Lafarge North America in Sugar Creek, MO. The specific gravity was 3.2. It had a Blaine fineness of 378 m^2/kg and a Bogue composition of 55% C_3S, 18% C_2S, 7% C_3A, and 10% C_4AF.

The Type II coarse-ground (Type II CG) cement was produced by the Ash Grove Cement Company in Seattle, WA. The specific gravity was 3.2. It had a Blaine fineness of 306 m^2/kg and a Bogue composition of 61.5% C_3S, 13.44% C_2S, 7.69% C_3A, and 8.94% C_4AF.

2.3.2 Coarse Aggregates

The Coarse aggregates included 25mm (1in.) limestone, 19mm (3/4 in.) limestone, 25mm (1in.) quartzite, quartzite chip, and 19mm (3/4 in.) quartzite.

Limestone:

The 25-mm (1-in.) limestone was a Class I limestone from the Martin Marietta Quarry in DeSoto, KS. The absorption (dry) was 3.92% and the specific gravity SSD was 2.57. The gradations are presented in Table 2.8.

The 19-mm (3/4-in.) limestone was Class I KDOT Approved limestone from the Hunts Midwest Mining Sunflower Quarry in DeSoto, KS. The absorption (dry) was 3.0 percent and the specific gravity SSD was 2.58. The gradations are presented in Table 2.9.

Quartzite:

The quartzite aggregates were from L.G. Everist Inc. in Dell Rapids, SD. The 25-mm (1-in.) quartzite had an absorption (dry) of 0.44 percent and the specific gravity SSD was 2.63. The quartzite chip has an absorption (dry) of 0.49 percent and the specific gravity SSD was 2.63. The 19-mm (3/4-in.) quartzite had an absorption (dry) of 0.44 percent and the specific gravity SSD was 2.64. The gradations are presented in Tables 2.10, 2.11, and 2.12 respectively.

2.3.3 Fine Aggregate

Kansas River sand was used in combination with pea gravel in all programs.

The pea gravel was KDOT classification UD-1 from Midwest Concrete Materials in Manhattan, KS. The absorption (dry) was 0.7 percent and the specific gravity SSD was 2.62. The gradations are presented in Table 2.13.

The Kansas River sand was from Victory Sand and Gravel Company in Topeka, Kansas. The absorption (dry) was 0.35 percent and the specific gravity SSD was 2.63. The gradations are presented in Table 2.14.

2.3.4 Mineral Admixtures

Fly ash, slag, and silica fume were used in Program II.

The fly ash is a type C fly ash from Ash Grove Resources, LLC in Topeka, Kansas. It has a specific gravity of 2.83 and a composition of 26.7% SiO_2, 17.57% Al_2O_3, 6.19% Fe_2O_3, 32.01% CaO, 7.3% MgO, 2.35% Na_2O, 0.31% K_2O, and 4.17% SO_3.

The ground granulated blast-furnace slag is from Holcim Inc. in Chicago, Illinois. It has a specific gravity of 2.86 and a composition of 0.78% Na_2O, 64% C_3S, 19% C_2S, 8% C_3A, and 8.69% C_4AF.

The silica fume is Force 10,000 D from Grace Construction Products. It has a specific gravity of 2.20 and a composition of 95% SiO_2, 0.5% Al_2O_3, 2.1% Fe_2O_3, 0.3% MgO, 0.8% CaO, 0.1% Na_2O, 1.0% K_2O, and 0.2% SO_3.

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2.3.5 Chemical Admixtures

Superplasticizers were used in Programs V, VI, and VII.

Superplasticizers:

Glenium 3000 NS is a carboxylated polyether base superplasticizer that conforms to ASTM C494 as a Type A and Type F admixture. It is produced by Master Builders Inc. It has a specific gravity of 1.08 and contains between 27 to 33 percent solids. The manufacturer's recommended dosage range is between 260 and 780 mL/100 kg (4 and 12 fl oz/cwt) of cementitious materials.

Rheobuild 1000 is a naphthalene based superplasticizer that conforms to ASTM C494 as a Type A and Type F admixture. It is produced by Master Builders Inc. It has a specific gravity of 1.20 and contains between 38.5 and 42.5 percent solids. The manufacturer's recommended dosage range is 650 to 1600 mL/100 kg (10 to 25 fl oz/cwt) of cementitious materials.

Adva 100 is a carboxylated polyether superplasticizer that conforms to ASTM C494 as a Type F admixture. It is produced by Grace Construction Products. It has a specific gravity of 1.1 and contains 27.5 to 32.5 percent solids. The manufacturer's recommended dosage range is 195 to 650 mL/100 kg (3 to 10 fl oz/cwt) of cementitious materials.

Air Entraining Agents:

Air Entraining Agents were used in Programs VI and VII.

Micro Air conforms to ASTM C260 and is produced by Master Builders Inc. It has a specific gravity of 1.01 and contains 13 percent solids. The manufacturer's dosage rate is 8 to 98 mL/100 kg (0.125 to 1.5 fl oz/cwt) of cementitious materials.

Daravair 1000 conforms to ASTM C260 and is produced by Grace Construction Products. It has a specific gravity of 1.0 to 1.1 and contains 4.5 to 6.0 percent solids. The manufacturer's recommended dosage range is 30 to 200 mL/100 kg (0.5 to 3 fl oz/cwt) of cementitious materials.

Shrinkage Reducing Admixture:

A shrinkage reducing admixture was used in Programs VI and VII.

The shrinkage reducing admixture used was Tetraguard AS20 from Master Builders Inc. It has a specific gravity of 0.985 and is 100 percent water soluble according to the manufacturer. The manufacturer's recommended dosage range is 1000 to 2500 mL/100 kg (16 to 40 fl oz/cwt) of cementitious materials.

2.4 AGGREGATE OPTIMIZATION

The aggregates in every program were blended to produce an optimized aggregate gradation (Shilstone 1990).

2.5 MIXER

Concrete in each program was either hand mixed or mixed in a concrete counter-current pan mixer. Each program described below will specify the batch size and whether hand mixing or a mixer was used. The mixing procedure is described in Section 2.13.

2.6 PROGRAM I (WATER-CEMENT RATIO VS AGGREGATE CONTENT WITH TWO CEMENT TYPES)

Program I was used to evaluate the effects of aggregate content, water-cement ratio, and cement type on free shrinkage. The program involved 18 batches of concrete. Three free shrinkage specimens were made for each batch. Nine batches were made with Type I/II cement and had water-cement ratios of 0.40, 0.45, and 0.50 with aggregate contents of 60, 70, and 80 percent. The batch numbers were 62 through 70. Nine batches were made with Type II coarse-ground cement and also had water-cement ratios of 0.40, 0.45, and 0.50 with aggregate contents of 60, 70, and 80 percent. The batch numbers were 71 through 79. The test matrix is shown in 2.1. No mineral or chemical admixtures were used. The aggregates used for all mixes were an optimized blend of 25-mm (1-in.) limestone, 19-mm (3/4-in.) limestone, pea gravel, and sand. All batches were 0.008 m^3 (0.01 yd^3) hand batches. The proportions from these mixes are listed in Table 2.15.

2.7 PROGRAM II (MINERAL ADMIXTURES)

Program II was used to determine the effect of three mineral admixtures, slag, fly ash, and silica fume, on shrinkage. Four batches were made with three specimens per batch of Type I/II cement. The batch numbers were 85 through 88. The test matrix is shown in Table 2.2. The mineral admixtures were used as a cement replacement by volume, rather than weight. This allowed the aggregate volume and water content to remain constant. Subsequently, the water-cementitious material ratio is different for each batch. An optimized blend of 25-mm (1-in.) limestone, 19-mm (3/4-in.) limestone, pea gravel and sand was used for all batches and an aggregate content of 70 percent. No chemical admixtures were used for any of these batches. The first batch (85) served as a control and did not contain a mineral admixture and it had a water-cement ratio of 045. Batch 86 had a 30 percent slag replacement with a water-cementitious ratio of 0.455, Batch 87 had a 30 percent Class C Fly Ash replacement with a water-cementitious ratio of 0.469, and Batch 88 had a 10 percent silica fume replacement with a water-cementitious ratio of 0.470. These proportions were chosen to approximate the replacements used in industry. The concrete contained Type I/II cement.

All batches were 0.008 m^3 (0.01 yd^3) hand batches. The proportions from these mixes are listed in Table 2.16.

2.8 PROGRAM III (AGGREGATE TYPE)

Program III was used to determine the effect of different types of coarse aggregates on shrinkage. The aggregates studied were quartzite and limestone.

Four batches were made with three specimens per batch in Program III. The batch numbers were 94, 95, 138, 157. The test matrix is shown in Table 2.3.

Batches 94 and 95 (Table 2.3a) had a water-cement ratio of 0.45 and an aggregate content of 70 percent. Three specimens were made per batch. Batch 94 used an optimized blend of 25-mm (1-in.) quartzite, quartzite chip, pea gravel, and sand. Batch 95 used and optimized blend of 25-mm (1-in.) limestone, 19-mm (3/4-

in.) limestone, pea gravel, and sand. No chemical or mineral admixtures were used in these batches. Batches 94 and 95 were 0.008 m^3 (0.01 yd^3) hand batches with Type I/II cement.

Batches 138 and 157 (Table 2.3b) had a water-cement ratio of 0.45 and both contained Adva 100 superplasticizer and Daravair 1000 air entraining agent. Three specimens were made from each batch. Batch 138 had an aggregate content of 69.5 percent consisting of an optimized blend of 19-mm (3/4-in.) limestone, pea gravel, and sand. It also contained 6.15 percent air. Batch 159 had an aggregate content of 67.5 percent consisting of an optimized blend of 19-mm (3/4-in.) quartzite, pea gravel, and sand. It contained 8.15 percent air. The concrete contained Type I/II cement and was mixed in 0.0478 m^3 (0.0625 yd^3) mixer batches.

The proportions for these mixes are listed in Table 2.17.

2.9 PROGRAM IV (CURING)

Batches 138, 140, 143, 165, and 166 were used to evaluate the effect of the length of curing on free shrinkage. The test matrix is shown in Table 2.4.

Batches 138, 140, and 143 (Table 2.4c) were cast in 0.0478 m^3 (0.0625 yd^3) batches, mixed with the mixer and were cured for, 3, 7, and 14 days, respectively. These batches had a water-cement ratio of 0.45 and 45 and contained Adva 100 superplasticizer and Daravair 1000 air entraining agent. Three specimens were made from each batch using Type I/II cement. The concrete contained an optimized blend of 19-mm (3/4-in.) limestone, pea gravel, and sand. Batch 138 had an aggregate content of 69.5 percent and an air content of 6.15 percent, Batch 140 had an aggregate content of 66.4 percent and an air content of 9.25 percent, while Batch 143 had an aggregate content of 66.6 percent and an air content of 9 percent.

Batches 165 and 166 (Tables 2.4b and c) were 0.0335 m^3 (0.0425 yd^3) mixer batches with a water-cement ratio of 0.45 and an aggregate content of 70 percent. Both batches contained an optimized blend of 25-mm (1-in.) limestone, 19-mm (3/4-in.) limestone, pea gravel, and sand. Twelve specimens were made from each batch. Of the 12 specimens, three specimens were each cured for 3, 7, 14, or 28 days. Batch 165 was made using Type I/II cement, while Batch 166 was made using Type II coarse-ground cement. No chemical or mineral admixtures were used.

The proportions for the batches in Program IV are listed in Table 2.18.

2.10 PROGRAM V (SUPERPLASTICIZERS)

Batches 167 through 169 and 171 through 173 were used to evaluate the effect of superplasticizers on free shrinkage. The test matrix is shown in Table 2.5. All batches were 0.008 m^3 (0.01 yd^3) hand batches containing Type I/II cement. The concrete had an aggregate content of 70 percent and a water-cement ratio of 0.45. Each batch contained an optimized blend of 25-mm (1-in.) limestone, 19-mm (3/4-in.) limestone, pea gravel, and sand. Three specimens were made from each batch. The manufacturer's recommended ranges were used to determine the dosage rate of the superplasticizers. A control batch was made along with batches containing a low, medium, and high dosages of Glenium 3000NS and Rheobuild 1000. These two superplasticizers were chosen because they were based on different chemicals.

Batch 167 was a control batch that contained no superplasticizer. Batches 168 and 169 were used to evaluate the concrete with low and medium dosages respectively of Glenium 3000NS, while batches 170 and 174 were used to evaluate the concrete with a high dosage of Glenium 3000NS. Batch 174 was a repeat batch of Batch 170 because Batch 170 was not cast correctly. Batch 171, 172, and 173 were used to evaluate concrete with low, medium and high dosages respectively of Rheobuild. Significant retardation occurred for the concrete containing the high dosage ranges for each superplasticizer. For the high dosage range of Glenium 3000NS and Rheobuild, Batches 174 and 173 respectably, the retardation was about 5 to 7 hours, while the medium dosage rates, Batches 169 and173 respectively, were retarded for 2 to 5 hours. The low dosages were retarded for 1 to 1.5 hours. The extended retardation may be due to the fact the two admixtures qualify as both Type A and Type F admixtures and are not true Type F high-range water reducers.

The proportions for the batches in Program V are listed in Table 2.19.

2.11 PROGRAM VI (PRACTICAL MIXES)

Work in Program VI was previously reported in Tritsch, Darwin and Browning (2005). Program VI was used to evaluate the shrinkage of air entrained concrete that are proposed for use or have been used on a bridge decks. This program included batches 81, 82, 83, and 84. The test matrix is shown in Table 2.6. An optimized blend of 19-mm (3/4-in.) limestone, pea gravel, and sand was used for all batches. Three specimens were made from each batch and all the batches contained Adva 100 superplasticizer and Daravair 1000 air entraining agent. Each batch was cast in 0.0459 m^3 (0.06 yd^3) batches, mixed with the mixer. Batch 81 was used as a control mix. This batch had a water-cement ratio of 0.45 and an aggregate content of 70 percent and an air content of 5.65 percent producing a paste content of 24.4 percent. A paste content at or below 27 percent is desirable because that is the percentage above which cracking in bridge decks appears to significantly increase (Lindquist, Darwin, Browning 2005). Batch 81 contained Type I/II cement. Batch 82 was similar to Batch 81, except that it used Type II coarse-ground cement instead of Type I/II cement it had an aggregate content of 70.5 percent and an air content of 5.15 percent. Batch 83 replicated a mix used by the Missouri Department of Transportation (MoDOT) for bridge decks. It had a water-cement ratio of 0.37, an aggregate content of 66.9 percent, an air content of 3.25 percent, and contained Type I/II cement. Batch 84 replicated a mix used by the Kansas Department of Transportation (KDOT) for bridge decks. It had a water-cement ratio of 0.44, an aggregate content of 67.5 percent, an air content of 5.4 percent, and contained Type I/II cement.

The proportions for batches in Program V are listed in Table 2.20.

2.12 PROGRAM VII (PRACTICAL MIXES)

Program VII was similar to Program VI and was previously reported in Tritsch, Darwin and Browning (2005). The control, Type II coarse-ground cement, MoDOT, and KDOT batches were duplicated. A batch with reduced cement content and a batch using shrinkage reducing admixture were added to this program. The test matrix is shown in Table 2.7. Each batch was cast in 0.0478 m^3 (0.0625 yd^3) batches, mixed with the mixer. Batch 138 was the control mix and replicated Batch 81 from Program VI except that it had an aggregate content of 69.5 percent and an air content of 6.15 percent. Batch 145 contained Type II coarse-ground cement was similar to Batch 82 except that it had an air content of 8.4 percent, an aggregate content of 67.2 percent, contained Glenium 3000NS superplasticizer and Micro Air air entraining agent. Batch 132 was the MoDOT mix, replicating Batch 83 from Program VI, and Batch 130 was the KDOT mix, replicating Batch 84. Batch 132 had an air content of 5.15 percent and an aggregate content of 65 percent while Batch 130 had an air content of 7.25 percent and an aggregate content of 65.7 percent. Batch 147 was similar to the control mix, Batch 138, but it also contained a shrinkage reducing admixture, Tetraguard AS20. Batch 147 used Glenium 3000NS superplasticizer, Micro Air air entraining agent and it had an air content of 8.4 percent and an aggregate content of 67.2 percent. Batch 149 was a reduced paste content mix it had a paste content of 22.7 percent. Batch 149 was modified from the control batch 138 which had a paste content of 24.4 percent. Batch 149 had an air content of 8.4

percent, an aggregate content of 68.9 percent and used Adva 100 superplasticizer and Daravair 1000 air entraining agent.

The proportions for the batches in Program VII are listed in Table 2.21.

2.13 MIXING PROCEDURE

The concrete in Programs I, II, and Batches 94 and 95 in Program III, were hand mixed in 0.008 m^3 (0.01 yd^3) batches. Fine aggregates were corrected for free surface moisture according to ASTM C70 while the coarse aggregates were saturated surface dry in accordance with ASTM C127. Mixing was performed in prewetted a 533 × 787 × 76 mm (21 × 31 × 3 in.) steel pan. First, the coarse and fine aggregates were combined and mixed in the pan. Next, the cementitious material was thoroughly mixed with the aggregates until a uniform mixture was achieved. The dry mix then was placed in a ring and water was added in the middle of the ring. As the water soaked in, dry material from the sides of the ring was moved to the center of the ring. Once of all the water appeared to be soaked in, the batch was hand mixed for three minutes, allowed to sit for three minutes, and then mixed for two more minutes.

The concrete in Program V was mixed a little differently because superplasticizers were used. Batches in Program V were mixed in a 864 × 406 × 140 mm (34 × 16 × 5 ½ in.) Rubber Maid plastic container with lids. Ten percent of the mix water was held back to mix with the superplasticizer. The coarse aggregate, fine aggregate, cement, and 90 percent of the mix water combined as described for Program I and II and mixed for one minute. The balance of the mix water with the superplasticizer was added, and the concrete was mixed for three minutes, followed by a three minute rest period, and two more minutes of mixing. If the mix was too wet to cast, it was allowed to sit in the covered containers until it was stiff enough to cast.

Concrete in Program IV was mixed in 0.035 m^3 (0.0425 yd^3) batches using the mixer. For these batches, the aggregates were prepared as described before. The coarse aggregates and water were added to the mixer pan and the mixer was started. The fine aggregate and cement were then, added to the moving pan. Mixing continued for three minutes, followed by a three-minute rest period, and two more minutes of mixing.

Concrete in Batches 138 and 159 in Programs III and Programs VI and VII was mixed in 0.0478 m^3 (0.0625 yd^3) batches in the Counter-Current pan mixer. The moisture content of the coarse and fine aggregates was corrected according to ASTM C70. The coarse aggregate was soaked in 80 percent of the mix water for 30 minutes. After 30 minutes, the mixer was started, the fine aggregate and cement were added to the mixer, and the combination mixed for one minute. Ten percent of the mix water and the air-entraining agent were then added to the mixer, followed by one minute of mixing. The final 10 percent of the mix water, with the superplasticizer, was then added to the mixer, followed by a three-minute mix period, a three-minute rest period followed, during which a preliminary temperature reading was taken, followed by two more minutes of mixing. If the preliminary temperature reading was above 21^o C (70^o F) liquid nitrogen was added during the final two minutes of mixing to lower the temperature to 20 to 21° C (68 to 70° F). After mixing was completed, the plastic concrete was tested for slump (ASTM C143), air content by the volumetric method (ASTM C173), temperature (ASTM C1064), and unit weight according to ASTM C138. A few batches deviated from this mix procedure for various reasons. Batch 138 was allowed to rest for 30 minutes after mixing to allow the air content to drop to a desirable level. Batch 147 contained the shrinkage-reducing admixture and was allowed to rest for 45 minutes after mixing to allow the air content to stabilize in accordance with recommendations from the manufacturer. Batch 159 contained 19-mm (3/4-in.) quartzite. During trial batching, excessive fines on the 19-mm (3/4-in.) quartzite produced a stiff mix that was attributed to the high water demand from the excess fines. To eliminate excess fines, the 19-mm (3/4-in.) quartzite was washed. Since the quartzite was already fairly wet, it was not soaked for 30 minutes prior to mixing.

2.14 CASTING PROCEDURE

The inside of the steel molds was coated with mineral oil. Each specimen was cast in two layers using a vibrating table. The vibration frequency and vibration time for each batch were determined on an individual basis to ensure proper consolidation as a function of the workability of the mix. After consolidation, the top of the specimen was struck off using a 51 × 133 mm (2 × 5¼ in.) metal plate with a handle. The outsides of the molds were wiped free of concrete, and the specimens were moved to the floor for initial curing.

2.15 CURING PROCEDURE

Immediately after casting, the specimens were covered with 6 mil marlex plastic, then covered with 3.5 mil. plastic sheeting. Rubber bands were placed around the specimens to secure the 3.5 mil. plastic sheeting. A ½ in. piece of Plexiglas that was big enough to cover three specimens (one batch) was placed on top of the specimens. Then four 152 × 305 mm (6 × 12 in.) concrete cylinders were placed on top of the Plexiglas to add weight to the Plexiglas. This was done to ensure the top of the concrete would not dry out. The specimens were demolded 23 ½ ± ½ hours after casting in accordance with ASTM C157. The specimens were then placed in a lime tank that met ASTM C511 for two days, which gave a total of three days curing for each specimen. Before putting the specimen in the lime tank, the initial length after demolding was measured (Section 2.16). After the third day, the specimens were allowed to dry. This is referred to as a three day cure. All specimens were cured in this fashion, except for the curing batches in Program VI, which had specimens that were cured 7, 14, and 28 day in addition to 3 days.

2.16 DRYING CONDITIONS

Initially specimens from Programs I, II, III, and VI were kept in a tent fabricated from structural lumber and 3.5 mil. plastic sheeting. The specimens were stored on wooden racks and allowed to dry from all sides with clearance of 25 mm (1 in.) on all sides in accordance with ASTM C157. The tent was approximately 1905 × 1524 × 584mm (75 × 60 × 23 in.) and was kept in a temperature-controlled laboratory. The humidity inside the tent was maintained using a saturated magnesium nitrate salt solution that was kept in plastic containers on the floor of the tent. In theory, this maintained a relative humidity of 53 percent at 25^{o} C (77^{o} F) (CRC 2003). Specimens were taken out of the tent to take the measurements. Later, all specimens were moved to a 3.7 × 3.7 × 2.1 m (12 × 12 × 6.8 ft) drying room that was in the same temperature-controlled laboratory. Like the tent, the room was fabricated using structural lumber and 3.5 mil. plastic sheeting. The relative humidity was maintained at 50 ± 4 percent using a humidifier, and the temperature was maintained at 23 ± 2^{o} C (73 ± 3^{o} F) in accordance with ASTM C157. All specimen readings were taken inside the drying room. Eventually, every batch was housed inside the drying room.

2.17 DATA COLLECTION

When taking free shrinkage readings, a reference bar is used to establish a reference reading each day. Using a length comparator in accordance with ASTM C157, the comparator dial is read with the specimen in the comparator. The difference between the two is the 'CRD' (difference between the comparator reading of the specimen and the reference bar at any age). On the first day after demolding, this is referred to as the 'initial CRD'. The length change is calculated by subtracting the initial CRD from the CRD at a desired age divided by the gage length, 254 mm (10 in.). The length change is reported in microstrain.

For specimens stored in are, ASTM C157 required comparator at 4, 7, 14 and 28 days and after 8, 16, 32, and 64 weeks. In this study, however, the initial shrinkage is of great concern. Therefore, for most specimens in this study, comparator readings were taken 24 hours after casting, everyday after the three day curing period for 30 days, every other day from 31 to 90 days, once a week from 91 to 180 days, and once a month from 181 to 365 days, ending exactly on 365 days. For some of the initial programs, shrinkage readings were taken more often.

For the batches designed to evaluate the effect of the curing period, the specimens were taken out of the lime tank 3, 7, 14, and 28 days after casting. The specimens were temporarily stored in a bucket of water by the length comparator in order to avoid drying out. Then the specimens were either put back into the lime tank if they were not finished curing or put into the tent if they were finished curing. Once they were put into the tent, the data collection proceeded as stated above.

CHAPTER 3: RESULTS AND EVALUATION

3.1 GENERAL

This chapter presents the results of the free shrinkage tests. The results are evaluated to determine the effect of aggregate content, water-cement ratio, cement type, aggregate type, mineral admixtures, chemical admixtures, and curing period on the free shrinkage of concrete. Bridge deck mixes used previously by the Kansas Department of Transportation (KDOT), Missouri Department of Transportation (MoDOT), and potential bridge deck mixes developed in the laboratory are also evaluated.

Three free shrinkage specimens were made for each batch of concrete, except where noted. Concrete in all programs was cured for three days, except for Program IV, which had batches cured for 3, 7, 14, and 28 days. After curing, the concrete was dried in a temperature and humidity controlled environment at 23 ± 2^{o} C (73 ± 3^{o} F) and at a relative humidity of 50 ± 4 percent. Individual shrinkage results for each specimen are presented in Appendix A. The average of the three free shrinkage specimens in each batch is used for the evaluations that follow.

On the free shrinkage figures (except for Program IV), the reading on day 1 indicates the measurement that was taken after the specimens were demolded and before curing was initiated. Day 3 indicates the reading that was taken after the specimens were taken from the lime tank when curing was completed and immediately before the specimens were placed in the drying tents. Swelling is indicated by a negative strain reading.

In Program IV, which included curing periods of 7, 14, and 28 days, as well as 3 days, the day corresponding to the curing period indicates the day on which drying was initiated. For example, if the concrete were cured for 7 days, day 7 on the figure indicates the first day of drying. Figures labeled "drying only" eliminate the curing period, allowing specimens with different curing periods to be compared based on shrinkage after curing has been completed. On the drying only figures, day 1 indicates the first day of drying, which is 24 hours after a specimen has been removed from the lime tank.

3.2 STATISTICAL CERTAINTY

The Student's t-test is used to determine if the differences observed in shrinkage values are statistically significant. This test is often used for hypothesis testing when there are small sample sizes and the true population standard deviation is not known. In the Student's t-test, the level of the statistical significance for differences between two groups is based on the means of the groups, the sample size, and the standard deviation of each group. The test determines whether differences in the sample means (X_1 and X_2), correspond to differences in the population means (μ_1 and μ_2) at a particular level of significance (α). For example, $\alpha = 0.05$ this indicates there is a 5 percent chance that the test will incorrectly indicate (or 95 percent chance it will correctly indicate) a statistically significant difference in sample means when, in fact, there is no difference. A test can be one-sided or two-sided. In this study a two-sided test is used, which means that there is a probability of $\alpha/2$ that $\mu_1 > \mu_2$ and the $\alpha/2$ that $\mu_1 < \mu_2$ when in fact, μ_1 and μ_2 are equal. In the tables describing the Student's t-test, the differences between samples that are statistically significant at a confidence level of 98 percent ($\alpha = 0.02$) are indicated by "Y". Differences between samples that are not statically significant at the lowest confidence level of 80 percent ($\alpha = 0.20$) are indicated by "N". Confidence levels at 80 percent ($\alpha = 0.20$), 90 percent ($\alpha = 0.10$) and 95 percent ($\alpha = 0.05$) are also presented and are indicated by "80", "90" and "95", respectively.

3.3 PROGRAM I (WATER-CEMENT RATIO VS AGGREGATE CONTENT WITH TWO CEMENT TYPES)

Program I was used to evaluate the effects of aggregate content, water-cement ratio, and cement type on free shrinkage. Three water-cement ratios were evaluated (0.40, 0.45, and 0.50) at three different aggregates contents (60, 70, and 80 percent). This was done using both Type I/II cement and Type II coarse-ground cement. The test matrix and proportions for these mixes are listed in Tables 2.1 and 2.15, respectively. Individual specimen data are presented in Figures A3.1 through A3.18 in Appendix A.

3.3.1 Comparison Between Batches

The average free shrinkage curves that compare batches in Program I are shown in Figures 3.1 through 3.12. None of the specimens in this program experienced swelling (indicated by a negative strain measurement).

For Figures 3.1 through 3.6, the legend to the right of the plot represents the aggregate content and the water-cement ratio, both in percent. For example, 70-45 indicates that the concrete contained 70 percent aggregate by volume and had a water-cement ratio of 0.45.

For Figures 3.7 through 3.12, the legend to the right of the plot displays the cement type and the aggregate content in percent. For example, I/II-70 indicates that the batch contained Type I/II cement and had an aggregate content of 70 percent. Type II coarse-ground cement is indicated on the legend as II CG.

Figure 3.1 compares shrinkage strain for the batches in Program I that contained Type I/II cement as a function of aggregate contents and water-cement ratio during the first 30 days after casting. It is clear from the data that increasing the aggregate content results in lower shrinkage, with batches containing 60, 70, and 80 percent aggregate by volume exhibiting progressively lower shrinkage. For a given aggregate content, water-cement ratio does not appear to have a significant effect on of concrete shrinkage. For example, among the highest shrinking mixes (aggregate content of 60 percent), the mix with the water-cement ratio of 0.40 produced the highest shrinkage followed by mixes with water-cement ratios of 0.50 and 0.45. For the mixes that produced the lowest shrinkage (aggregate content of 80 percent), the mix with the water-cement ratio of 0.40 had the greatest shrinkage followed by mixes with water-cement ratios of 0.45 and 0.50. Based on this data, water-cement ratio does not appear to have had a large effect on shrinkage.

Figure 3.2 is similar to Figure 3.1, except that it displays shrinkage though 180 days. The trend observed in Figure 3.1 becomes clearer. As the aggregate content is increased from 60 to 70 percent and from 70 to 80 percent, shrinkage decreases. Again, water-cement ratio does not appear to have an effect with respect to shrinkage. However, for a given aggregate content, the order of shrinkage among water-cement ratios is the same for 180 days as it is for 30 days. Figure 3.3 displays shrinkage up to 365 days after casting, and the same trend is observed; increases in aggregate content produce lower shrinkage, and for a given aggregate content, water-cement ratio has no particular effect on shrinkage. Figures 3.1 through 3.3 are summarized in 3.1, which presents the shrinkage readings at 3, 7, 30, 90, 180, and 365 days after casting. Values are interpolated if a reading was not taken on a particular day.

Figures 3.4, 3.5, and 3.6 show the average drying shrinkage, 30, 180, and 365 days after casting, respectively, for batches in Program I that contained Type II coarse-ground cement. As with the batches made with Type I/II cement, Figures 3.4 through 3.6 show that as the aggregate content increases, shrinkage decreases and water-cement ratio has no clear effect on shrinkage. Data from Figures 3.4 through 3.6 are summarized in Table 3.1, which presents shrinkage readings at 3, 7, 30, 90, 180, and 365 days.

Figures 3.7 through 3.12 compare shrinkage strains for the batches that contain Type I/II to Type II coarse-ground cement at the same water-cement ratio. Figures 3.7 and 3.8 show the results for concrete with a 0.40 water-cement ratio through 180 and 365 days, respectively. The order of shrinkage for the batches, highest to lowest, is 60 percent (aggregate) Type I/II cement, 70 percent Type I/II cement, 60 percent Type II coarse-ground, 80 percent Type I/II, 70 percent Type II coarse-ground, and 80 percent Type II coarse-ground. The results show that, for a given cement type, as the aggregate content increases the shrinkage decreases, and that for a given aggregate content, Type II coarse-ground cement consistently produces lower shrinkage than Type I/II cement. In practice, using Type II coarse-ground cement could provide an added advantage because it allows a more workable mix to be achieved for a given amount of shrinkage. For example, in Figure 3.7, to obtain shrinkage between 350 and 400 $\mu\varepsilon$ at 180 days, either a concrete with an aggregate volume of 70 percent and Type II coarse-ground cement, or a concrete with an aggregate volume of 80 percent and Type I/II cement could be used. Using Type II coarse-ground cement allows a lower aggregate content (and thus a higher paste content) to be used to achieve a given amount of shrinkage. Using a lower aggregate content equates to increased workability. As shown in Figure 3.8, the effect of aggregate content on shrinkage increases with time. For example, at 180 days the difference between the mixes containing 60 percent and 70 percent aggregate by volume and Type I/II cement was 139 $\mu\varepsilon$ and the difference between 70 percent and 80 percent mixes was 147 $\mu\varepsilon$, but at 365 days these differences increased to 183 $\mu\varepsilon$ and 153 $\mu\varepsilon$, respectively. Similar results can be observed for the concretes with water-cement ratios of 0.45 and 0.50 in Figures 3.9 through 3.12. A summary of shrinkage measurements from Figures 3.7 through 3.12 is presented in Table 3.2.

The Student's t-test results in Tables 3.3 through 3.8 show whether the differences in shrinkage between concretes having a constant water-cement ratio but different aggregate contents is statistically significant based on data shown in Figures 3.7 through 3.12. As described above, Figures 3.7 through 3.12 show that as the aggregate content increases for concretes with a constant water-cement ratio and cement type, shrinkage decreases. The Student's t-test results demonstrate that in almost every case that these differences are statistically significant. Figures 3.7 through 3.9 show the results for concrete containing Type I/II cement and a water-cement ratio of 0.40. Table 3.3 confirms that at 30, 180, and 365 days, the differences in shrinkage as a function of aggregate content are statistically significant, with the exception of the mixes with aggregate contents of 70 percent and 80 percent at 30 days. 3.4 covers the data taken from Figures 3.9 and 3.10 for concrete containing Type I/II cement and a water-cement ratio of 0.45 and confirms that the differences based on aggregate content are statistically significant with α between 0.02 and 0.10. 3.5 shows the results for concrete containing Type I/II cement and a water-cement ratio of 0.50 and confirms that the differences in shrinkage for concretes with different aggregate contents is statistically significant with $\alpha = 0.02$ in all cases. Tables 3.6 through 3.8 show the Student's t-test results for the concretes containing Type II coarse-ground cement with water-cement ratios of 0.40, 0.45, and 0.50, respectively. The results in these tables show similar results to those for the concrete containing Type I/II cement, with the differences in shrinkage between concretes as a function of aggregate content to be statistically significant.

3.3.2 Summary

Based on Figures 3.1 through 3.12 and Tables 3.1 through 3.8, it is observed that increases in the aggregate content of concrete results in decreases in shrinkage. Not only does aggregate provide restraint against shrinkage, but higher aggregate content means lower paste content, and paste is the component of concrete that undergoes shrinkage. It is also observed that for a given aggregate content and water-cement ratio, concrete containing Type II coarse-ground cement shrinks less than concrete containing Type I/II cement. This may be attributed to the large cement particles in the Type II coarse-ground that cannot be fully hydrated. The middle portion of the particles acts almost like aggregate and does not shrink. In addition, Holt and Leivo (2004) suggest that finer cement will lead to a finer pore structure, which can lead to higher surface tensions within the pores producing more shrinkage. Concretes made with the finer cement (Type I/II) consistently produced higher shrinkage in this study than concretes container the coarser cement. These results are consistent with the results of several authors. Bennett and Loat (1970) studied concretes with water-cement ratios of 0.30, 0.375, 0.45, 0.525 cured for 1 and 28 days. The concretes were made using five different cements with varying fineness but similar compositions. They consistently found that increased long-term (500-day) shrinkage resulted from an increase in the water-cement ratio (accompanied by an increase in water content) for all mixes and degrees of cement fineness. Bennett and Loat (1970) also observed that an increase in cement fineness led to an increase in shrinkage after 500 days for a constant water-cement ratio, and aggregate-paste content (leading to varying concrete workabilities, which was also done in the current study). Their observations are consistent with the current results.

Picket (1956) studied mortars with two water-cement ratios (0.35 and 0.50) and different aggregate contents, ranging from 0 to 65 percent by volume, to determine the effect of aggregate content on shrinkage. Mortars with different types of aggregate (pulverized silica, Ottawa sand, and graded Elgin sand) were also tested to determine the effect of the type of aggregate on concrete shrinkage. For mortars with a water-cement ratio of 0.50 made with pulverized silica and aggregate contents of 5, 15, 30, and 50 percent, less shrinkage was observed as aggregate content was increased. Ottawa sand and Elgin sand also yielded less shrinkage as the aggregate content was increased. For mortars with a water-cement ratio of 0.35, increased aggregate contents produced lower shrinkage concrete for all types of aggregates. When comparing the effect of aggregate type at the same water-cement (0.50) and aggregate content (30 percent), Ottawa sand produced the most shrinkage followed by the Elgin Sand mixes, and the pulverized silica mix had the least shrinkage. This effect of the type of aggregate on shrinkage was observed for different aggregate contents and at the other water-cement ratio tested. This was attributed to by Picket to the aggregates' different restraining properties against shrinkage.

3.4 PROGRAM II (MINERAL ADMIXTURES)

Program II was used to determine the effects of three mineral admixtures, slag, fly ash, and silica fume, on shrinkage. In this program, Type I/II cement was replaced on a volume basis with 30 percent slag (Batch 86), 30 percent Class C fly ash (Batch 87), or 10 percent silica fume (Batch 88). A mix without mineral admixtures was used as a control (Batch 85). The test matrix and proportions for these mixes are listed in Tables 2.2 and 2.16, respectively. Individual specimen data are presented in Figures A3.19 through A3.22 in Appendix A.

3.4.1 Comparison Between Batches

The average free shrinkage curves for the batches in Program II are presented in Figures 3.13 through 3.15. No specimens in this test program experienced swelling. The legends on the bottom of Figures 3.13 through 3.15 display a description of the batch, followed by the batch number in parentheses. Table 3.9 summarizes the shrinkage results for Program II at 3, 7, 30, 90, 180, and 365 days. Values are interpolated where needed.

Figure 3.13 compares the average free shrinkage strains for the first 30 days after casting for the batches in Program II. At 30 days, the Class C Fly Ash mix experienced the most shrinkage, with 337 $\mu\varepsilon$, closely followed by the slag mix with 333 $\mu\varepsilon$, then the control mix with 303 $\mu\varepsilon$, and finally the silica fume mix with 293 $\mu\varepsilon$. For most of the 30 day period, however, the control mix had 10-15 $\mu\varepsilon$ less shrinkage than the silica fume mix (just not on day 30 specifically), as shown in Figure 3.13. 3.10 displays the results of the Student's t-test for Program II at 30, 180, and 365 days. As seen in Figure 3.13 and 3.9, the difference between the silica fume mix and the control mix (10 $\mu\varepsilon$) is not statically significant at 30 days, but the differences between the control and the slag mix (30 με) and between the control and the fly ash mix (34 με) are statistically significant at 30 days.

Figure 3.14 is similar to 3.13 except that it compares the average free shrinkage during the first 180 days of the test. At 180 days, the Class C fly ash mix experienced the most shrinkage, with 462 με, followed by the control mix with 431 με, the slag mix with 426 με, and the silica fume mix with 419 με. Figure 3.14 shows that the shrinkage values for the slag, silica fume, and control mixes are beginning to converge, while the Class C fly ash mix still has the highest shrinkage. 3.10 shows that the differences at 180 days between slag, silica fume, and the control mix is not statistically significant but that the difference between fly ash and each of the other mixes is statistically significant. The results of the Student's t-test in Table 3.10 confirm the trend that is seen in Figure 3.14 at 180 days that the slag, control, and silica fume mixes are similar and that the fly ash mix produces a higher shrinkage.

Figure 3.15 shows the average free shrinkage through 365 days. Shrinkage for all batches experienced an unexplained drop over a 75-day period from day 290 to day 365. At 365 days, the Class C fly ash mix had experienced the most shrinkage (478 με), followed by the silica fume mix (441 με), the slag mix (435 με), and the control mix with 402 με. Between 225 and 365 days, the control mix stopped shrinking after 320 days. Throughout the test, all of the curves exhibit periodic dips; this was due to problems with the length comparator at the time. After 200 days, all mixes, excluding the slag and silica fume mixes, exhibited more shrinkage than the control mix. At 365 days, the control mix had a shrinkage of 402 με, compared with the slag and silica fume mixes, which had shrinkage strains of 435 and 441 $\mu\varepsilon$, respectively. The results from the Student's t-test shown in Table 3.10 for shrinkage at 365 days are consistent with the values shown in Figure 3.15, in that the difference in shrinkage between the control and the fly ash mixes is statistically significant at a confidence level of 98 percent. The difference between the values for the silica fume and the control mixes and between the slag to the control mixes is significant at a (lower) confidence level of 80 percent.

3.4.2 Summary

Based on these observations it appears that Class C fly ash and slag produce concrete with greater shrinkage than concrete with no mineral admixtures, particularly at 30 days of drying when the concrete is cured for 3 days. The silica fume mix, however, had very similar shrinkage to that of the control mix, at least through the first 290 days of the test, and had noticeably lower shrinkage than the concrete made with slag and fly ash at earlier ages of drying. Lower shrinkage at an early age could prove to be beneficial to limiting cracking of bridge decks.

As discussed in Chapter 1, many authors have observed different results when evaluating the effects of mineral admixtures on the shrinkage of concrete. It is worth noting that the mineral admixture replacement in this study was by volume to keep the paste content constant, while some authors have replaced the admixtures on the basis of mass and noted the change in volume of paste as a factor affecting the observed shrinkage results.

Atis (2003) studied the effects of high-volume replacement (50 and 70 percent by weight) using Class F fly ash on the shrinkage of concrete. Concrete mixtures with a constant slump and cementitious content were compared by changing the water content. Atis found that over six months, the 70 percent fly ash replacement mix had on average 36 percent less shrinkage than the control mix and the 50 percent fly ash replacement mix had on average 30 percent less shrinkage than the control mix. Atis attributed the decrease in shrinkage to the decreased water and paste contents and lower amounts of hydrated paste in the replacement mixes. Unhydrated cementitious material may act as aggregate, restraining shrinkage. It should be noted that the specimens were only cured for 24 hours and fly ash needs a much longer curing period to combine chemically with the calcium hydroxide in the hydrating cement paste. Gopalan and Haque (1987) studied concretes with cement volume replacements of 0, 20, 35, and 50 percent using Class F fly ash. Overall, they found the shrinkage of the fly ash replacement mixes to be slightly higher than that of the control mix. The authors pointed out that for the fly-ash concrete, the total cementitious content was lower because the replacement was by an equal volume basis and concluded that fly ash has little effect on shrinkage.

Hogan and Meusel (1981) found that slag replacements of cement of 40, 50, and 65 percent produced higher shrinkage by as much as 63 percent after 64 weeks. They believed that the increased shrinkage may be due to the greater volume of paste in the concrete when slag is substituted on an equal mass basis. Khatri, Sirivivatnanon, and Gross (1995) studied concrete mixes with a constant slump, a binder content of 430 kg/m^3 (725 lb/yd^3), and a water-cementitious ratio material of 0.35 with varying slag replacements. Overall Khatri et al. found that all slag mixes has higher long-term and early-age drying shrinkage and that increasing the slag content increased drying shrinkage.

Carette and Malhortra (1983) tested silica fume replacements of cements of 15 and 30 percent by weight in concrete and found no effect on concrete shrinkage in the short and long term, which is consistent with the results shown in Figures 3.13 through 3.16.

Rao (2001) found a significant increase in shrinkage after 28 days of drying with an increase in silica fume replacement. Two different series were studied both with a water-cementitious ratio of 0.5 and cement replacement by mass. The Series I mortar mixes had silica fume with cement replacements of 0, 5, 10, 15, 17.5, 20, 22.5, 25, 27.5, and 30 percent, while Series II replacements were limited to 0, 10, 15, and 20 percent. Series I had a 1.18-mm (No. 16) maximum size aggregate and Series II had a 2.36-mm (No. 8) maximum size aggregate. Rao found that the addition of silica fume increased shrinkage with increasing silica fume content after 28 days. The mortars with the highest 28 day shrinkage for Series I and II were those with silica fume contents of 30 and 20 percent, respectively. These were the mortars with the highest silica fume replacements in the respective series. After 730 days, Rao observed an increase in shrinkage with addition of silica fume, but the highest shrinkage was not observed for the highest silica fume replacement mix in each series. All mortars with silica fume replacement had more shrinkage then the control for both series. For Series I, the highest shrinkage was observed for the mortar with 17.5 percent silica fume replacement followed by the mortars with 15, 10, 20, 30, 22.5, 5, 27.5, and 25 percent silica fume replacements. For Series II, the mortar with 15 percent silica fume replacement had the most shrinkage followed the mortars with 10 and 20 percent silica fume. The difference in shrinkage between the silica fume mixes and the control, however, was not as pronounced at 730 days as it was at 28 days.

Looking at Rao's data for a mix with a similar silica fume replacement to that used in the current study, Rao observed that the 10 percent silica fume replacement mortars exhibited significantly higher shrinkage at 28 days than the control mix. At 28 days, the 10 percent silica fume replacement mortars showed 173 percent (Series I) and 300 percent (Series II) more shrinkage than the control mortars. For long-term shrinkage (greater than 365 days), Rao contended that the amount of silica fume replacement did not play a significant role in the degree of drying shrinkage. However, his results did show that the control mix had at least 5 percent less shrinkage than the lowest shrinking silica fume mix at 1095 days of drying. The results of the current study (Figures 3.13 through 3.16) show little difference between silica fume with a 10 percent volume replacement and the control mix throughout the life of the test, which is similar to the long-term effects observed by Rao. The short-term results (Figure 3.13) show that the shrinkage values of the control mix and the silica fume are virtually identical, and Table 3.10 shows there is no statistical difference between the mixes after 30 days of drying. Rao contended that the significant increase in early shrinkage was due to the pore size refinement that silica fume can produce. As noted for other studies, a factor that could account for the difference in results observed in this study and to those of Rao's is that the silica fume replacement in this study was made by volume, and while Rao's use of mass replacement resulted in an increase in paste content. Rao did not report enough information to compare paste contents with the paste contents in this study.

Neville (1996) states that concrete made with silica fume requires increased mixing time to thoroughly disperse the silica fume particles in the mix, and the use of a high-range water reducer may be needed for adequate workability. Since the silica fume mix in the current study was hand mixed and no superplastizer was used, the mix was very stiff. In this study, the silica fume particles may not have been thoroughly blended with the cement, thus causing clumps of silica fume particles. If there were clumps of unhydrated silica fume particles, the clumps could have acted like aggregate to restrain shrinkage, causing the shrinkage of the silica fume mixes to be similar to the control mix.

3.5 PROGRAM III (AGGREGATE TYPE)

Program III was used to determine the effect of coarse aggregate type on shrinkage. Two types of coarse aggregate, limestone and quartzite, were evaluated. The test matrix and proportions for the mixes are listed in Tables 2.3 and 2.17, respectively. Individual specimen data are presented in Figures A3.23 through A3.26 in Appendix A.

3.5.1 Comparison Between Batches

The average free shrinkage curves for the batches in Program III are presented in Figures 3.16 through 3.21. The legends at the bottom of these figures identify the aggregate type followed by the batch number in parentheses. Table 3.11 summarizes the average shrinkage strains for specimens in Program III at 3, 7, 30, 90, 180, and 365 days. Batches 94 (quartzite) and 95 (limestone) (Figures 3.16 through 3.18) did not experience swelling, while Batches 138 (limestone) and 159 (quartzite) (Figures 3.19 through 3.21) experienced some swelling during the curing period. Batches 94 and 95 had aggregate contents of 70 percent by volume and were not air-entrained, while batches 138 and 159 had aggregate contents of 69.5 and 67.5 and air contents of 6.15 and 8.15 percent, respectively. It is not clear weather the differences in air content, or the presence of entrained air played a role in the observed behavior.

Figure 3.16 shows the shrinkage of the non-air-entrained batches (Batches 94 and 95) during the first 30 days after casting. At 227 $\mu\varepsilon$, the limestone batch (Batch 95) experienced 54 $\mu\varepsilon$ more shrinkage than the quartzite batch (Batch 94) (173 $\mu\varepsilon$). Figure 3.17 shows the shrinkage of the two batches through 180 days, with the limestone batch (387 $\mu\varepsilon$) producing 80 $\mu\varepsilon$ more shrinkage than the quartzite batch (307 $\mu\varepsilon$). At 365 days (Figure 3.18), the limestone and quartzite batch produced shrinkage values of 407 and 333 $\mu\varepsilon$ respectively, a difference of 74 $\mu\varepsilon$. Between 180 and 365 days, the shrinkage rate of each mixture leveled off while, the difference in shrinkage between the two remained approximately constant. Table 3.12 displays the results of the Student's t-test for the batches at 30, 180 and 365 days. It confirms the results from Figures 3.16 through 3.18; the differences in shrinkage are statistically significance at all these dates.

Figures 3.19 and 3.20 show the shrinkage results for the air-entrained batches (Batches 138 and 159) for the first 30 and 180 days after casting, respectively. At 30 days, the quartzite batch (Batch 159) and the limestone batch (Batch 138) produced shrinkage values of 323 and 313 $\mu\varepsilon$, respectively, a difference of 10 $\mu\varepsilon$. At 180 days, the quartzite batch (Batch 159) and the limestone batch (Batch 138) produced shrinkage values of 420 and 464 $\mu\varepsilon$, respectively, a difference of 44 $\mu\varepsilon$. Figure 3.21 shows the shrinkage of these batches through 365 days. Between days 150 through 365, there is a drop in shrinkage values of both batches, a drop that is more noticeable in the limestone batch. A drop in shrinkage would indicate swelling of the specimens. It is not likely, however, that the specimens experienced swelling, and the drop is most likely due to problems with the length comparator at the time of testing. Even with this observed discrepancy in the data, the limestone batch consistently exhibited slightly less shrinkage than the quartzite batch. Table 3.13 displays the results of the Student's t-test for the air-entrained batches at 30, 180, and 365 days. At 30 and 365 days, the differences between the batches are not statistically significant, and at 180 days, the difference is only significant at the lowest confidence level (80 percent). From these results and the figures, the non-air-entrained mixes show that limestone had the higher shrinkage, while the air-entrained mixes showed that the quartzite produced higher shrinkage. It is important to note that both non-air-entrained mixes had an aggregate content of 70 percent, while the air-entrained mixes had different aggregate contents, for the limestone mix 69.5 percent, compared to 67.5 percent for the quartzite mix. The difference could be a contributing factor to the lower observed shrinkage of the air-entrained limestone batch. The air contents of the non-air-entrained mixes were constant, while the air-entrained mixes were not. The limestone batch had an air content of 6.5 percent, while the quartzite mix had an air content of 8.5 percent. As stated earlier, it is not clear weather the differences in air content, or the presence of entrained air played a role in the observed behavior.

3.5.2 SUMMARY

In the non-air-entrained aggregate mixes (Batches 94 and 95), the results showed that limestone results in more shrinkage than the quartzite. Carlson (1938) found that aggregates with high absorption, and thus high porosity, are usually associated with a low modulus of elasticity and that absorption can serve as an indication of an aggregate's ability to restrain shrinkage in concrete. Carlson concluded that the compressibility of the aggregate is the most important single property of an aggregate in affecting concrete shrinkage. Picket (1956) and Powers (1959) also observed the degree of shrinkage restraint provided by different aggregates. Because of its higher absorption (3 percent compared to 0.44 percent), it is expected that the limestone used in this study has a lower modulus of elasticity and, therefore, will provide less restraint against shrinkage than the quartzite.

In the air-entrained aggregate batches (Batches 138 and 159), the results showed that the quartzite produces more shrinkage than the limestone. The difference is most likely due to the difference in aggregate content between the two mixes. The limestone mix had a higher aggregate content (69.5 percent) than the quartzite (67.5 percent). As observed in Program I, as the aggregate content increases, shrinkage tends to decrease. Another difference between the two mixes was the air content. The quartzite batch had 2 percent more air than the limestone batch. Ultimately, these differing parameters could have contributed to the unexpected results, and tighter control of the parameters needs to be established for future testing.

Overall, additional tests with a wider range of aggregate types should be used to evaluate the effect of aggregate type on shrinkage. Care should be taken to obtain similar air contents.

3.6 PROGRAM IV (CURING)

Program IV was used to evaluate the effect of the length of the curing period on free shrinkage. The test matrix and proportions for the mixes are listed in Tables 2.4 and 2.18, respectively. Individual specimen data are presented in Figures A3.27 through A3.37 in Appendix A.

3.6.1 Effect of Length of Curing Period

The effect of the length of the curing period on free shrinkage is investigated for concretes made with Type I/II and Type II coarse-ground cement in Program IV. Curves that compare concrete with different curing periods are presented in Figures

3.22 through 3.27. The legends on the bottom of these figures indicate the curing time. All of the specimens shown in each figure were made from the same batch. Table 3.14 summarizes the shrinkage results for Program IV 3, 7, 14, 28, 30, 90, 180, and 300 days after casting and Table 3.15 summarizes the results based on days after the initiation of drying. The results on both tables are interpolated where needed.

Figure 3.22a shows the shrinkage for the first 30 days after casting of concrete containing Type I/II cement and no air-entraining agent from the same batch (Batch 165) but cured for different periods of time plotted. The curing times were 3, 7, 14, and 28 days. Specimens cured for 7, 14, and 28 days experience swelling, but the specimens cured for 3 days did not. Based on Tables 3.14a and Figure 3.22a, it can be observed that the longer the curing time, the greater the amount of swelling, and that an increase in curing time results in less shrinkage for a given day after casting. Figure 3.22b is similar to Figure 3.22a, except the comparison is made based on the drying time. Based on drying time only, after 30 days, the concretes cured for 3, 7, and 14 days had very similar values of shrinkage at 333, 337, and 320 $\mu\varepsilon$, respectively, while the concrete cured for 28 days had only 227 $\mu\varepsilon$ of shrinkage. Table 3.16 shows the results of the Student's t-test for concrete containing Type I/II cement with no air-entraining agent (Batch 165). The results support the results shown in Figure 3.22b; that is, after 30 days of drying, the differences between the specimens cured for 3, 7, and 14 days are not statistically significant but the differences between those cured for 3, 7, or 14 days and to specimens cured for 28 days are statistically significant (98 percent confidence).

Figure 3.23a shows the shrinkage results for Batch 165 through 180 days. After 180 days, the concrete cured for 28 days still had the lowest shrinkage, followed by the concretes cured for 14, 3, and 7 days with shrinkage strains of 471, 533, 547 and 586 $\mu\varepsilon$, respectively. Figure 3.23b is similar to Figure 3.23a, except that it displays the results based on drying times. Table 3.16 presents the results of the Student's t-test. It shows that the differences between specimens cured for 3 and 14 days are not statistically significant but that the differences between all others are.

Figure 3.24a shows the shrinkage results of concrete containing Type I/II cement for Batch 165 through 330 days after casting. Table 3.14b summarizes shrinkage up to 300 days after casting, and Table 3.15b summarizes shrinkage up to 300 days of drying. Figure 3.24b is similar to Figure 3.24a, except it shows the results based on drying time. At 300 days, the order of shrinkage remains the same as it did at 180 days. The concrete cured for 28 days had the lowest shrinkage followed by concretes cured for 14, 3, and 7 days, with shrinkage strains of 443, 506, 515 and 564 $\mu\varepsilon$, respectively. Based on the Student's t-test results at 300 days (Table 3.16), the differences between the specimens cured for 3 and 14 days are not statistically significant, but the differences among all others are statistically significant.

Figure 3.25a shows shrinkage during the first 30 days after casting of concrete containing Type II coarse-ground cement and no air-entraining agent made from the same batch (Batch 166) but cured for different periods. The curing times were 3, 7, 14, and 28 days. As for Batch 165, the specimens cured for 7, 14, and 28 days experienced swelling, but the specimens cured for 3 days did not. Based on Tables

3.14a and Figure 3.25a, it can be observed that the longer the curing time, the greater the amount of swelling and that an increase in curing results in less shrinkage for a given day after casting. This is similar to the results observed for the concrete made with Type I/II cement. Figure 3.25b is similar to Figure 3.25a, except that it shows shrinkage as a function of drying time. After 30 days of drying, the concrete cured for 3 days had the most shrinkage, followed by the concretes cured for 7, 14, and 28 days, with shrinkage strain values of 302, 270, 237, and 193 $\mu\varepsilon$, respectively. Results from the Student's t-test for drying at 30 days are shown in Table 3.17. For 30 days of drying, the differences observed between concretes cured for 3 and 7 days and the differences observed between concretes cured for 7 and 14 days are not statistically significant. The differences observed between all other concretes are.

Figure 3.26a shows the shrinkage results for Batch 166 through 180 days after casting. The results are similar to those at 30 days. Figure 3.26b shows the shrinkage through 180 days of drying. The shrinkage strains after 180 days of drying for concrete cured for 3, 7, 14, and 28 days are 556, 513, 457, and 411 $\mu\varepsilon$, respectively. Results from the Student's t-test for drying at 180 days are shown in Table 3.17. The difference in shrinkage between specimens cured for 3 or 7 days are not statistically significant, but the differences observed between all other cases are.

Figure 3.27a shows the results through 330 days. Figure 3.27b is similar to Figure 3.27a, except it shows shrinkage as a function of drying time. Tables 3.14 and 3.15 summarize shrinkage up to 300 days after casting and after 300 days of drying, respectively. At 300 days, the order of shrinkage remains the same as it did at 30 and

180 days, with concrete cured for 3, 7, 14, and 28 days, respectively, exhibiting shrinkage values of 520, 487, 433, and 376 $\mu\varepsilon$. The results of the Student's t-test at 300 days of drying (Table 3.17) show that the difference in shrinkage between 3 and 7 days of curing is not statistically significant but that the differences between all other concretes are.

3.6.2 Effect of Cement Type at Different Curing Periods

The effects of cement type for each curing period are presented in Figures 3.28 through 3.31. The legend on the bottom of the figures identifies the cement type, followed by the batch number in parentheses. Table 3.14 summarizes the shrinkage results for Program IV 3, 7, 30, 90, 180, and 300 days after casting, and Table 3.15 summarizes the results for days of drying. Both tables are interpolated where needed.

Figure 3.28a compares the shrinkage of concrete containing Type I/II cement (Batch 165) with that of concrete containing Type II coarse-ground cement (Batch 166) cured for 3 days. Figure 3.28b shows the results based on the drying period. For 3 days of curing, there appears to be no difference in shrinkage for concretes made with Type I/II cement and Type II coarse-ground cement. Table 3.18 shows the results of the Student's t-test comparing the free shrinkage of the concretes made with Type I/II and Type II coarse-ground cement with different curing periods after 30, 180, and 300 days of drying. The results confirm that the difference in shrinkage between concretes made with Type I/II and Type II coarse-ground cement cured for 3 days is not statistically significant after drying periods of 30, 180, or 300 days.

Figure 3.29a compares the shrinkage of concretes containing Type I/II cement (Batch 165) and Type II coarse-ground cement (Batch 166) cured for 7 days. Figure 3.29b shows the results based on drying period. The concrete made with Type II coarse-ground exhibits lower shrinkage than that of concrete made with the Type I/II cement throughout the test. The results of the Student's t-test are shown in Table 3.18. After 30 days of drying, the concretes made with Type II coarse-ground cement and Type I/II cement exhibited shrinkage strains of 270 and 337 $\mu\varepsilon$, respectively, a difference that is statistically significant with a confidence level of 90 percent ($\alpha = 0.10$). After 180 days of drying, the concrete made with Type II coarse-ground cement and Type I/II exhibited shrinkage strains of 513 and 583 $\mu\varepsilon$, respectively. This difference in shrinkage is also statistically significant, but only at a confidence interval of 80 percent ($\alpha = 0.20$). After 300 days of drying, the concretes made with Type II coarse-ground cement and Type I/II cement exhibited shrinkage strains of 487 and 564 $\mu\varepsilon$, respectively. This difference in shrinkage is statistically significant at a confidence level of 90 percent ($\alpha = 0.10$).

Figure 3.30a compares the shrinkage of the concretes containing Type I/II cement (Batch 165) and Type II coarse-ground cement (Batch 166) cured for 14 days. Figure 3.30b shows the results based on the drying period. As for concrete cured for 7 days, the concrete made with Type II coarse-ground cement consistently shrinks less than the concrete made with Type I/II cement. After 30 days of drying, the concretes made with Type II coarse-ground cement and Type I/II cement exhibited shrinkage strains of 237 and 320 με, respectively. After 180 days of drying, concretes made with Type II coarse-ground cement and Type I/II cement exhibited shrinkage strains of 457 and 529 με, respectively. After 300 days of drying, the concretes made with Type II coarse-ground cement and Type I/II cement exhibited shrinkage strains of 433 and 506 με, respectively. From Table 3.18 shows at all ages, this difference in shrinkage is statistically significant at a confidence level of 98 percent ($\alpha = 0.02$) for concretes cured for 14 days.

Figure 3.31a compares the shrinkage of concretes cured for 28 days. Figure 3.31b shows the results based on drying period. As observed for the 7 and 14 day curing periods, the concrete made with Type II coarse-ground shrinkage less than the concrete made with Type I/II cement. After 30 days of drying, the concretes made with Type II coarse-ground cement and Type I/II cement exhibited shrinkage strains of 193 and 227 με, respectively. This difference in shrinkage is statistically significant at a confidence level of 90 percent ($\alpha = 0.10$). After 180 days of drying, the concretes made with Type II coarse-ground cement and Type I/II cements exhibited shrinkage strains of 411 and 465 με, respectively. This difference in shrinkage is statistically significant at a confidence level of 95 percent ($\alpha = 0.05$). After 300 days of drying, the concretes made with Type II coarse-ground cement and Type I/II cement exhibited shrinkage strains of 376 and 443 με, respectively. This difference in shrinkage is statistically significant at a confidence level of 98 percent ($\alpha = 0.02$).

3.6.3 Air-Entrained Concrete at Different Curing Times

Average free shrinkage curves that compare air-entrained concretes made with Type I/II cement that have different curing periods are shown in Figures 3.32 through 3.34. Unlike the earlier comparisons in this section, a different batch was used for each curing period. The mix proportions (Table 2.18) differed only in the final air content, with Batches 138, 140, and 143, cured for 3, 7, and 14 days, containing 6.15, 9.25, and 9.0 percent air, respectively. The legends on the bottom of the figures identify the curing period, followed by the batch number in parentheses. Table 3.14b summarizes the shrinkage results for the three batches 3, 7, 30, 90, 180, and 300 days after casting and Table 3.15b summarizes the results based on the drying period. As before, the data in the tables are interpolated where needed.

Figure 3.32a shows the shrinkage of the batches during the first 30 days after casting. All batches experienced swelling. Figure 3.32b is similar to Figure 3.32a, except that it shows shrinkage based on the drying period. The two figures indicate that during the first 30 days of drying, the batch with the 3-day curing period experienced the most shrinkage (313 $\mu\varepsilon$), followed by batches cured for 7 (290 $\mu\varepsilon$), and 14 days (253 $\mu\varepsilon$). Table 3.19 shows the results of the Student's t-test for the batches after drying periods of 30, 180, and 300 days. After 30 days of drying, the difference observed between batches cured for 3 and 7 days is not statically significant, but the differences between the rest of the batches are.

Figures 3.33a and 3.33b show the shrinkage results for the three batches 180 days after casting and after drying, respectively. After about 60 days of drying, the rate of shrinkage for all batches started to level off, and between 60 and 180 days of drying, the curves converged, with the concrete cured for 7 days experiencing the most shrinkage (425 με), followed by the concretes cured for 3 days (420 με), and 14 days (408 με). From the Student's t-test results (Table 3.19), none of the differences are statistically significant.

Figures 3.34a and 3.34b show the shrinkage results for the three batches 365 days after casting and after drying, respectively. After 300 days of drying, the curves have converged, with batch cured for 7 days experiencing the greatest shrinkage (425 με), followed by concretes cured for 14 days (391 με) and 3 days (387 με). Between 180 and 365 days, the rate of shrinkage among all batches appeared to level off. Based on the Student's t-test results (Table 3.19), the difference observed after 300 days of drying between the concretes cured for 7 and 14 days is statistically significant as is the differences observed between the concretes cured for 7 and 3 days, but the difference observed between concretes cured for 3 and 14 days is not statistically significant. It is important to note that the specimens were made from three different batches. Some of the differences observed may be due to the variations among batches.

3.6.4 Summary

Some authors feel that an increased curing period can lead to an increase in shrinkage because a larger proportion of the cement particles hydrate, thus decreasing the volume of unhydrated particles that provide restraint against shrinkage (Powers 1959), while other authors have found that an increased curing period can lead to a decrease in long-term shrinkage (500 days) by prolonging the initial onset of shrinkage by allowing the concrete to experience swelling during the curing period (Bennett and Loat 1970). Bennett and Loat, however, did not compare or comment on the drying only period when comparing concretes of different curing periods. Carlson (1938) also stated that the duration of curing has little effect on concrete shrinkage. The observation in this study is that increased curing leads to lower shrinkage. This is observed from the concrete containing Type I/II cement (Batch 165). The specimens cured for 7 days were the only specimens exhibiting shrinkage value that are out of the expected order, but a trend can still be distinguished. For the concrete containing Type II coarse-ground cement, longer curing corresponds to a decrease in shrinkage in all cases. An obvious trend can be observed; longer curing results in a decrease in shrinkage for the concrete in this study for which comparisons are made for the same batch of concrete.

The current results are consistent with those obtained by Bennett and Loat (1970). They used the free shrinkage test to study concrete made with three different finenesses of cement, an aggregate to cement ratio of 3, and varying water-cement ratios (0.3, 0.375, 0.450, and 0.525) subjected to curing times of 1 and 28 days. They found that prolonged curing decreased the shrinkage throughout the 500 day test for each combination of materials.

Based on Figures 3.28 through 3.31 and Table 3.18, it appears that for a given curing period, concrete containing Type II coarse-ground cement produces lower shrinkage than concrete containing Type I/II cement for curing times of 7, 14, and 28 days. There does not appear to be a difference in shrinkage for concrete with just 3 days of curing.

Powers (1959) stated that coarser cements should produce paste that will shrink less than those produced with finer cements. This matches the current findings. Powers (1959) also stated that curing time ultimately has little effect on overall shrinkage, which conflicts with the current results.

Using cements with five different finenesses Bennett and Loat (1970) found that the shrinkage was consistently increased as the fineness of the cement increased. Unfortunately, finding that concrete made with finer cement has a higher water demand, Bennett and Loat accounted for this difference and compared concrete with *equal workability* made with cements of different fineness. The increased water demand resulted in an increase in paste content thus leading to the increase in shrinkage

A trend between shrinkage and curing period (Figures 3.32 through 3.34) is not as clear for the air-entrained batches as it was for the non-air-entrained batches (Figures 3.28 through 3.31). However, the specimens with entrained air were not made from the same batch, while the non-air-entrained specimens were. The main variations between the batches of the air-entrained concretes were the slump and the air content. The air contents of the air-entrained batches were 6.15, 9.25, and 9.0 percent for the batches cured for 3, 7, and 14 days, respectively. The slumps of the air-entrained batches were 70 mm (2.75 in.), 100 mm (4 in.), and 75 mm (3 in.) for the batches cured for 3, 7, and 14 days, respectively. Further investigation is needed and air-entrained concrete from the same batch with different curing periods should be investigated.

3.7 PROGRAM V (SUPERPLASTICIZERS)

Program V was used to evaluate the effect of two superplasticizers, Glenium 3000NS and Rheobuild 1000, on free shrinkage. The effects of using different dosage rates were explored. Dosage rates identified as low, medium, and high, were based on dosage ranges recommended by the manufacturers. The test matrix and proportions for these mixes are listed in Tables 2.5 and 2.19, respectively. Individual specimen data are presented in Figures A3.38 through A3.45 in Appendix A.

3.7.1 Comparison Between Batches

The average free shrinkage curves that compare batches in Program V are presented in Figures 3.35 through 3.40. The legends on the bottom of these figures indicate the dosage rate followed by the batch number in parentheses. Table 3.20 summarizes the shrinkage results for Program V, 3, 7, 30, 90, 180, and 300 days after casting. Tables 3.21 and 3.22 show the results of the Student's t-test for concretes containing Glenium 3000NS and Rheobuild 1000, respectively.

Figure 3.35 shows the shrinkage of concrete containing Glenium 3000NS with different dosage rates 30 days after casting. Unexpected swelling occurred for all batches during the first few days of drying. Between 0 and 30 days, all concretes increased in shrinkage. The readings, however, were erratic, and there was no consistent trend in the order of superplasticizer dosage rate on the amount of shrinkage. Large increases and decreases in shrinkage were observed from day to day in some batches, sometimes as much as 100 με. This could be attributed to problems with the length comparator during this period of testing. Between 0 and 30 days, the order of concretes from lowest to highest shrinkage changed due to the erratic jumps in shrinkage values; however, the values for all mixes throughout the 30 days were still close together. After 30 days, the mix with the lowest shrinkage was the concrete with the high dosage (233 με), followed by the control mix (237 με), then the low dosage (267 με), and the medium dosage concrete had the highest shrinkage (280 με). Based on the figure and the results of the Student's t-test (Table 3.21), the differences in shrinkage observed as a function of superplasticizer dosage are not statistically significant at 30 days.

Figure 3.36 shows the shrinkage of concrete containing Glenium 3000NS through 180 days, and once again, the differences in shrinkage between batches are not statistically significant (Table 3.31). The rate of shrinkage for all batches is still increasing; however, between 50 and 180 days, the readings appear to become less erratic. There were times when the order changed, but not as drastically as observed during the first 30 days. At 180 days, the shrinkage strains were close, all within a range of 46 με. After 180 days, the mix with the lowest shrinkage was the concrete with the medium dosage (434 με), followed by the control mix (457 με), then the low dosage (460 με), and the high dosage concrete had the highest shrinkage (480 με).

Figure 3.37 shows the shrinkage of the concretes containing Glenium 3000NS through 300 days. Between 125 and 300 days, the rate of shrinkage of all concretes levels off. Although the curves appear to separate, specifically the concrete with the medium dosage (Batch 169) ends up with the lowest shrinkage and appears to decrease in shrinkage towards the end of the test, the curves remain very close. After 300 days, the mix with the lowest shrinkage was the concrete with the medium dosage (397 με), followed by the control mix (434 με), then the low dosage (453 με), and the high dosage concrete had the highest shrinkage with shrinkage (473 με). The results of the Student's t-test (Table 3.21) show the difference between the control and the concrete containing the medium dosage range and also between the concretes containing the low and the high dosage ranges are not statistically significant. The differences between the rest of the batches are statistically significant.

Figure 3.38 shows the shrinkage of concrete containing Rheobuild 1000 with different dosage rates at 30 days after casting. As with the concrete made with the Glenium 3000NS admixture, some of the batches made with Rheobuild 1000 experienced erratic behavior from day to day and experienced unexpected swelling during the first few days. Differences in shrinkage from day to day for some batches could be as much as 100 με. As with the concretes made with Glenium 3000NS, this was due to complications with the length comparator at the time of the test. After 30 days, the concrete with the lowest shrinkage was the concrete containing the low dosage range (210 με), followed by the concrete with the medium dosage range (217 με), the control mix (237 με), and high dosage range (260 με). The total range is only 60 με, which provides little evidence that there is much difference between the batches. The results of the Student's t-test (Table 3.22) show the differences between some of the batches are statistically significant (the control-low dosage, the low-high dosage, and the medium-high dosage concretes), while other differences are not (between the control-medium dosage, the control-high dosage, and the low-medium dosage concretes).

Figure 3.39 shows the shrinkage values through 180 days. The concrete with the high dosage of Rheobuild 1000 appears to have distinctly higher shrinkage (513 με), with the rest of the batches clustered together about 50 με below, with the concrete with the low dosage (467 με) having the next highest shrinkage followed by the control (457 με), and the medium dosage concrete (457 με). Between 30 and 180 days, the rate of shrinkage is still consistently rising, and the erratic shrinkage from day to day appears to have ceased except for one batch. The results of the Student's t-test (Table 3.22) support Figure 3.39, showing that the differences in shrinkage between the concrete with the high dosage and the rest of the concretes are statistically significant, but that the differences between the rest of the concretes are not statistically significant.

Figure 3.40 shows the shrinkage of concrete containing Rheobuild 1000 through 300 days. Once again, the concrete containing the high dosage appears to have about 50 $\mu\varepsilon$ more shrinkage than the other concretes. The concrete with the high dosage ended with a shrinkage of 503 $\mu\varepsilon$, followed by the concretes with the medium (457 $\mu\varepsilon$) and low dosage (453 $\mu\varepsilon$) and then the control (434 $\mu\varepsilon$). Between days 125 and 300 days, the rate of shrinkage for all concretes appears to level off. Once again, the Student's t-test shows that differences between the concrete containing the high dosage range and the control, low, and medium batches are statistically significant. Also the difference between the control and the concrete containing the low dosage is statistically significant, but only at the lowest confidence level (80 percent). As shown in Figure 3.40, the concretes with the low and medium dosages exhibit similar shrinkage to the control mix between 150 and 300 days, but the last shrinkage reading for the control mix drops unexpectedly. Ignoring this unexpected drop in shrinkage at the end of the test for the control batch, there is no statistically difference between the control mix and the concretes containing the low and medium dosages.

3.7.2 Summary

Overall, increased shrinkage was observed for concretes containing the superplasticizers. However, it should be noted that the concretes, as produced, did not have practical physical properties. A water-cement ratio of 0.45 was used for all mixes, as was the same total water content. As a result, the addition of even a low dosage of superplasticizer produced a mix with noticeable bleed water. Water was replaced in the mix design only to account for the liquid in the superplasticizer, the slump for the batches was not constant, and the water reducing aspect of the superplasticizer was not utilized in this study. As stated in Chapter 2, each batch was allowed to set up in a covered container until it was stiff enough to cast. Retardation was observed for both admixtures, even at the lowest dosage. The mixes with high dosages of superplasticizer also experienced significant segregation and bleeding. Retardation, segregation, and bleeding of concrete using superplasticizers have been observed by others (Holt 2004, Johnston et al. 1979, Faroug et al. 1999).

Brooks (1999) analyzed 96 sets of data collected by various authors studying the effects of superplasticizer on shrinkage. He found no significant difference in shrinkage among concretes with different types of superplasticizers, but overall, he observed a general increase in shrinkage of 20 percent compared to control mixes without the admixtures. He stated this increase in shrinkage may be due to the admixture's ability to entrain air, making the hardened paste weaker and more susceptible to deformation.

Johnston et al. (1979) studied four different types of superplasticizers (melamine formaldehyde condensate, sufoaryl alklene, sulfonate polymer, and polymerized naphthalene condensate) in concretes with (1) a 100 mm (4 in.) slump and a 32 percent paste content and (2) zero slump and a 23.7 percent paste content. All four superplasticizers increased bleeding, and all but the melamine formaldehyde condensate superplasticizer increased the setting time of the concrete by about 20 percent. The authors found some types of superplasticizers had little effect on shrinkage while others produced concrete with greater shrinkage.

Both superplasticizers in this study are classified as Type A (water reducer) and Type F (high-range water reducer) admixtures. Type A admixtures can often cause retardation, as observed in all of the batches in this program. Concretes with the high workability produced in this program would not be suitable for applications on bridge decks. Further investigations are being performed at the University of Kansas to determine how each superplasticizer, proportioned to produce concrete with a constant slump, affects shrinkage.

3.8 PROGRAM VI (PRACTICAL MIXES)

Work in Program VI was previously reported by Tritsch, Darwin, and Browning (2005). Program VI was used to evaluate the shrinkage of air-entrained concretes that are proposed for use or have been used on bridge decks. The batches evaluated were a control mix, a mix with Type II coarse-ground cement mix, a MoDOT bridge deck mix with Type I/II cement, and a KDOT bridge deck mix with Type I/II cement with cement contents of 317 kg/m^3 (535 lb/yd^3), 317 kg/m^3 (535 lb/yd^3), 432 kg/m^3 (729 lb/yd^3), and 357 kg/m^3 (602 lb/yd^3), respectively. The concrete was cured for three days. The test matrix and proportions for these mixes are listed in Tables 2.6 and 2.20, respectively. Individual specimen data are presented in Figures A3.46 through A3.49 in Appendix A.

3.8.1 Comparison Between Batches

The average free shrinkage curves of concretes in Program VI are presented in Figures 3.41 through 3.43. The legends on the bottom of these figures display a description of the batch followed by the batch number in parentheses. Table 3.23 summarizes the shrinkage results for Program VI at 3, 7, 30, 90, 180, and 365 days after casting and interpolated where needed. Table 3.24 shows the results of the Student's t-test for Program VI.

Figure 3.41 shows the shrinkage of the batches 30 days after casting with the control mix (387 με) having the most shrinkage, followed by the MoDOT mix (350 με), then the KDOT mix (340 με), and finally the Type II coarse-ground cement mix (257 με). All batches experienced swelling during the three day curing period. From the results of the Student's t-test (Table 3.24), the only batches that did not have a statistically significance difference between in shrinkage were the MoDOT and KDOT mixes.

Figure 3.42 shows the shrinkage through 180 days and the results were similar. The control mix (484 με) has the most shrinkage, followed by the MoDOT mix (461 με), then the KDOT mix (457 με), and finally the Type II coarse-ground cement mix (381 με). Between days 60 and 180 days, the rate of shrinkage begins to decrease for all batches, but the shrinkage is still increasing. Once again the results of the Student's t-test show that the only batches that do not have a statistically significance difference in shrinkage are the MoDOT and KDOT mixes.

Figure 3.43 shows the results through 365 days. From this figure, it can be seen that between 125 and 365 days, the shrinkage rates for each mix start to level off. Toward the last part of the test, around day 347, the KDOT mix shrinkage appears to jump 47 $\mu\varepsilon$ ending at 520 $\mu\varepsilon$. Between days 125 and 316, the shrinkage of the KDOT mix varied between 463 and 473 $\mu\varepsilon$. The sudden jump in shrinkage after 316 days could be due to user error in a transition between individuals collecting data. Ignoring this jump, the shrinkage value of the KDOT mix at 365 days is similar to those at 30 and 180 days. At 365 days, the control mix has the most shrinkage (513 $\mu\varepsilon$), followed by the MoDOT mix (480 $\mu\varepsilon$), the KDOT mix (473 $\mu\varepsilon$), and finally the Type II coarse-ground cement mix (417 $\mu\varepsilon$).

3.8.2 Summary

As seen in the other programs, the Type II coarse-ground cement (batch 82) had significantly lower shrinkage than the Type I/II cement (batch 81).

The KDOT and MoDOT mixes were expected to have greater shrinkage than the control mix because both have a higher paste content than the control mix, but this was not observed. A reason may be the water-cement ratios of each mix. The MoDOT mix has a water-cement ratio of 0.37, the KDOT mix has a water-cement ratio of 0.44, and the control mix has a water-cement ratio of 0.45. A lower water-cement ratio results in a denser paste that slows the rate at which pore water can escape during drying.

3.9 PROGRAM VII (PRACTICAL MIXES)

Program VII was similar to Program VI and was previously reported by Tritsch, Darwin, and Browning (2005). Program VII was used to evaluate the shrinkage of air-entrained concretes that are proposed for use or have been used on bridge decks, some of which are duplicated from Program VI. The batches evaluated were a control mix made with 317 kg/m^3 (535 lb/yd^3) of Type I/II cement, a mix with 317 kg/m^3 (535 lb/yd^3) of Type II coarse-ground cement, a MoDOT bridge deck mix, and a KDOT bridge deck mix that were replicated from Program VI. Two additional mixes were added, a reduced cement content mix [295 kg/m^3 (497 lb/yd^3)] using Type I/II cement and a 317 kg/m^3 (535 lb/yd^3) mix with Type I/II cement mix and a shrinkage reducing admixture. The concrete was cured for three days. The test matrix and proportions for these mixes are listed in Tables 2.7 and 2.21, respectively. Individual specimen data are presented in Figures A3.50 through A3.55 in Appendix A.

3.9.1 Comparison Between Batches

The average free shrinkage curves for the concretes in Program VII are presented in Figures 3.44 through 3.46. The legend on the bottom of these figures displays a description of the batch followed by the batch number in parentheses. Table 3.25 summarizes the shrinkage results for Program VII 3, 7, 30, 90, 180, and 365 days after casting . The values are interpolated where needed. Table 3.26 shows the results of the Student's t-test for Program VII.

Figure 3.44 shows the shrinkage of the batches through 30 days after casting, with the KDOT mix (413 με) having the most shrinkage, followed by the MoDOT mix (357 με), the reduced cement content mix (320 με), then both the control mix and the Type II coarse-ground cement with (313 με), and finally the shrinkage reducing admixture mix with shrinkage equal to less than one-half of that for the control mix. The shrinkage for all mixes consistently increased between 0 and 30 days; some mixes experienced swelling during the curing period. The results of the Student's t-test (Table 3.26) show that the only batches that do not exhibit statistically significance differences are the control mix, the Type II coarse-ground cement mix, and the reduced cement content mix.

Figure 3.45 shows shrinkage through 180 days. Once again, the KDOT mix (584 με) and the MoDOT mix (518 με) had the highest shrinkage, the mix containing the shrinkage reducing admixture had the lowest shrinkage (290 με), and the Type II coarse-ground mix (461 με), reduced cement content mix (440 με), and the control mix (420 με) are clustered in the middle. Between 30 and 180 days all mixes exhibited increased shrinkage, but the rate of shrinkage was not as high as during the first 30 days. The results of the Student's t-test (Table 3.26) show that the only differences that are not statistically significant are those between the reduced cement content mix and the Type II coarse-ground cement and between the reduced cement content mix and the control mix. The plots of shrinkage values for the control mix, the Type II coarse-ground mix, and the reduced cement content mix cross over each other, and even though there is statistically significant difference between the Type II coarse-ground cement and the control mix, it is only at the lowest confidence level (80 percent). As shown in Figure 3.45, after 180 days there does not appear to be much difference in shrinkage between the three middle mixes.

Figure 3.46 shows shrinkage through 365 days after casting. Between days 150 and 365 days, the rate of shrinkage for all mixes starts to level off. The same trend is observed as seen from 30 through 180 days. The KDOT mix (536 με) and MoDOT mix (505 με) had the highest shrinkage, the mix containing the shrinkage reducing admixture (280 με) had the lowest shrinkage, and Type II coarse-ground cement mix (420 με), control mix (413 με), and the reduced cement content mix (393 με) were clustered in the middle.

3.9.2 Summary

In theory, the mixes developed in the laboratory (control, Type II coarse-ground cement, reduced cement content mix, and mix containing shrinkage reducing admixture) should perform better in terms of shrinkage than the actual bridge deck mixes (MoDOT and KDOT mixes) because the paste content is lower for those developed in the lab. This was observed throughout the duration of the test.

It was expected that the reduced cement content mix (Batch 149) would have a lower shrinkage than the control mix (Batch 138) because of its lower paste content. Overall, the two batches performed about the same. It may be worthy of note that the reduced cement content was cast at an 200 mm (8 in.) slump while the control mix was cast at a 70 mm (2.75 in.) slump. The reduced cement content mix also contained a much large amount of superplasticizer [1341 mL/m^3 (34.7 oz/yd^3)] than the control mix [523 mL/m^3 (13.5 oz/yd^3)].

As expected, the mix containing the shrinkage reducing admixture displayed the lowest shrinkage with a 48 percent decrease in shrinkage after 30 days, a 31 percent decrease in shrinkage after 180 days, and a 32 percent decrease in shrinkage after 365 days compared to the control mix.

Shah et al. (1992) studied the use of three different types of SRAs on concrete shrinkage and found that the use of 2 percent SRA by weight of cement could reduce the shrinkage by as much as 40 percent at 42 days. Folliard and Berke (1997) studied one type of SRA and found the use of 1.5 percent SRA by weight of cement in concrete reduced shrinkage at 28 days by about 43 percent and at 120 days by 29 percent.

Shrinkage reducing admixtures are still under investigation, however, because entrained air is difficult to maintain when this admixture is used. The mix had to rest for 45 minutes as recommended by the manufacturer and was then tested for the air content to ensure a stable air content. The benefit of the decrease in shrinkage must be weighed against the disadvantage of an unstable air content. If the advantages of shrinkage reducing admixtures outweigh the disadvantages, SRAs may be a logical option to considerably reduce shrinkage in bridge decks.

3.10 CHAPTER SUMMARY

Results of free shrinkage tests were reported in this chapter to review the effects of aggregate content, water-cement ratio, cement type, aggregate type, mineral admixtures, chemical admixtures, and curing period on shrinkage. It was observed that an increased aggregate content resulted in decreased shrinkage because of the decreased paste content, while the water-cement ratio had little effect in and of itself. For a given aggregate content and water-cement ratio, concrete made with a finer cement exhibited greater shrinkage than one containing a coarser cement. Aggregate type was observed to have an effect on shrinkage, with concrete containing limestone coarse aggregate producing more shrinkage than concrete containing quartzite. The aggregate with the higher absorption appears to have provided less restraint against shrinkage. Further investigation should include different types of aggregate, such as granite. Concretes containing a 30 percent volume replacements of cement by either Class C fly ash or granulated ground blast furnace were observed to have higher shrinkage than concrete containing only Type I/II cement (the control mix), while concrete with a 10 percent volume replacement of cement by silica fume had equal or less shrinkage than the control mix. However, further investigation is needed for concretes containing mineral admixtures. Increased curing periods were observed to lead to decreased shrinkage for concretes made with both Type I/II and Type II coarse-ground cement. Chemical admixtures such as shrinkage reducing admixtures have obvious benefits for decreasing shrinkage in concrete, while the effects of superplasticizers need further investigation. Concretes batched in the laboratory with a reduced cement content [295 kg/m^3 (497 lb/yd^3)] of Type I/II produced lower shrinkage than a control mix [317 kg/m^3 (535 lb/yd^3)].

CHAPTER 4: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

4.1 SUMMARY

This report describes an experimental study that uses the ASTM C157 free shrinkage test to evaluate the effects of mix proportioning parameters and curing on concrete shrinkage with the goal of providing recommendations that will reduce concrete shrinkage in bridge decks. Concrete prisms were cast and tested up to an age of 365 days under controlled conditions of 23 ± 2^o C (73 ± 3^o F) and 50 ± 4 percent relative humidity. The specimens were cured in lime-saturated water until drying began. The study parameters include aggregate content, cement fineness, water-cement ratio, curing period, partial cement replacement by slag, Class C fly ash, or silica fume, superplasticizer dosage, the use of a shrinkage reducing admixture, and aggregate type.

The study consisted of seven programs. Program I evaluated non-air-entrained concrete mixtures with aggregate contents of 60, 70, and 80 percent by volume, water-cement ratios of 0.40, 0.45, and 0.50 and Type I/II and Type II coarse-ground portland cement, for a total of 18 concrete mixes.

Program II evaluated non-air-entrained concrete with partial cement replacements by Class C fly ash, slag, and silica fume. Each concrete mix had an aggregate content of 70 percent by volume, a water-cementitious material ratio of 0.45, and contained Type I/II cement. Mineral admixtures replacements of cement were made by volume of 30 percent slag, 30 percent Class C fly ash, and 10 percent silica fume, a concrete mix with the same proportions but without mineral admixtures was also evaluated as a control mix. The program consisted of four batches.

Program III evaluated the effect of aggregate type on concrete shrinkage. Two types of aggregate, limestone and quartzite were evaluated. Four mixes were compared, two with limestone and two with quartzite; all used Type I/II cement and had a water-cement ratio of 0.45 and aggregate contents close to 70 percent. Of the four concrete mixes evaluated, the first set of limestone and quartz mixes were non–air-entrained, while the second set of mixes air-entrained. The program included four batches.

Program IV evaluated the effect of curing period (3, 7, 14, and 28 days) on concrete shrinkage. One non-air entrained batch with Type I/II cement, 70 percent aggregate and 0.45 water-cement ratio was made and specimens were cured for either 3, 7, 14, or 28 days. Another non-air-entrained batch was made and cured with similar proportions and curing periods, except it was made of Type II coarse-ground cement. Three additional air-entrained batches were evaluated with similar proportions cured for 3, 7, and 14 days for a total of five batches.

Program V evaluated two types of superplasticizers at dosages rates that varied within the manufacturer's recommended dosage range. Type I/II cement was used with proportions of 70 percent aggregate by volume and a water-cement ratio of 0.45. The program included seven batches.

Programs VI and VII consisted of concrete mixes that had been or could have been used for bridge decks. Two concrete mixes in this study were from the Missouri

Department of Transpiration (MoDOT) and Kansas Department of Transpiration (KDOT). Other mixes contained a shrinkage reducing admixture, used Type II coarse-ground cement, or a reduced cement content for a total of ten batches.

4.2 CONCLUSIONS

The following conclusions are based on the data and analysis presented in this report.

1. Increasing the aggregate content of a concrete mix decreases the shrinkage by providing restraint against shrinkage and by decreasing the amount of cement paste, the component of concrete that shrinks.
2. The water-cement ratio has little effect in and of itself on concrete shrinkage. For a fixed cement content, however, a change in water-cement ratio changes the paste content, which leads to an increase or decrease in shrinkage.
3. For a given aggregate content and water-cement ratio, concretes made with Type I/II cement shrink more than concretes made with Type II coarse-ground cement.
4. Concrete containing a 30 percent cement replacement (by volume) of either Class C fly ash or granulated ground blast-furnace slag exhibit higher shrinkage than concrete with only Type I/II cement when cured for three days.

5. Concrete containing a 10 percent cement replacement (by volume) of silica fume exhibit equal or lower shrinkage than concrete made with only Type I/II cement. This result, however, is in question due to the mixing practices and batch sizes used in this study.
6. Limestone coarse aggregate produces concrete with higher shrinkage than concrete made with quartzite coarse aggregate. Aggregates with higher absorptions such as the limestone used in this study, typically have a lower modulus of elasticity and provide less restraint against shrinkage.
7. Increased curing periods lead to a decrease in shrinkage for concretes made with Type I/II cement and concretes made with Type II coarse-ground cement.
8. No consistent effect of dosage rate on shrinkage was observed for concretes made with superplasticizers Glenium 3000NS and Rheobuild 1000.
9. Concretes made with even the lowest dosage of Glenium 3000NS and Rheobuild 1000 experienced retardation in set. Concretes made with high dosages of Glenium 3000NS and Rheobuild 1000 experienced prolonged retardation in set and experienced segregation.
10. Concrete with 295 kg/m^3 (497 lb/yd^3) of Type I/II cement experienced less shrinkage then a control mix made with a 317 kg/m^3 (535 lb/yd^3) of Type I/II cement, further reinforcing the benefits of reduced paste content on shrinkage and (potentially) cracking tendency.

11. The use of a shrinkage reducing admixture at a dosage rate of 2 percent by weight of cement reduced the shrinkage of concrete nearly 32 percent after 365 days. The shrinkage reducing admixture, however, produced concrete that at times exhibited an unstable air content.

4.3 RECOMMENDATIONS

1. To minimize shrinkage and, in turn, cracking on bridge decks, use concretes with a reduced paste content and increased aggregate content.
2. Use coarse-ground cement to reduce shrinkage of concrete. Further testing should be done to evaluate the effects of coarse-ground cement on permeability and compressive strength to ensure that the use of coarse-ground cement does not have any adverse effects on concrete performance.
3. The use of mineral admixtures on bridge decks should be avoided if possible and further study should be conducted. The program with the mineral admixtures should be repeated with a range of mineral admixture replacement and curing period. A superplasticizer should be used with silica fume to properly disperse the silica fume particles. Batch sizes should be larger and a mechanical mixer should be used in lieu of hand mixing. The use of Class F fly ash should also be explored.
4. Use an aggregate with a high modulus of elasticity to reduce concrete's susceptibility to shrinkage.

5. Test more aggregate types to compare how they affect shrinkage; testing should include granite.
6. Prolonged moist curing on bridge decks should be used when possible.
7. The program with superplasticizers Glenium 3000NS and Rheobuild 1000 should be repeated. The concrete mixes should be proportioned to a consistent slump and cement content to further explore the effects of superplasticizers on concrete shrinkage.
8. Use a concrete mix with a reduced cement content when possible.
9. The use of shrinkage reducing admixtures should be explored further, including their effect on the final air void system of the concrete.
10. Aggregates should be blended to produce an optimized aggregate content to help with workability and help reduce the overall paste content.

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Table 2.1 –Program I Test Matrix

w/c Ratio	Aggregate content		
	60%	70%	80%
0.40	Batch 68	Batch 66	Batch 62
0.45	Batch 69	Batch 64	Batch 63
0.50	Batch 70	Batch 65	Batch 67

Type I/II cement, 0.01 yd^3 hand batches

Table 2.1 – Program I Test Matrix continued

w/c Ratio	Aggregate content		
	60%	70%	80%
0.40	Batch 77	Batch 74	Batch 71
0.45	Batch 78	Batch 75	Batch 72
0.50	Batch 79	Batch 76	Batch 73

Type II cement coarse-ground cement, 0.01 yd^3 hand batches

Table 2.2 –Program II Test Matrix

Control	Batch 85
30% Slag replacement	Batch 86
30% Fly Ash replacement	Batch 87
10% Silica Fume replacement	Batch 88

Type I/II cement, 0.45 w/c ratio, 70% aggregate content, 0.01 yd^3 hand batches

Table 2.3 –Program III Test Matrix

Quartzite	Batch 94
Limestone	Batch 95

Type I/II cement, 0.45 w/c ratio, 70% aggregate content, 0.01 yd^3 hand batches

Table 2.3 –Program III Test Matrix continued

Limestone	Batch 138
Quartzite	Batch 159

0.0625 yd^3 mixer batches
See 2.17 for full details

Table 2.4 –Program IV Test Matrix

3 Day Cure	Batch 165
7 Day Cure	Batch 165
14 Day Cure	Batch 165
28 Day Cure	Batch 165

Type I/II cement, 0.45 w/c ratio, 70% aggregate content, 0.0425 yd^3 mixer batches

Table 2.4 –Program IV Test Matrix continued

3 Day Cure	Batch 166
7 Day Cure	Batch 166
14 Day Cure	Batch 166
28 Day Cure	Batch 166

Type I/II cement, 0.45 w/c ratio, 70% aggregate content, 0.0425 yd^3 mixer batches

Table 2.4 –Program IV Test Matrix continued

3 Day Cure	Batch 138
7 Day Cure	Batch 140
14 Day Cure	Batch 143

Type I/II cement, 0.45 w/c ratio, 73% aggregate content, 0.0425 yd^3 mixer batches, chemical admixtures: air entraining agent and superplasticizer

Table 2.5 –Program V Test Matrix

Control	Batch 167
Low dosage Glenium 3000NS	Batch 168
Medium dosage Glenium 3000NS	Batch 169
High dosage Glenium 3000NS	Batch 174
Low dosage Rheobuild 1000	Batch 171
Medium dosage Rheobuild 1000	Batch 172
High dosage Rheobuild 1000	Batch 173

Type I/II cement, 0.45 w/c ratio, 70% aggregate content, 0.01 yd^3 hand batches
Glenium 3000NS base chemical: Polycarboxalate
Rheobuild 1000 base chemical: Naphthalene

Table 2.6 –Program VI Test Matrix

Control	Batch 81
Type II Coarse-Ground Cement	Batch 82
MoDOT	Batch 83
KDOT	Batch 84

0.0625 yd^3 mixer batches
See 2.20 for full details.

Table 2.7 –Program VII Test Matrix

Control	Batch 138
Type II Coarse-Ground Cement	Batch 145
MoDOT	Batch 132
KDOT	Batch 130
Shrinkage Reducing Admixture	Batch 147
Reduced Cement Content	Batch 149

0.0625 yd^3 mixer batches
See 2.21 for full details.

Table 2.8 –25-mm (1 in.) Limestone Gradations

	% Retained	
	Program I, II, V, III: 94	**Program IV: 165, 166**
38.1 mm (1 ½ in.)	0	0
25.4 mm (1 in.)	0	0
19.0 mm (3/4 in.)	25.9	25.9
12.7 mm (1/2 in.)	71.7	71.7
9.51 mm (3/8 in.)	1.5	1.5
4750 µm (No. 4)	0.2	0.2
2360 µm (No. 8)	0.0	0.0
1180 µm (No. 16)	0.6	0.6

Table 2.9 –19-mm (3/4 in.) Limestone Gradations

	% Retained		
	Program I, II, III: 95	**Program IV, V, VII, III: 138**	**Program VI**
38.1 mm (1 ½ in.)	0	0	0
25.4 mm (1 in.)	0	0.1	0
19.0 mm (3/4 in.)	0	0.1	0
12.7 mm (1/2 in.)	23.0	11.3	23.0
9.51 mm (3/8 in.)	26.5	18.7	26.5
4750 µm (No. 4)	42.1	48.7	42.1
2360 µm (No. 8)	6.1	15.1	6.1
1180 µm (No. 16)	2.3	6.1	2.3

Table 2.10 –25-mm (1-in.) Quartzite Gradations

	% Retained
	Program III: 94
38.1 mm (1 ½ in.)	0
25.4 mm (1 in.)	0
19.0 mm (3/4 in.)	8.3
12.7 mm (1/2 in.)	46.9
9.51 mm (3/8 in.)	23.0
4750 µm (No. 4)	17.6
2360 µm (No. 8)	2.3
1180 µm (No. 16)	1.9

Table 2.11 –Quartzite chip Gradations

	% Retained Program III: 94
38.1 mm (1 ½ in.)	0
25.4 mm (1 in.)	0
19.0 mm (3/4 in.)	0
12.7 mm (1/2 in.)	0.3
9.51 mm (3/8 in.)	17.5
4750 μm (No. 4)	76.0
2360 μm (No. 8)	5.5
1180 μm (No. 16)	0.7

Table 2.12 – 19-mm (3/4 in.) Quartzite Gradation

	% Retained Program III: 159
38.1 mm (1 ½ in.)	0
25.4 mm (1 in.)	0
19.0 mm (3/4 in.)	1.6
12.7 mm (1/2 in.)	25.9
9.51 mm (3/8 in.)	28.4
4750 μm (No. 4)	36.8
2360 μm (No. 8)	3.5
1180 μm (No. 16)	3.9

Table 2.13 –Pea Gravel Gradation

	% Retained	
	Program I, II, VI, III: 94, 95	**Program IV, V, VII, III: 138, 159**
9.51 mm (3/8 in.)	0	0
4750 μm (No. 4)	10.3	12.5
2360 μm (No. 8)	41.0	40.5
1180 μm (No. 16)	32.9	30.2
600 μm (No. 30)	8.6	9.0
300 μm (No. 50)	4.9	5.6
150 μm (No. 100)	1.8	1.7
75 μm (No. 200)	0.4	0.4
Pan	0.1	0.2

Table 2.14 –Sand Gradation

	% Retained	
	Program I, II, VI, III: 94, 95	**Program IV,V, VII, III: 138, 159**
9.51 mm (3/8 in.)	0	0
4750 µm (No. 4)	1.4	1.6
2360 µm (No. 8)	13.1	12.7
1180 µm (No. 16)	21.3	20.9
600 µm (No. 30)	24.2	25.4
300 µm (No. 50)	28.6	29.5
150 µm (No. 100)	10.3	8.6
75 µm (No. 200)	1.0	1.0
Pan	0.1	0.2

Table 2.15 – Mix Proportions-Program I-Aggregate content and water cement ratio with variable cement type

Batch	**62**	**63**	**64**
w/c	0.40	0.45	0.45
Aggregate content %	80	80	70
Cement, kg/m^3 (lb/yd^3):			
Type I/II	281 (473)	262 (442)	393 (663)
Coarse-ground Type II	-	-	-
Water, kg/m^3 (lb/yd^3)	112 (189)	118 (199)	177 (298)
Coarse Aggregate, kg/m^3 (lb/yd^3):			
1 in. Limestone	416 (701)	416 (701)	364 (613)
3/4 in. Limestone	688 (1159)	688 (1159)	602 (1014)
Fine Aggregate, kg/m^3 (lb/yd^3)	623 (1049)	623 (1049)	545 (918)
Pea Gravel, kg/m^3 (lb/yd^3)	353 (595)	353 (595)	309 (521)

Batch	**65**	**66**	**67**
w/c	0.5	0.40	0.50
Aggregate content %	70	70	80
Cement, kg/m^3 (lb/yd^3):			
Type I/II	369 (622)	421 (709)	246 (415)
Coarse-ground Type II	-	-	-
Water, kg/m^3 (lb/yd^3)	185 (311)	169 (284)	123 (207)
Coarse Aggregate, kg/m^3 (lb/yd^3):			
1 in. Limestone	364 (613)	364 (613)	416 (701)
3/4 in. Limestone	602 (1014)	602 (1014)	688 (1159)
Fine Aggregate, kg/m^3 (lb/yd^3)	545 (918)	545 (918)	623 (1049)
Pea Gravel, kg/m^3 (lb/yd^3)	309 (521)	309 (521)	353 (595)

Batch	**68**	**69**	**70**
w/c	0.40	0.45	0.5
Aggregate content %	60	60	60
Cement, kg/m^3 (lb/yd^3):			
Type I/II	561 (946)	525 (884)	492 (829)
Coarse-ground Type II	-	-	-
Water, kg/m^3 (lb/yd^3)	224 (378)	236 (398)	246 (415)
Coarse Aggregate, kg/m^3 (lb/yd^3):			
1 in. Limestone	312 (526)	312 (526)	312 (526)
3/4 in. Limestone	516 (869)	516 (869)	516 (869)
Fine Aggregate, kg/m^3 (lb/yd^3)	467 (787)	467 (787)	467 (787)
Pea Gravel, kg/m^3 (lb/yd^3)	265 (446)	265 (446)	265 (446)

Quantities of cement, water and aggregate based on 2% air

Table 2.15 – Mix Proportions-Program I-Aggregate content and water cement ratio with variable cement type-continued

Batch	**71**	**72**	**73**
w/c	0.40	0.45	0.50
Aggregate content %	80	80	80
Cement, kg/m^3 (lb/yd^3):			
Type I/II	-	-	-
Coarse-ground Type II	281 (473)	262 (442)	246 (415)
Water, kg/m^3 (lb/yd^3)	112 (189)	118 (199)	123 (207)
Coarse Aggregate, kg/m^3 (lb/yd^3):			
1 in. Limestone	416 (701)	416 (701)	416 (701)
3/4 in. Limestone	688 (1159)	688 (1159)	688 (1159)
Fine Aggregate, kg/m^3 (lb/yd^3)	623 (1049)	623 (1049)	623 (1049)
Pea Gravel, kg/m^3 (lb/yd^3)	353 (595)	353 (595)	353 (595)

Batch	**74**	**75**	**76**
w/c	0.40	0.45	0.50
Aggregate content %	70	70	70
Cement, kg/m^3 (lb/yd^3):			
Type I/II	-	-	-
Coarse-ground Type II	421 (709)	393 (663)	369 (622)
Water, kg/m^3 (lb/yd^3)	169 (284)	177 (298)	185 (311)
Coarse Aggregate, kg/m^3 (lb/yd^3):			
1 in. Limestone	364 (613)	364 (613)	364 (613)
3/4 in. Limestone	602 (1014)	602 (1014)	602 (1014)
Fine Aggregate, kg/m^3 (lb/yd^3)	545 (918)	545 (918)	545 (918)
Pea Gravel, kg/m^3 (lb/yd^3)	309 (521)	309 (521)	309 (521)

Batch	**77**	**78**	**79**
w/c	0.40	0.45	0.50
Aggregate content %	60	60	60
Cement, kg/m^3 (lb/yd^3):			
Type I/II	-	-	-
Coarse-ground Type II	561 (946)	525 (884)	492 (829)
Water, kg/m^3 (lb/yd^3)	224 (378)	236 (398)	246 (415)
Coarse Aggregate, kg/m^3 (lb/yd^3):			
1 in. Limestone	312 (526)	312 (526)	312 (526)
3/4 in. Limestone	516 (869)	516 (869)	516 (869)
Fine Aggregate, kg/m^3 (lb/yd^3)	467 (787)	467 (787)	467 (787)
Pea Gravel, kg/m^3 (lb/yd^3)	265 (446)	265 (446)	265 (446)

Quantities of cement, water and aggregate based on 2% air

Table 2.16 – Mix Proportions-Program II-Mineral Admixtures

Batch	**85**	**86**
w/c	0.45	0.45
Aggregate content %	70	70
Cementitious material, kg/m^3 (lb/yd^3):		
Type I/II	374 (630)	253 (426)
30% Slag	-	108 (182)
30% Fly Ash	-	-
10% Silica Fume	-	-
Water, kg/m^3 (lb/yd^3)	168 (283)	168 (283)
Coarse Aggregate, kg/m^3 (lb/yd^3):		
1 in. Limestone	364 (613)	364 (613)
3/4 in. Limestone	635 (1070)	635 (1070)
Fine Aggregate, kg/m^3 (lb/yd^3)	639 (1076)	639 (1076)
Pea Gravel, kg/m^3 (lb/yd^3)	182 (307)	182 (307)

Batch	**87**	**88**
w/c	0.45	0.45
Aggregate content %	70	70
Cementitious material, kg/m^3 (lb/yd^3):		
Type I/II	251 (423)	322 (542)
30% Slag	-	-
30% Fly Ash	107 (181)	-
10% Silica Fume	-	36 (60)
Water, kg/m^3 (lb/yd^3)	168 (283)	168 (283)
Coarse Aggregate, kg/m^3 (lb/yd^3):		
1 in. Limestone	364 (613)	364 (613)
3/4 in. Limestone	635 (1070)	635 (1070)
Fine Aggregate, kg/m^3 (lb/yd^3)	639 (1076)	639 (1076)
Pea Gravel, kg/m^3 (lb/yd^3)	182 (307)	182 (307)

Quantities of cement, water, and aggregates based on 2% air

Table 2.17 – Mix Proportions-Program III-Aggregate Type

Batch	**94**	**95**
w/c	0.45	0.45
Aggregate content %	70	70
Cement, kg/m^3 (lb/yd^3): Type I/II	 374 (630)	 374 (630)
Water, kg/m^3 (lb/yd^3)	168 (283)	168 (283)
Coarse Aggregate, kg/m^3 (lb/yd^3): 1 in. Limestone 3/4 in. Limestone 1 in. Quartzite Quartzite Chip	 - - 883 (1488) 130 (219)	 364 (613) 635 (1070) - -
Fine Aggregate, kg/m^3 (lb/yd^3)	582 (981)	639 (1076)
Pea Gravel, kg/m^3 (lb/yd^3)	245 (412)	182 (307)

Batch	**Control, 138**	**Quartzite, 159**
w/c	0.45	0.45
Cement, kg/m^3 (lb/yd^3): Type I/II	 317 (535)	 317 (535)
Water, kg/m^3 (lb/yd^3)	143 (241)	143 (241)
Coarse Aggregate, kg/m^3 (lb/yd^3): 3/4 in. Limestone 3/4 in. Quartzite	 1006 (1695) -	 - 1019 (1718)
Fine Aggregate, kg/m^3 (lb/yd^3)	538 (906)	545 (918)
Pea Gravel, kg/m^3 (lb/yd^3)	218 (368)	221 (373)
Superplasticizer, mL/m^3 (oz/yd^3)	523 (13.5)[a]	497 (12.8)[a]
Air-entraining Agent, mL/m^3 (oz/yd^3)	170 (4.4)[b]	111 (2.9)[b]
Slump, mm (in.)	70 (2.75)	70 (2.75)
Air Content, %	6.15	8.15
Unit Weight, kg/m^3 (lb/ft^3)	2248 (140.3)	2237 (139.7)
Temperature, ˚C (˚F)	18 (65)	20 (68)
28 Day Compressive Strength, MPa (psi)	38 (5460)	28 (4050)

Quantities of cement, water, and aggregates based on 2% air

[a] – Adva® 100 (Grace Construction Products)

[b] – Daravair® 1000 (Grace Construction Products)

Table 2.18 – Mix Proportions-Program IV Curing (Tritsch, Darwin, Browning 2005)

Batch	Control, 138	7-day, 140	14-day, 143
w/c	0.45	0.45	0.45
Cement, kg/m^3 (lb/yd^3): Type I/II	317 (535)	317 (535)	317 (535)
Water, kg/m^3 (lb/yd^3)	143 (241)	143 (241)	143 (241)
Coarse Aggregate, kg/m^3 (lb/yd^3): 3/4 in. Limestone	1006 (1695)	1006 (1695)	1006 (1695)
Fine Aggregate, kg/m^3 (lb/yd^3)	538 (906)	538 (906)	538 (906)
Pea Gravel, kg/m^3 (lb/yd^3)	218 (368)	218 (368)	218 (368)
Superplasticizer, mL/m^3 (oz/yd^3)	523 (13.5)[a]	523 (13.5)[a]	523 (13.5)[a]
Air-entraining Agent, mL/m^3 (oz/yd^3)	170 (4.4)[b]	170 (4.4)[b]	170 (4.4)[b]
Slump, mm (in.)	70 (2.75)	100 (4)	75 (3)
Air Content, %	6.15	9.25	9.0
Unit Weight, kg/m^3 (lb/ft^3)	2248 (140.3)	2237 (139.6)	2230 (139.2)
Temperature, ˚C (˚F)	18 (65)	20 (68)	20 (68)
28 Day Compressive Strength, MPa (psi)	38 (5460)	35 (5050)	35 (5050)

[a] – Adva® 100 (Grace Construction Products)

[b] – Daravair® 1000 (Grace Construction Products)

Table 2.18 – Mix Proportions-Program IV-Curing continued

Batch	165	166
w/c	0.45	0.45
Aggregate content %	70	70
Cement, kg/m^3 (lb/yd^3): Type I/II Coarse-ground Type II	 374 (630) -	 - 374 (630)
Water, kg/m^3 (lb/yd^3)	168 (283)	168 (283)
Coarse Aggregate, kg/m^3 (lb/yd^3): 1 in. Limestone 3/4 in. Limestone	 364 (613) 635 (1070)	 364 (613) 635 (1070)
Fine Aggregate, kg/m^3 (lb/yd^3)	639 (1076)	639 (1076)
Pea Gravel, kg/m^3 (lb/yd^3)	182 (307)	182 (307)

Quantities of cement, water and aggregate based on 2% air

Table 2.19 – Mix Proportions-Program V-Superplasticizers

Batch	**167**	**168**	**169**
w/c	0.45	0.45	0.45
Aggregate content %	75	75	75
Cement, kg/m^3 (lb/yd^3):			
Type I/II	328 (552)	328 (552)	328 (552)
Water, kg/m^3 (lb/yd^3)	148 (249)	148 (249)	148 (249)
Coarse Aggregate, kg/m^3 (lb/yd^3):			
1 in. Limestone	497 (837)	497 (837)	497 (837)
3/4 in. Limestone	554 (933)	554 (933)	554 (933)
Fine Aggregate, kg/m^3 (lb/yd^3)	573 (965)	573 (965)	573 (965)
Pea Gravel, kg/m^3 (lb/yd^3)	287 (483)	287 (483)	287 (483)
Superplasticizers, mL/m^3 (oz/yd^3)			
Rheobuild® 1000	-	-	-
Glenium® 3000 NS	-	854 (22.1)	1708 (44.2)

Batch	**170**	**171**
w/c	0.45	0.45
Aggregate content %	75	75
Cement, kg/m^3 (lb/yd^3):		
Type I/II	328 (552)	328 (552)
Water, kg/m^3 (lb/yd^3)	148 (249)	148 (249)
Coarse Aggregate, kg/m^3 (lb/yd^3):		
1 in. Limestone	497 (837)	497 (837)
3/4 in. Limestone	554 (933)	554 (933)
Fine Aggregate, kg/m^3 (lb/yd^3)	573 (965)	573 (965)
Pea Gravel, kg/m^3 (lb/yd^3)	287 (483)	287 (483)
Superplasticizers, mL/m^3 (oz/yd^3)		
Rheobuild® 1000	-	2135 (55.2)
Glenium® 3000 NS	2562 (66.2)	-

Quantities of cement, water and aggregate based on 2% air.

Table 2.19 – Mix Proportions-Program V-Superplasticizers continued

Batch	**172**	**173**	**174**
w/c	0.45	0.45	0.45
Aggregate content %	75	75	75
Cement, kg/m^3 (lb/yd^3): Type I/II	328 (552)	328 (552)	328 (552)
Water, kg/m^3 (lb/yd^3)	148 (249)	148 (249)	148 (249)
Coarse Aggregate, kg/m^3 (lb/yd^3): 1 in. Limestone 3/4 in. Limestone	 497 (837) 554 (933)	 497 (837) 554 (933)	 497 (837) 554 (933)
Fine Aggregate, kg/m^3 (lb/yd^3)	573 (965)	573 (965)	573 (965)
Pea Gravel, kg/m^3 (lb/yd^3)	287 (483)	287 (483)	287 (483)
Superplasticizers, mL/m^3 (oz/yd^3) Rheobuild® 1000 Glenium® 3000 NS	 3737 (96.6) -	 5338 (138.0) -	 - 2562 (66.2)

Batch 174 is redo of batch 170
Quantities of cement, water and aggregate based on 2% air

Table 2.20 – Mix Proportions Program VI (Tritsch, Darwin, Browning 2005)

Batch	**Control, 81**	**Type II C.G., 82**	**MoDOT, 83**	**KDOT, 84**
w/c	0.45	0.45	0.37	0.44
Cement, kg/m^3 (lb/yd^3): Type I/II Coarse-ground Type II	 317 (535) -	 - 317 (535)	 432 (729) -	 357 (602) -
Water, kg/m^3 (lb/yd^3)	143 (241)	143 (241)	161 (271)	157 (265)
Coarse Aggregate, kg/m^3 (lb/yd^3): 3/4 in. Limestone 3/4 in. Quartzite	1006 (1695) -	1007 (1697) -	1059 (1785) -	874 (1474) -
Fine Aggregate, kg/m^3 (lb/yd^3)	538 (906)	538 (906)	640 (1078)	872 (1469)
Pea Gravel, kg/m^3 (lb/yd^3)	218 (368)	218 (368)	-	-
Superplasticizer, mL/m^3 (oz/yd^3) plus additional	621 (16.1)[a] 872 (22.5)	748 (19.3)[a] -	504 (13.0)[a] 2725 (70.4)	196 (5.1)[a] 1090 (28.2)
Air-Entraining Agent, mL/m^3 (oz/yd^3)	186 (4.8)[b]	203 (5.2)[b]	242 (6.3)[b]	209 (5.4)[b]
SRA, kg/m^3 (lb/yd^3)	-	-	-	-
Slump, mm (in.)	90 (3.5)	70 (2.75)	145 (5.75)	145 (5.75)
Air Content, %	5.65	5.15	3.25	5.4
Unit Weight, kg/m^3 (lb/ft^3)	2250 (140.4)	2302 (143.7)	2354 (147.0)	2291 (143.0)
Temperature, ˚C (˚F)	24 (75)	23 (74)	27 (80)	25 (77)

[a] – Adva® 100 (Grace Construction Products)

[b] – Daravair® 1000 (Grace Construction Products)

Table 2.21 – Mix Proportions Program VII (Tritsch, Darwin, Browning 2005)

Batch	**KDOT, 130**	**MoDOT, 132**	**Control, 138**
w/c	0.44	0.37	0.45
Cement, kg/m^3 (lb/yd^3):			
Type I/II	357 (602)	432 (729)	317 (535)
Coarse-ground Type II	-	-	-
Water, kg/m^3 (lb/yd^3)	157 (265)	161 (272)	143 (241)
Coarse Aggregate, kg/m^3 (lb/yd^3):			
3/4 in. Limestone	874 (1474)	1059 (1785)	1006 (1695)
Quartzite	-	-	-
Fine Aggregate, kg/m^3 (lb/yd^3)	872 (1469)	640 (1078)	538 (906)
Pea Gravel, kg/m^3 (lb/yd^3)	-	-	218 (368)
Superplasticizer, mL/m^3 (oz/yd^3)	327 (8.5)[a]	379 (9.8)[a]	523 (13.5)[a]
Air-entraining Agent, mL/m^3 (oz/yd^3)	157 (4.1)[b]	412 (10.7)[b]	170 (4.4)[b]
SRA, kg/m^3 (lb/yd^3)	-	-	-
Slump, mm (in.)	110 (4.25)	30 (1.25)	70 (2.75)
Air Content, %	7.25	5.15	6.15
Unit Weight, kg/m^3 (lb/ft^3)	2215 (138.3)	2291 (143.0)	2248 (140.3)
Temperature, ˚C (˚F)	18 (64)	19 (66)	18 (65)
28 Day Compressive Strength, MPa (psi)	35 (5060)	40 (5801)	38 (5460)

[a] – Adva® 100 (Grace Construction Products)
[b] – Daravair® 1000 (Grace Construction Products)
[c] – Glenium® 3000 NS (Master Builders, Inc.)
[d] – Micro Air® (Master Builders, Inc.)
[e] – Tetraguard AS20 (Master Builders, Inc.)

Table 2.21 – Mix Proportions Program VII-continued (Tritsch, Darwin, Browning 2005)

Batch	Type II C.G., 145	SRA, 147	Reduced. Cement 149
w/c	0.45	0.45	0.45
Cement, kg/m^3 (lb/yd^3):			
Type I/II	-	317 (535)	295 (497)
Coarse-ground Type II	317 (535)	-	-
Water, kg/m^3 (lb/yd^3)	143 (241)	143 (241)	133 (224)
Coarse Aggregate, kg/m^3 (lb/yd^3):			
3/4 in. Limestone	1007 (1697)	1006 (1695)	1031 (1738)
Quartzite	-	-	-
Fine Aggregate, kg/m^3 (lb/yd^3)	538 (906)	538 (906)	551 (929)
Pea Gravel, kg/m^3 (lb/yd^3)	218 (368)	218 (368)	224 (377)
Superplasticizer, mL/m^3 (oz/yd^3)	360 (9.3)[c]	490 (12.7)[c]	1341 (34.7)[a]
Air-entraining Agent, mL/m^3 (oz/yd^3)	213 (5.5)[d]	1046 (27.1)[d]	92 (2.4)[b]
SRA, kg/m^3 (lb/yd^3)	-	6.3 (10.7)[e]	-
Slump, mm (in.)	55 (2.25)	120 (4.75)	200 (8)
Air Content, %	8.4	8.4	8.4
Unit Weight, kg/m^3 (lb/ft^3)	2216 (138.3)	2241 (139.9)	2235 (139.5)
Temperature, ˚C (˚F)	19 (66)	20 (68)	18 (65)
28 Day Compressive Strength, MPa (psi)	26 (3770)	31 (4430)	33 (4790)

[a] – Adva® 100 (Grace Construction Products)
[b] – Daravair® 1000 (Grace Construction Products)
[c] – Glenium® 3000 NS (Master Builders, Inc.)
[d] – Micro Air® (Master Builders, Inc.)
[e] – Tetraguard AS20 (Master Builders, Inc.)

Table 3.1-Summary of average free shrinkage data for Program I

Batch	68	66	62	69	64	63
Cement type	I/II	I/II	I/II	I/II	I/II	I/II
w/c ratio	0.40	0.40	0.40	0.45	0.45	0.45
% aggregate	60	70	80	60	70	80
Day[a]	**Average Shrinkage (με)**					
3	0	0	0	0	0	0
7	173	130	97	163	113	97
30	427	330	290	387	330	283
90	593	460	356	539	487	343
180	673	534	387	600	535	377
365	733	550	397	630	557	377

[a]Denotes days after casting

Batch	70	65	67	77	74	71
Cement type	I/II	I/II	I/II	II CG	II CG	II CG
w/c ratio	0.50	0.50	0.50	0.40	0.40	0.40
% aggregate	60	70	80	60	70	80
Day[a]	**Average Shrinkage (με)**					
3	0	0	0	0	0	0
7	147	83	93	117	90	100
30	393	313	237	297	260	217
90	540	457	310	439	347	272
180	610	503	344	510	370	278
365	627	497	343	527	313	263

[a]Denotes days after casting

Batch	78	75	72	79	76	73
Cement type	II CG	II CG	II CG	II CG	II CG	II CG
w/c ratio	0.45	0.45	0.45	0.50	0.50	0.50
% aggregate	60	70	80	60	70	80
Day[a]	**Average Shrinkage (με)**					
3	0	0	0	0	0	0
7	93	63	83	97	87	83
30	260	260	217	297	287	200
90	404	337	279	427	341	273
180	448	382	292	481	368	305
365	460	370	287	493	317	293

[a]Denotes days after casting

Table 3.2-Summary of average free shrinkage from Figures 3.8, 3.10, and 3.12.

Water-cement ratio of 0.40

Batch	**68**	**77**	**66**	**74**	**62**	**71**
Cement type	I/II	II CG	I/II	II CG	I/II	II CG
% aggregate	60	60	70	70	80	80
Day[a]	**Average Shrinkage (με)**					
3	0	0	0	0	0	0
7	173	117	130	90	97	100
30	427	297	330	260	290	217
90	593	439	460	347	356	272
180	673	510	534	370	387	278
365	733	527	550	313	397	263

[a]Denotes days after casting

Water-cement ratio of 0.45

Batch	**69**	**78**	**64**	**75**	**63**	**72**
Cement type	I/II	II CG	I/II	II CG	I/II	II CG
% aggregate	60	60	70	70	80	80
Day[a]	**Average Shrinkage (με)**					
3	0	0	0	0	0	0
7	163	93	113	63	97	83
30	387	260	330	260	283	217
90	539	404	487	337	343	279
180	600	448	535	382	377	292
365	630	460	557	370	377	287

[a]Denotes days after casting

Water-cement ratio of 0.50

Batch	**70**	**79**	**65**	**76**	**67**	**73**
Cement type	I/II	II CG	I/II	II CG	I/II	II CG
% aggregate	60	60	70	70	80	80
Day[a]	**Average Shrinkage (με)**					
3	0	0	0	0	0	0
7	147	97	83	87	93	83
30	393	297	313	287	237	200
90	540	427	457	341	310	273
180	610	481	503	368	344	305
365	627	493	497	317	343	293

[a]Denotes days after casting

Table 3.3-Program I Student's t-test results for concretes with different aggregate contents at a constant water-cement ratio of 0.40 and containing Type I/II cement, 30, 180, and 365 days after casting.

30 days

Average Shrinkage (με)		60%	70%	80%
427	60%		95	Y
330	70%			N
290	80%			

180 days

Average Shrinkage (με)		60%	70%	80%
673	60%		Y	Y
534	70%			Y
387	80%			

365 days

Average Shrinkage (με)		60%	70%	80%
733	60%		Y	Y
550	70%			Y
397	80%			

"Y" indicates confidence level of 98% ($\alpha = 0.02$)
Confidence levels at but not exceeding 80%, 90% and 95% are indicated by "80", "90", and "95"
"N" indicates confidence level below 80% ($\alpha = 0.20$)

Table 3.4-Program I Student's t-test results for concretes with different aggregate contents at a constant water-cement ratio of 0.45 and containing Type I/II cement, 30, 180, and 365 days after casting.

30 days

Average Shrinkage (με)		60%	70%	80%
387	60%		95	Y
330	70%			90
283	80%			

180 days

Average Shrinkage (με)		60%	70%	80%
600	60%		95	Y
535	70%			Y
377	80%			

365 days

Average Shrinkage (με)		60%	70%	80%
630	60%		90	Y
557	70%			Y
377	80%			

"Y" indicates confidence level of 98% ($\alpha = 0.02$)
Confidence levels at but not exceeding 80%, 90% and 95% are indicated by "80", "90", and "95"
"N" indicates confidence level below 80% ($\alpha = 0.20$)

Table 3.5-Program I Student's t-test results for concretes with different aggregate contents at a constant water-cement ratio of 0.50 and containing Type I/II cement, 30, 180, and 365 days after casting.

30 days

Average Shrinkage (με)		60%	70%	80%
393	60%		Y	Y
313	70%			Y
237	80%			

180 days

Average Shrinkage (με)		60%	70%	80%
610	60%		Y	Y
503	70%			Y
344	80%			

365 days

Average Shrinkage (με)		60%	70%	80%
627	60%		Y	Y
497	70%			Y
343	80%			

"Y" indicates confidence level of 98% ($\alpha = 0.02$)
Confidence levels at but not exceeding 80%, 90% and 95% are indicated by "80", "90", and "95"
"N" indicates confidence level below 80% ($\alpha = 0.20$)

Table 3.6-Program I Student's t-test results for concretes with different aggregate contents at a constant water-cement ratio of 0.40 and containing Type II coarse-ground (CG) cement, 30, 180, and 365 days after casting.

30 days

Average Shrinkage (με)		60%	70%	80%
297	60%		90	Y
260	70%			90
217	80%			

180 days

Average Shrinkage (με)		60%	70%	80%
510	60%		Y	Y
370	70%			95
278	80%			

365 days

Average Shrinkage (με)		60%	70%	80%
527	60%		Y	Y
313	70%			N
263	80%			

"Y" indicates confidence level of 98% ($\alpha = 0.02$)
Confidence levels at but not exceeding 80%, 90% and 95% are indicated by "80", "90", and "95"
"N" indicates confidence level below 80% ($\alpha = 0.20$)

Table 3.7-Program I Student's t-test results for concretes with different aggregate contents at a constant water-cement ratio of 0.45 and containing Type II coarse-ground (CG) cement, 30, 180, and 365 days after casting.

30 days

Average Shrinkage ($\mu\varepsilon$)		60%	70%	80%
260	60%		N	Y
260	70%			95
217	80%			

180 days

Average Shrinkage ($\mu\varepsilon$)		60%	70%	80%
448	60%		95	Y
382	70%			95
292	80%			

365 days

Average Shrinkage ($\mu\varepsilon$)		60%	70%	80%
460	60%		90	Y
370	70%			80
287	80%			

"Y" indicates confidence level of 98% ($\alpha = 0.02$)
Confidence levels at but not exceeding 80%, 90% and 95% are indicated by "80", "90", and "95"
"N" indicates confidence level below 80% ($\alpha = 0.20$)

Table 3.8-Program I Student's t-test results for concretes with different aggregate contents at a constant water-cement ratio of 0.50 and containing Type II coarse-ground (CG) cement, 30, 180, and 365 days after casting.

30 days

Average Shrinkage (με)		60%	70%	80%
297	60%		N	Y
287	70%			Y
200	80%			

180 days

Average Shrinkage (με)		60%	70%	80%
481	60%		Y	Y
368	70%			95
305	80%			

365 days

Average Shrinkage (με)		60%	70%	80%
493	60%		Y	Y
317	70%			80
293	80%			

"Y" indicates confidence level of 98% ($\alpha = 0.02$)
Confidence levels at but not exceeding 80%, 90% and 95% are indicated by "80", "90", and "95"
"N" indicates confidence level below 80% ($\alpha = 0.20$)

Table 3.9-Summary of average free shrinkage data from Program II

Batch	**85**	**86**	**87**	**88**
Cement replacement	Control	30% slag	30% Class C Fly Ash	10% silica fume
Day[a]	**Average Shrinkage (με)**			
3	0	0	0	0
7	110	107	113	107
30	303	333	337	293
90	418	420	443	423
180	431	426	462	419
365	402	435	478	441

[a]Denotes days after casting

Table 3.10-Program II Student's t-test results for concrete containing Type I/II cement with mineral admixtures by volume replacement at 30, 180, and 365 days after casting.

30 days

Average Shrinkage (με)		Control	Slag	Fly Ash	Silica Fume
303	Control		90	95	N
333	Slag			N	Y
337	Fly Ash				Y
293	Silica Fume				

180 days

Average Shrinkage (με)		Control	Slag	Fly Ash	Silica Fume
431	Control		N	95	N
426	Slag			95	N
462	Fly Ash				Y
419	Silica Fume				

365 days

Average Shrinkage (με)		Control	Slag	Fly Ash	Silica Fume
402	Control		80	Y	80
435	Slag			90	N
478	Fly Ash				80
441	Silica Fume				

"Y" indicates confidence level of 98% ($\alpha = 0.02$)
Confidence levels at but not exceeding 80%, 90% and 95% are indicated by "80", "90", and "95"
"N" indicates confidence level below 80% ($\alpha = 0.20$)

Table 3.11-Summary of average free shrinkage data from Program III

Batch	**94**	**95**	**138**	**159**
Aggregate Type	Quartzite	Limestone	Limestone	Quartzite
% aggregate[a]	70	70	69.5	67.5
% air content[b]	1 ½	1 ½	6 ½	8 ½
Day[c]	**Average Shrinkage (με)**			
3	0	0	-37	-20
7	80	80	63	87
30	173	227	313	323
90	314	378	402	433
180	307	387	420	464
365	333	407	413	430

[a]Percent by volume
[b]Assumed value
[c]Denotes days after casting

Table 3.12-Program III Student's t-test results for non-air-entrained concrete containing different aggregate types 30, 180, and 365 days after casting.

30 days

Average Shrinkage (με)		Limestone (95)	Quartzite (94)
227	Limestone (95)		Y
173	Quartzite (94)		

180 days

Average Shrinkage (με)		Limestone (95)	Quartzite (94)
387	Limestone (95)		95
307	Quartzite (94)		

365 days

Average Shrinkage (με)		Limestone (95)	Quartzite (94)
407	Limestone (95)		Y
333	Quartzite (94)		

Batch number in parentheses
"Y" indicates confidence level of 98% ($\alpha = 0.02$)
Confidence levels at but not exceeding 80%, 90% and 95% are indicated by "80", "90", and "95"
"N" indicates confidence level below 80% ($\alpha = 0.20$)

Table 3.13- Program III Student's t-test results for air-entrained concrete containing different aggregate types 30, 180, and 365 days after casting.

30 days

Average Shrinkage (με)		Limestone (138)	Quartzite (159)
313	Limestone (138)		N
323	Quartzite (159)		

180 days

Average Shrinkage (με)		Limestone (138)	Quartzite (159)
420	Limestone (138)		80
464	Quartzite (159)		

365 days

Average Shrinkage (με)		Limestone (138)	Quartzite (159)
413	Limestone (138)		N
430	Quartzite (159)		

Batch number in parentheses
"Y" indicates confidence level of 98% ($\alpha = 0.02$)
Confidence levels at but not exceeding 80%, 90% and 95% are indicated by "80", "90", and "95"
"N" indicates confidence level below 80% ($\alpha = 0.20$)

Table 3.14a-Summary of average free shrinkage data from Program IV-non-air-entrained concrete.

Batch	165-3d	165-7d	165-14d	165-28d	166-3d	166-7d	166-14d	166-28d
Cement type	I/II	I/II	I/II	I/II	II CG	II CG	II CG	II CG
Cure (days)	3	7	14	28	3	7	14	28
Day[a]	**Average Shrinkage (με)**							
3	0	0	0	0	0	0	0	0
7	83	-3	-30	-43	57	-7	-13	-37
14	217	180	0	-17	173	93	-13	-60
28	287	270	143	-33	267	243	180	-33
30	293	270	157	0	313	250	193	60
90	473	492	463	370	473	423	363	323
180	547	586	533	471	557	513	457	417
300	518	566	516	462	522	492	442	404

[a]Denotes days after casting

Table 3.14b-Summary of average free shrinkage data from Program IV-air-entrained concrete.

Batch	138	140	143
Cement type	I/II	I/II	I/II
Cure (days)	3	7	14
Day[a]	**Average Shrinkage (με)**		
3	-37	-7	-6
7	63	-20	-17
14	190	110	-37
28	280	240	163
30	313	260	193
90	402	400	343
180	420	425	402
300	387	425	390

[a]Denotes days after casting

Table 3.15a-Summary of average free shrinkage data from Program IV based on drying period-non-air-entrained concrete.

Batch	**165-3d**	**165-7d**	**165-14d**	**165-28d**	**166-3d**	**166-7d**	**166-14d**	**166-28d**
Cement type	I/II	I/II	I/II	I/II	II CG	II CG	II CG	II CG
Cure (days)	3	7	14	28	3	7	14	28
Day[b]	**Average Shrinkage (με)**							
3	53	70	63	87	57	40	-17	17
7	140	180	63	110	103	93	67	60
30	333	337	320	227	302	270	237	193
90	480	487	480	423	472	437	404	388
180	543	583	529	465	556	513	457	411
300	540	573	532	466	537	505	458	415

[b]Denotes days after drying period begins

Table 3.15b-Summary of average free shrinkage data from Program IV based on drying period-air-entrained concrete.

Batch	**138**	**140**	**143**
Cement type	I/II	I/II	I/II
Cure (days)	3	7	14
Day[b]	**Average Shrinkage (με)**		
3	40	55	17
7	130	110	80
30	313	290	253
90	393	420	382
180	420	425	408
300	387	425	391

[b]Denotes days after drying period begins

Table 3.16-Program IV Student's t-test results (Batch 165) for different curing period for non-air-entrained concrete containing Type I/II cement for different drying periods.

30 days

Average Shrinkage (με)		3 day	7 day	14 day	28 day
333	3 day		N	N	Y
337	7 day			N	Y
320	14 day				Y
227	28 day				

180 days

Average Shrinkage (με)		3 day	7 day	14 day	28 day
543	3 day		80	N	95
583	7 day			90	Y
529	14 day				90
465	28 day				

300 days

Average Shrinkage (με)		3 day	7 day	14 day	28 day
515	3 day		90	N	Y
564	7 day			95	Y
506	14 day				Y
443	28 day				

"Y" indicates confidence level of 98% ($\alpha = 0.02$)
Confidence levels at but not exceeding 80%, 90% and 95% are indicated by "80", "90", and "95"
"N" indicates confidence level below 80% ($\alpha = 0.20$)

Table 3.17-Program IV Student's t-test results (Batch 166) for different curing period for non-air-entrained concrete containing Type II coarse-ground cement for different drying periods.

30 days

Average Shrinkage (με)		3 day	7 day	14 day	28 day
302	3 day		N	90	Y
270	7 day			N	90
237	14 day				Y
193	28 day				

180 days

Average Shrinkage (με)		3 day	7 day	14 day	28 day
556	3 day		N	95	Y
513	7 day			80	95
457	14 day				Y
411	28 day				

300 days

Average Shrinkage (με)		3 day	7 day	14 day	28 day
520	3 day		N	90	95
487	7 day			80	Y
433	14 day				95
376	28 day				

"Y" indicates confidence level of 98% ($\alpha = 0.02$)
Confidence levels at but not exceeding 80%, 90% and 95% are indicated by "80", "90", and "95"
"N" indicates confidence level below 80% ($\alpha = 0.20$)

Table 3.18-Program IV Student's t-test results (Batch 165 and 166) comparing cement type with curing period for different drying periods of non-air-entrained concrete.

30 days

			Type I/II cement (Batch 165)			
			Average shrinkage (με)			
	Average shrinkage (με)		333	337	320	227
			3 day	7 day	14 day	28 day
Type II CG cement (Batch 166)	302	3 day	N			
	270	7 day		90		
	237	14 day			Y	
	193	28 day				90

180 days

			Type I/II cement (Batch 165)			
			Average shrinkage (με)			
	Average shrinkage (με)		543	583	529	465
			3 day	7 day	14 day	28 day
Type II CG cement (Batch 166)	556	3 day	N			
	513	7 day		80		
	457	14 day			Y	
	411	28 day				95

"Y" indicates confidence level of 98% ($\alpha = 0.02$)
Confidence levels at but not exceeding 80%, 90% and 95% are indicated by "80", "90", and "95"
"N" indicates confidence level below 80% ($\alpha = 0.20$)

Table 3.18 continued- Program IV Student's t-test results (Batch 165 and 166) comparing cement type with curing period for different drying periods of non-air-entrained concrete.

300 days

			Type I/II cement (Batch 165)			
			Average shrinkage (με)			
	Average shrinkage (με)		515	564	506	443
			3 day	7 day	14 day	28 day
Type II CG cement (Batch 166)	520	3 day	N			
	487	7 day		90		
	433	14 day			Y	
	376	28 day				Y

"Y" indicates confidence level of 98% (α = 0.02)
Confidence levels at but not exceeding 80%, 90% and 95% are indicated by "80", "90", and "95"
"N" indicates confidence level below 80% (α = 0.20)

Table 3.19-Program IV Student's t-test results for different curing period for air-entrained concrete containing Type I/II cement for different drying periods.

30 days

Average Shrinkage (με)		(Batch 138) 3 day	(Batch 140) 7 day	(Batch 143) 14 day
313	3 day		N	95
290	7 day			Y
253	14 day			

180 days

Average Shrinkage (με)		(Batch 138) 3 day	(Batch 140) 7 day	(Batch 143) 14 day
420	3 day		N	N
425	7 day			N
408	14 day			

300 days

Average Shrinkage (με)		(Batch 138) 3 day	(Batch 140) 7 day	(Batch 143) 14 day
387	3 day		80	N
425	7 day			90
391	14 day			

"Y" indicates confidence level of 98% ($\alpha = 0.02$)
Confidence levels at but not exceeding 80%, 90% and 95% are indicated by "80", "90", and "95"
"N" indicates confidence level below 80% ($\alpha = 0.20$)

Table 3.20a-Summary of average free shrinkage data (Glenium) from Program V.

Batch	167	168	169	170	174
Superplasticizer type	Control	Glenium 3000NS	Glenium 3000NS	Glenium 3000NS	Glenium 3000NS
Dosage range	None	Low	Medium	High	High
Day[a]	**Average Shrinkage (με)**				
3	0	0	0	0	0
7	53	60	30	23	117
30	237	267	280	193	233
90	387	393	333	310	437
180	457	460	434	357	480
300	434	453	397	317	473

Batch was 174 was a repeat batch of 170. Batch 170 was cast to early.
[a]Denotes days after casting

Table 3.20b-Summary of average free shrinkage data (Rheobuild) from Program V.

Batch	167	171	172	173
Superplasticizer type	Control	Rheobuild 1000	Rheobuild 1000	Rheobuild 1000
Dosage range	None	Low	Medium	High
Day[a]	**Average Shrinkage (με)**			
3	0	0	0	0
7	53	97	100	127
30	237	210	217	260
90	387	397	407	457
180	457	467	457	513
300	434	453	457	503

[a]Denotes days after casting

Table 3.21-Program V Student's t-test results for concrete containing Glenium 3000NS for different dosage rates, 30, 180, and 300 days after casting.

30 days

Average Shrinkage (με)		Control	Low	Medium	High
237	Control		N	N	N
267	Low			N	N
280	Medium				N
233	High				

180 days

Average Shrinkage (με)		Control	Low	Medium	High
457	Control		N	N	N
460	Low			N	N
434	Medium				N
480	High				

300 days

Average Shrinkage (με)		Control	Low	Medium	High
434	Control		90	N	90
453	Low			80	N
397	Medium				80
473	High				

"Y" indicates confidence level of 98% ($\alpha = 0.02$)
Confidence levels at but not exceeding 80%, 90% and 95% are indicated by "80", "90", and "95"
"N" indicates confidence level below 80% ($\alpha = 0.20$)
Batch 174 is used as "High" batch

Table 3.22-Program V Student's t-test results for concrete containing Rheobuild 1000 for different dosage rates, 30, 180, and 300 days after casting.

30 days

Average Shrinkage (με)		Control	Low	Medium	High
237	Control		80	N	N
210	Low			N	Y
217	Medium				95
260	High				

180 days

Average Shrinkage (με)		Control	Low	Medium	High
457	Control		N	N	95
467	Low			N	90
457	Medium				90
513	High				

300 days

Average Shrinkage (με)		Control	Low	Medium	High
434	Control		80	N	Y
453	Low			N	90
457	Medium				80
503	High				

"Y" indicates confidence level of 98% ($\alpha = 0.02$)
Confidence levels at but not exceeding 80%, 90% and 95% are indicated by "80", "90", and "95"
"N" indicates confidence level below 80% ($\alpha = 0.20$)

Table 3.23-Summary of average free shrinkage data from Program VI.

Batch	**81**	**82**	**83**	**84**
Description	Control	Type II CG	MoDOT	KDOT
Day[a]	**Average Shrinkage (με)**			
3	-30	-43	-37	-33
7	113	57	83	107
30	387	257	350	340
90	455	343	437	440
180	484	381	461	457
365	513	417	480	520

[a]Denotes days after casting

Table 3.24-Program VI Student's t-test results for bridge deck mixes, 30, 180, and 365 days after casting.

30 days

Average Shrinkage (με)		Control	MoDOT	KDOT	Type II CG
387	Control		95	Y	Y
350	MoDOT			N	Y
340	KDOT				Y
257	Type II CG				

180 days

Average Shrinkage (με)		Control	MoDOT	KDOT	Type II CG
484	Control		80	90	Y
461	MoDOT			N	Y
457	KDOT				Y
381	Type II CG				

365 days

Average Shrinkage (με)		Control	MoDOT	KDOT	Type II CG
513	Control		Y	N	Y
480	MoDOT			95	Y
520	KDOT				Y
417	Type II CG				

"Y" indicates confidence level of 98% ($\alpha = 0.02$)
Confidence levels at but not exceeding 80%, 90% and 95% are indicated by "80", "90", and "95"
"N" indicates confidence level below 80% ($\alpha = 0.20$)

Table 3.25-Summary of average free shrinkage data from Program VII.

Batch	**138**	**145**	**132**	**130**	**147**	**149**
Description	Control	Type II CG	MoDOT	KDOT	SRA	Reduced cement
Day[a]	**Average Shrinkage (με)**					
3	-37	-3	0	10	-10	7
7	63	123	113	157	33	100
30	313	313	357	413	143	320
90	402	408	490	533	242	407
180	420	461	518	584	290	440
365	413	420	505	536	280	393

[a]Denotes days after casting

Table 3.26-Program VII Student's t-test results for bridge deck mixes, 30, 180, and 365 days after casting.

30 days

Average Shrinkage (με)		KDOT	MoDOT	497 lb/yd³	Type II CG	Control	SRA
413	KDOT		Y	Y	Y	Y	Y
357	MoDOT			80	Y	80	Y
320	497 lb/yd³				N	N	Y
313	Type II CG					N	Y
313	Control						Y
143	SRA						

180 days

Average Shrinkage (με)		KDOT	MoDOT	497 lb/yd³	Type II CG	Control	SRA
584	KDOT		Y	Y	Y	Y	Y
518	MoDOT			Y	Y	Y	Y
440	497 lb/yd³				N	N	Y
461	Type II CG					80	Y
420	Control						Y
290	SRA						

365 days

Average Shrinkage (με)		KDOT	MoDOT	497 lb/yd³	Type II CG	Control	SRA
536	KDOT		80	Y	Y	Y	Y
505	MoDOT			Y	Y	Y	Y
393	497 lb/yd³				Y	Y	Y
420	Type II CG					N	Y
413	Control						Y
280	SRA						

"Y" indicates confidence level of 98% (α = 0.02)
Confidence levels at but not exceeding 80%, 90% and 95% are indicated by "80", "90", and "95"
"N" indicates confidence level below 80% (α = 0.20)

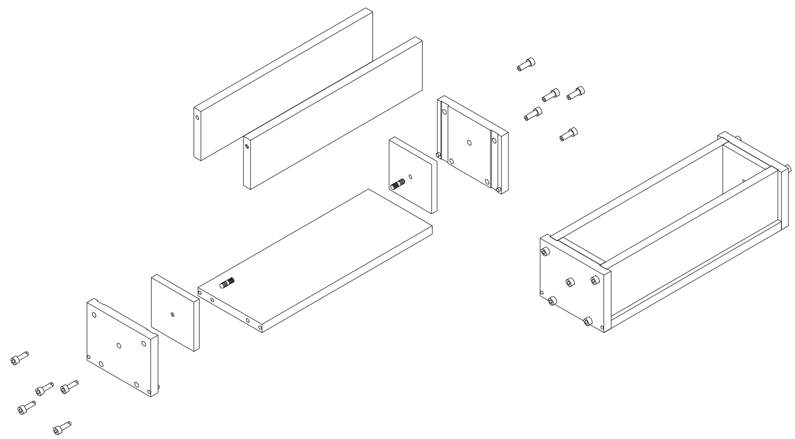

Figure 2.1 – Free Shrinkage Specimen Mold (Tritsch, Darwin, Browning 2005)

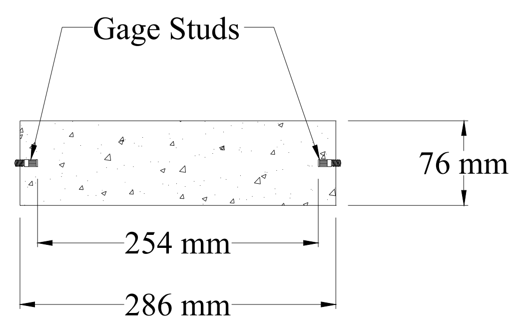

Figure 2.2 – Cross-section of Free Shrinkage Specimen (Tritsch, Darwin, Browning 2005)

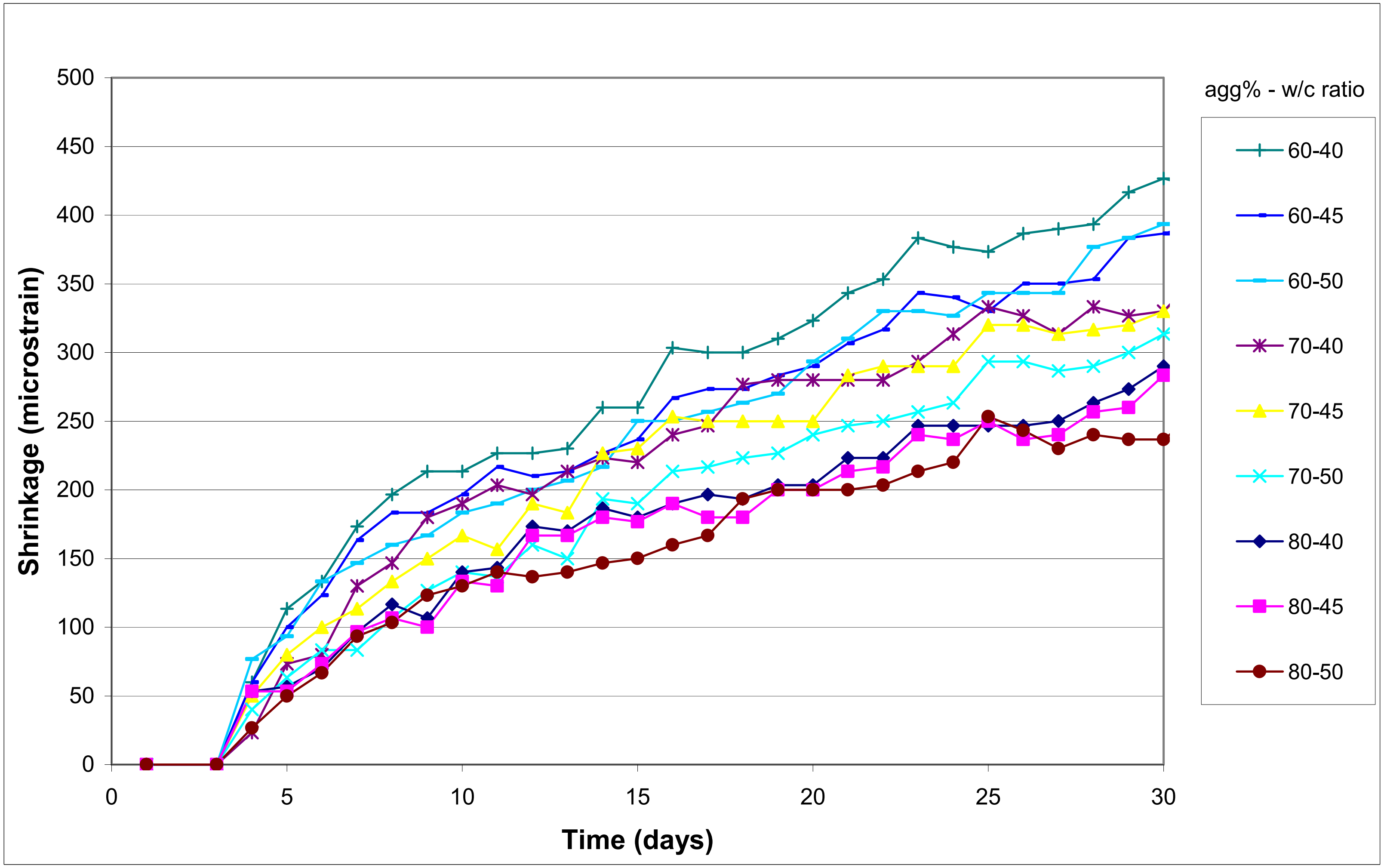

Figure 3.1 - Free Shrinkage Test, Program I. Average free shrinkage vs. time through 30 days. Type I/II Cement.

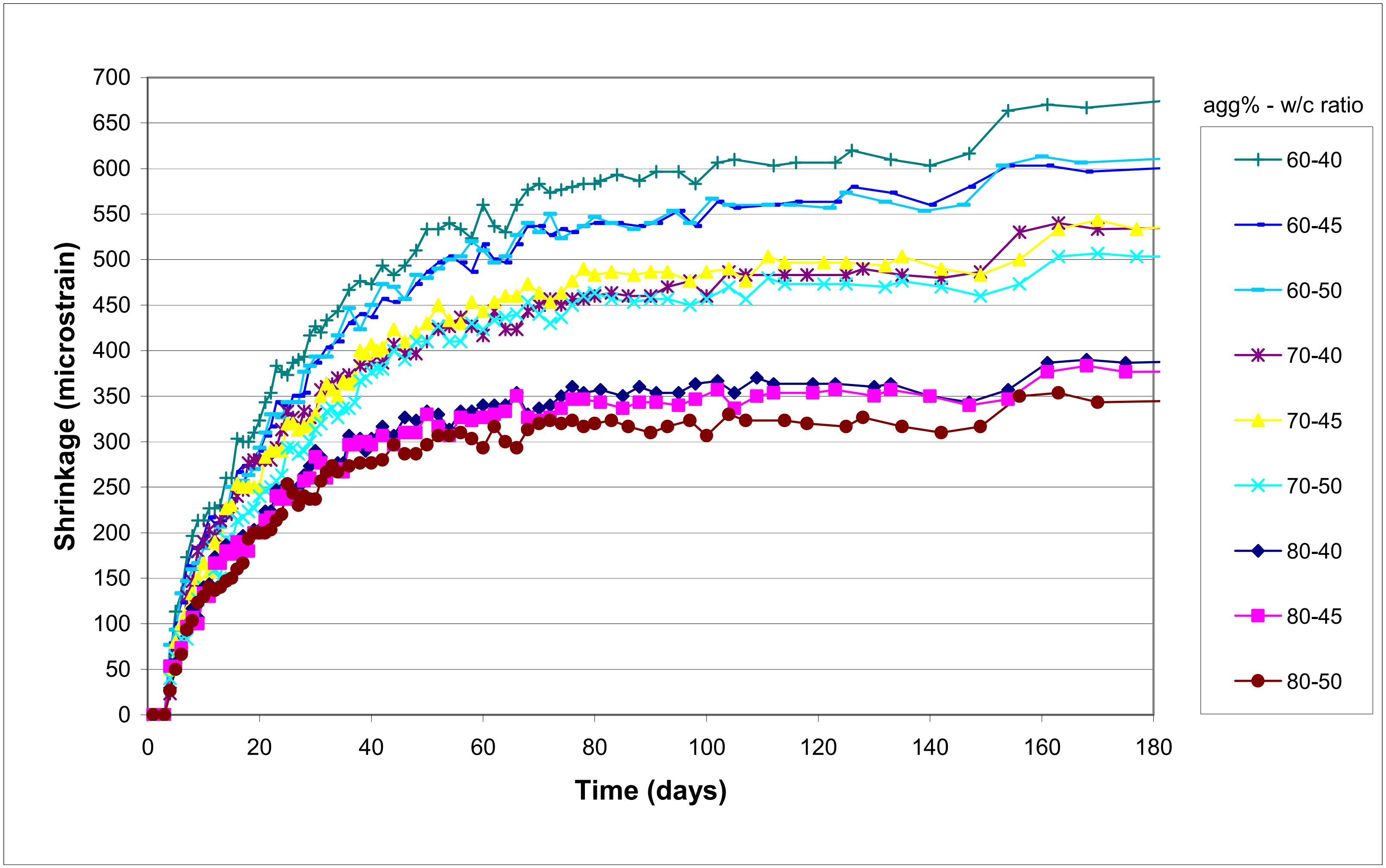

Figure 3.2 - Free Shrinkage Test, Program I. Average free shrinkage vs. time through 180 days. Type I/II Cement.

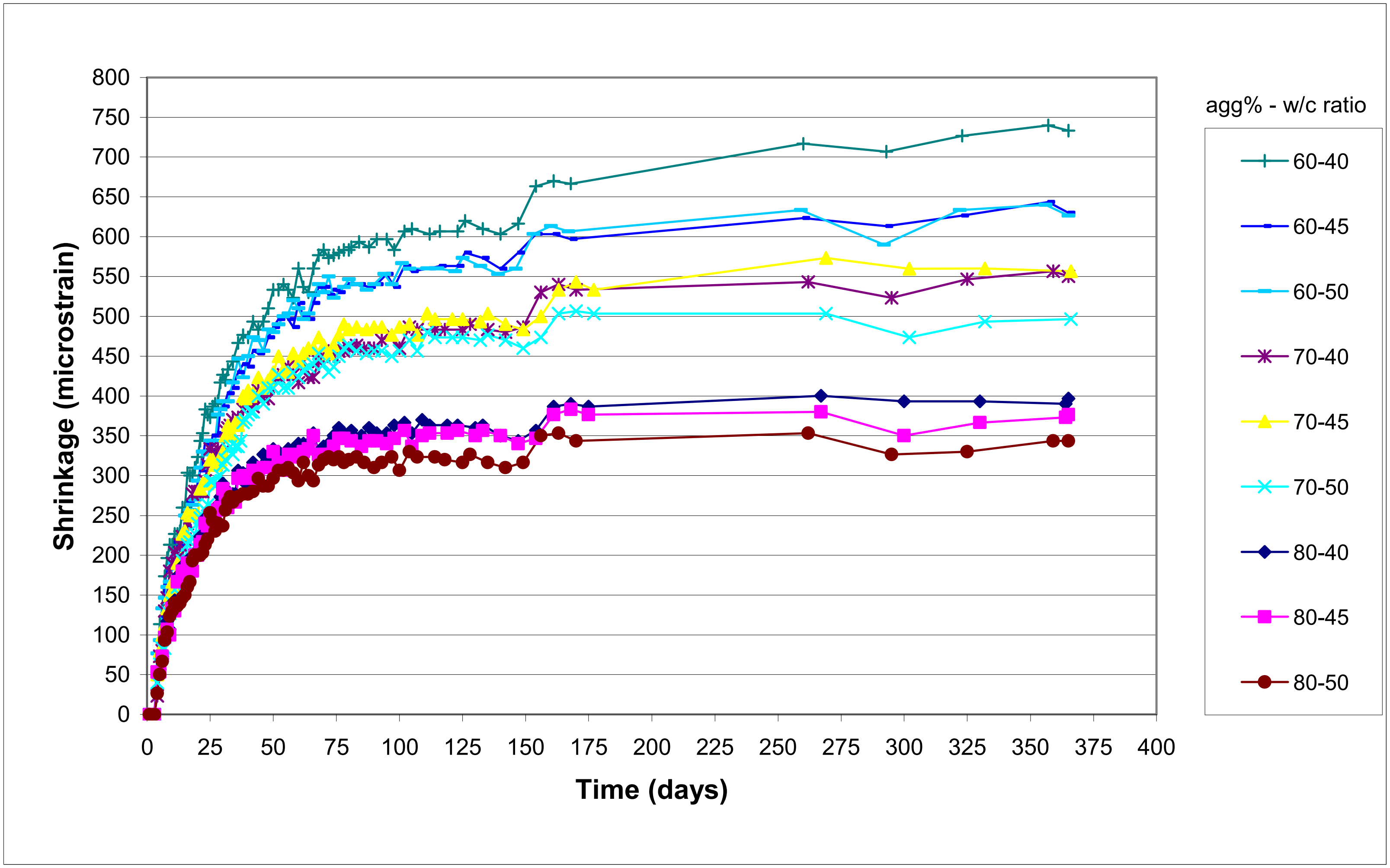

Figure 3.3 - Free Shrinkage Test, Program I. Average free shrinkage vs. time through 365 days. Type I/II Cement.

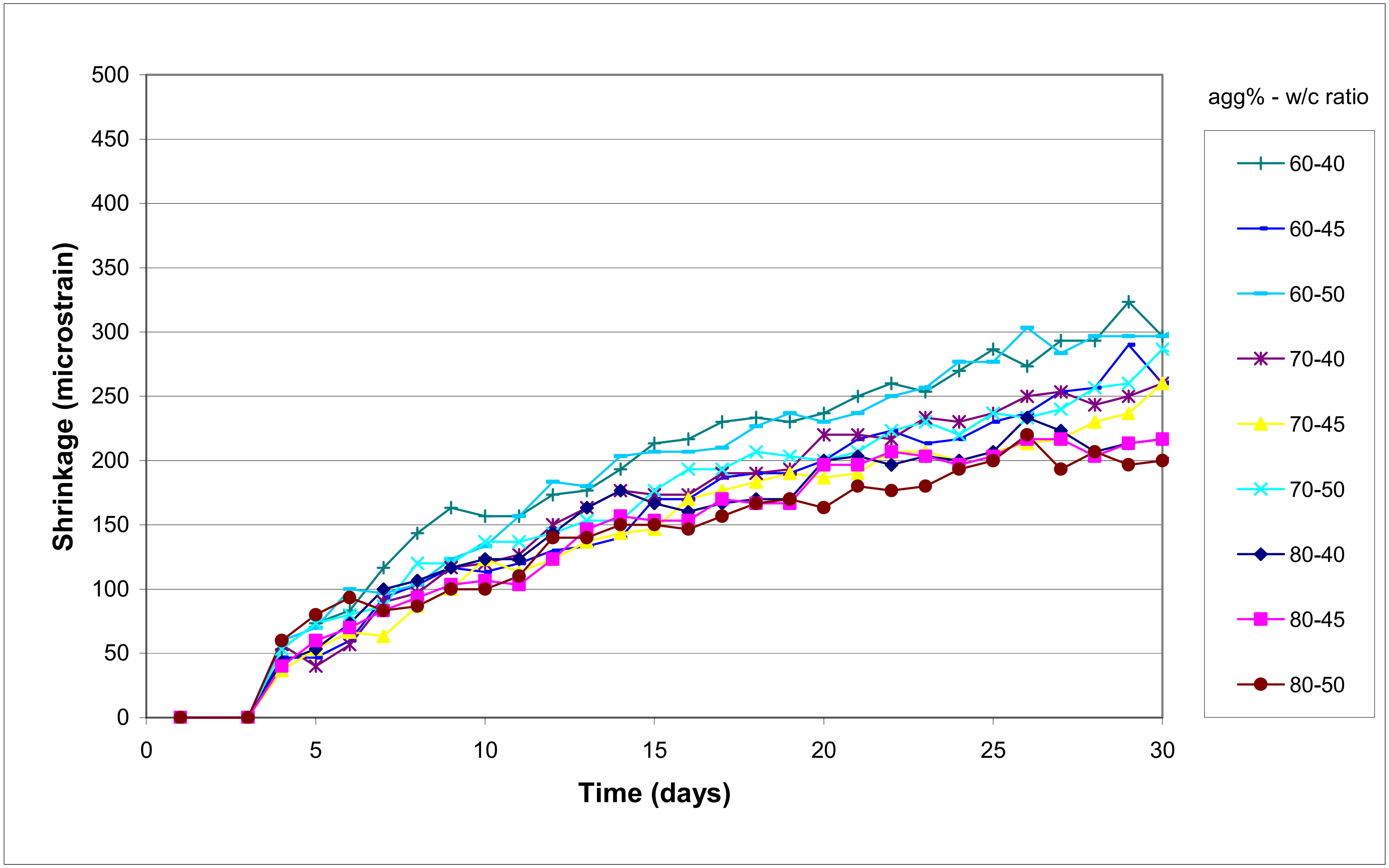

Figure 3.4 - Free Shrinkage Test, Program I. Average free shrinkage vs. time through 30 days. Type II Coarse-Ground Cement.

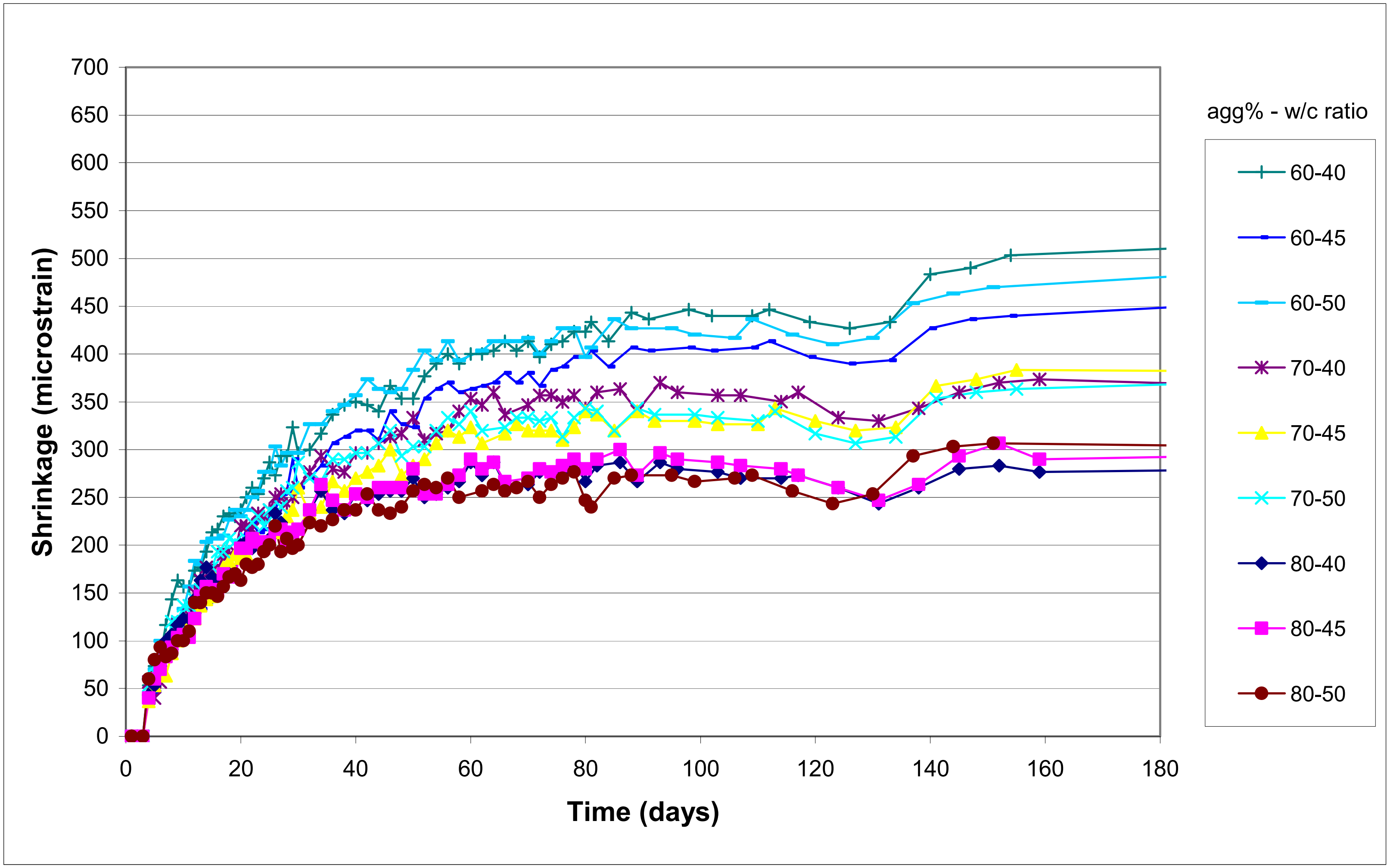

Figure 3.5 - Free Shrinkage Test, Program I. Average free shrinkage vs. time through 180 days. Type II Coarse-Ground Cement.

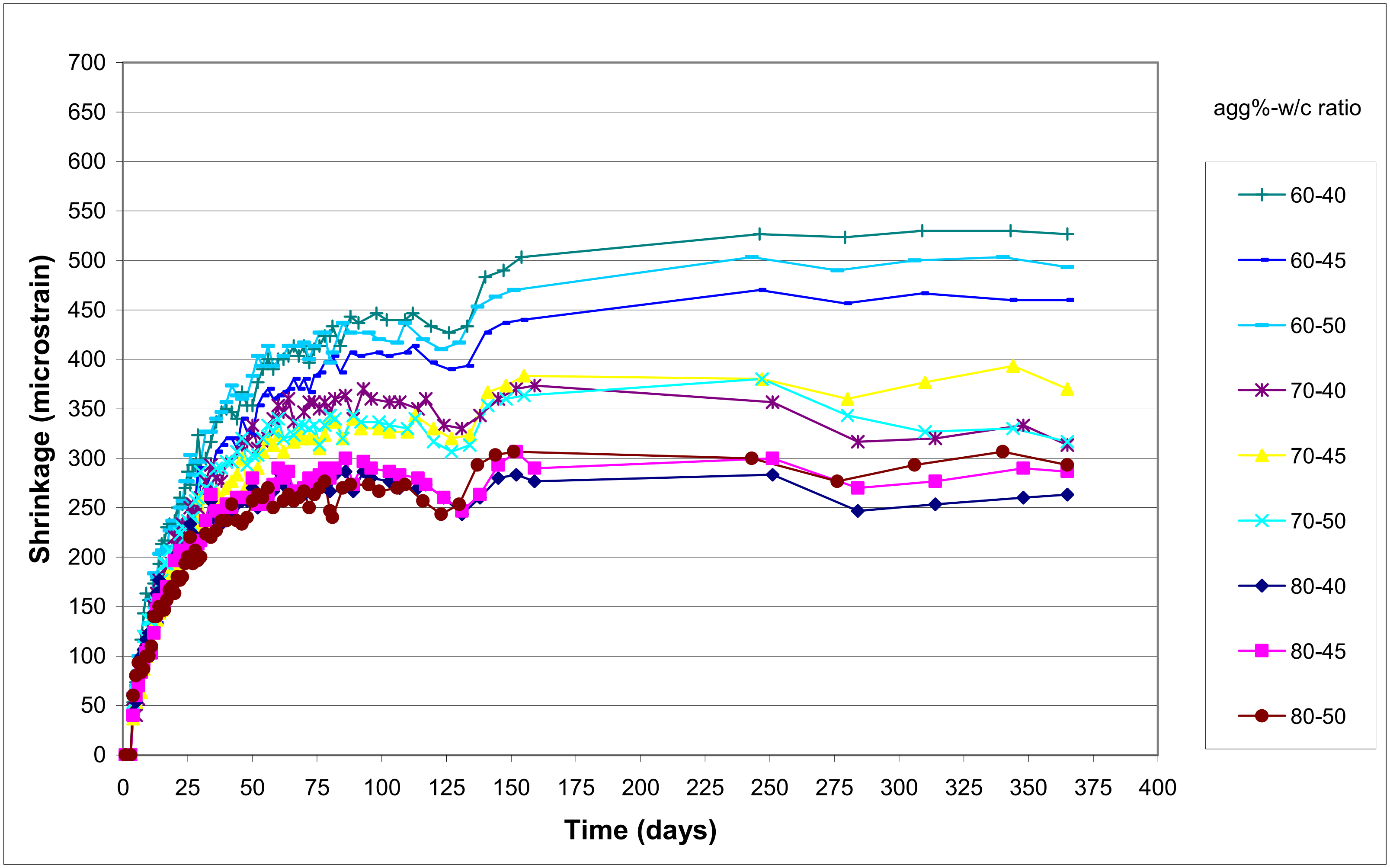

Figure 3.6 - Free Shrinkage Test, Program I. Average free shrinkage vs. time through 365 days. Type **II** Coarse-Ground Cement.

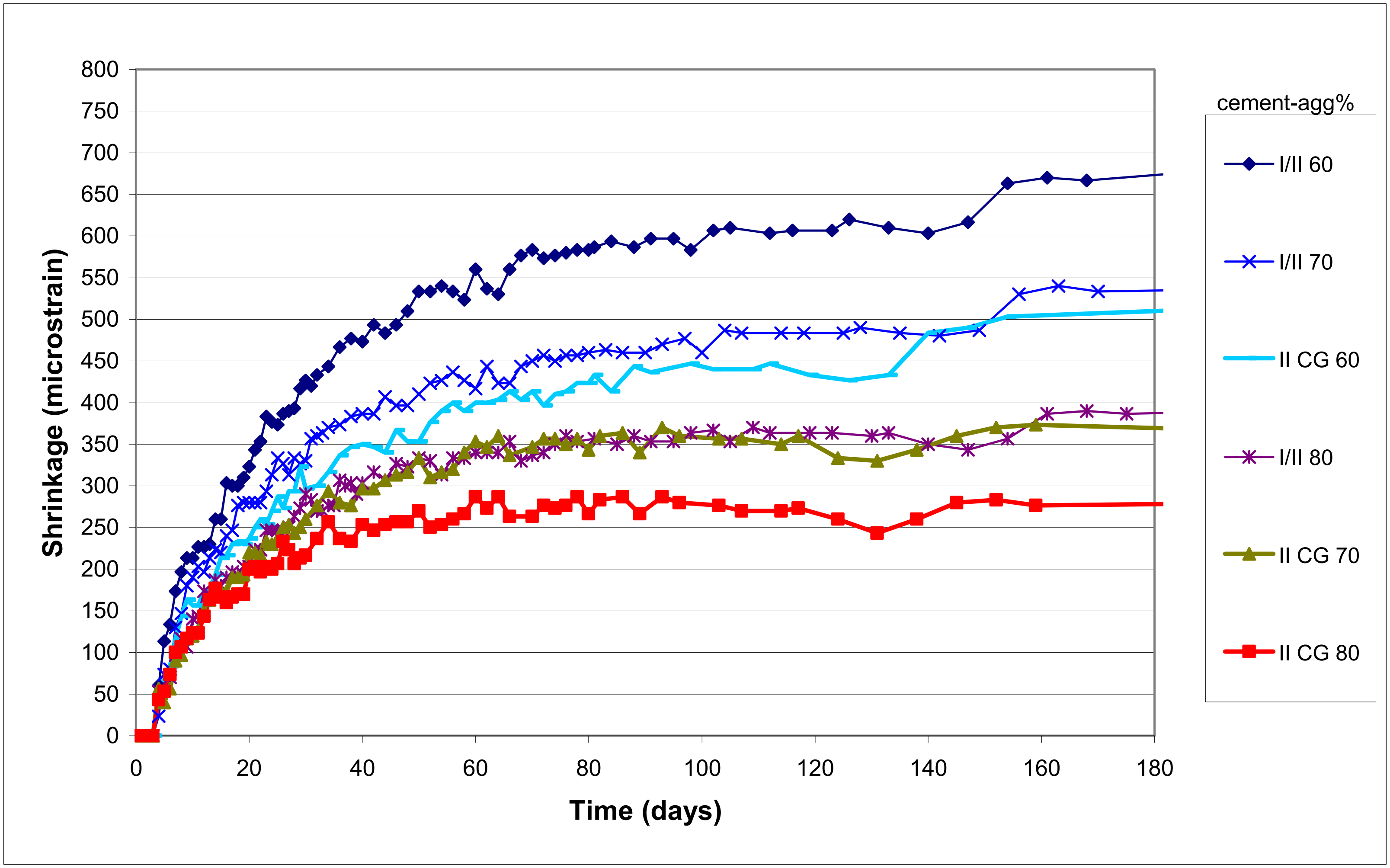

Figure 3.7 - Free Shrinkage Test, Program I. Average free shrinkage vs. time through 180 days. Type I/II and Type II Coarse-Ground Cement. w/c ratio = 0.40.

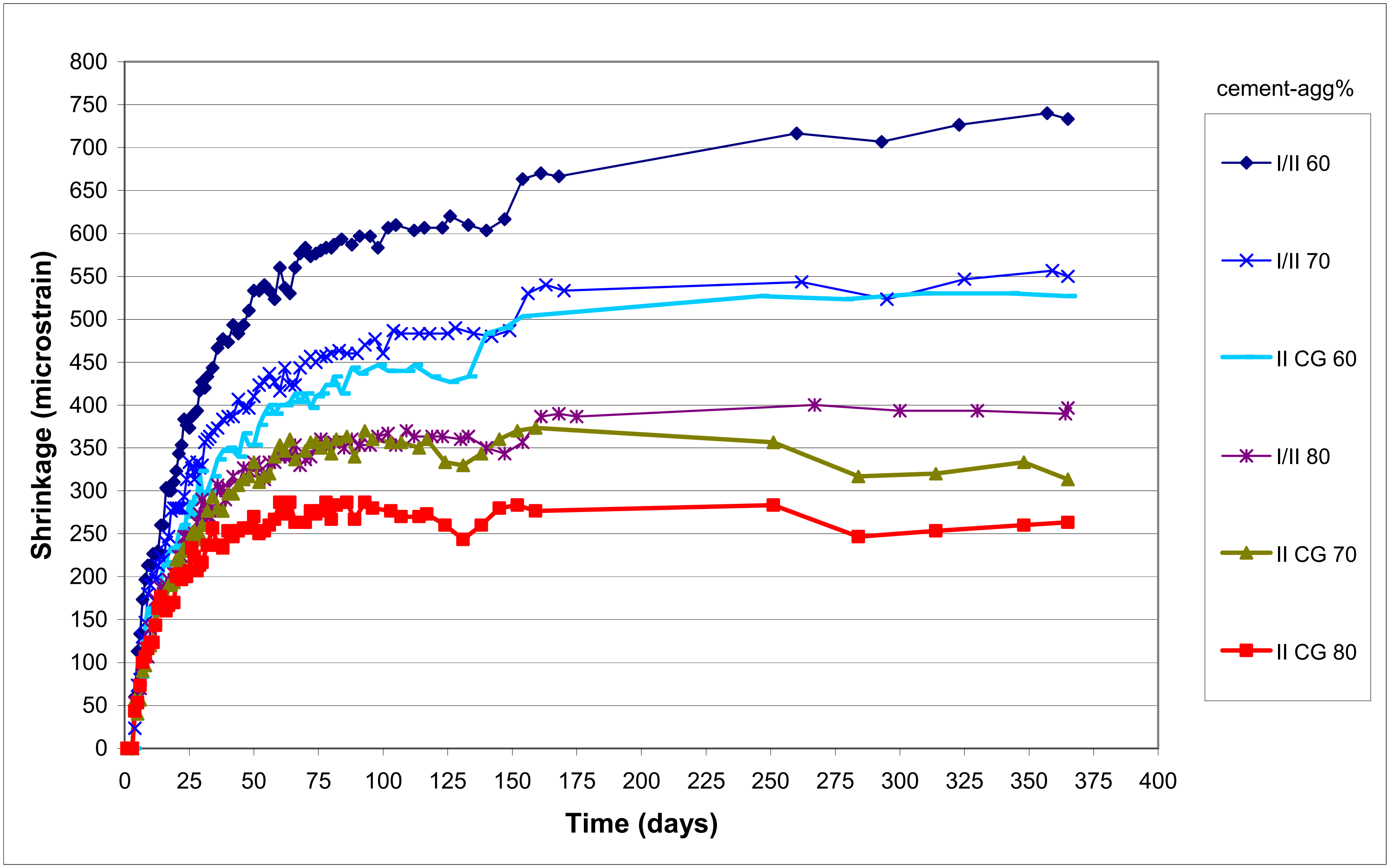

Figure 3.8 - Free Shrinkage Test, Program I. Average free shrinkage vs. time through 365 days. Type I/II and Type II Coarse-Ground Cement. w/c ratio = 0.40.

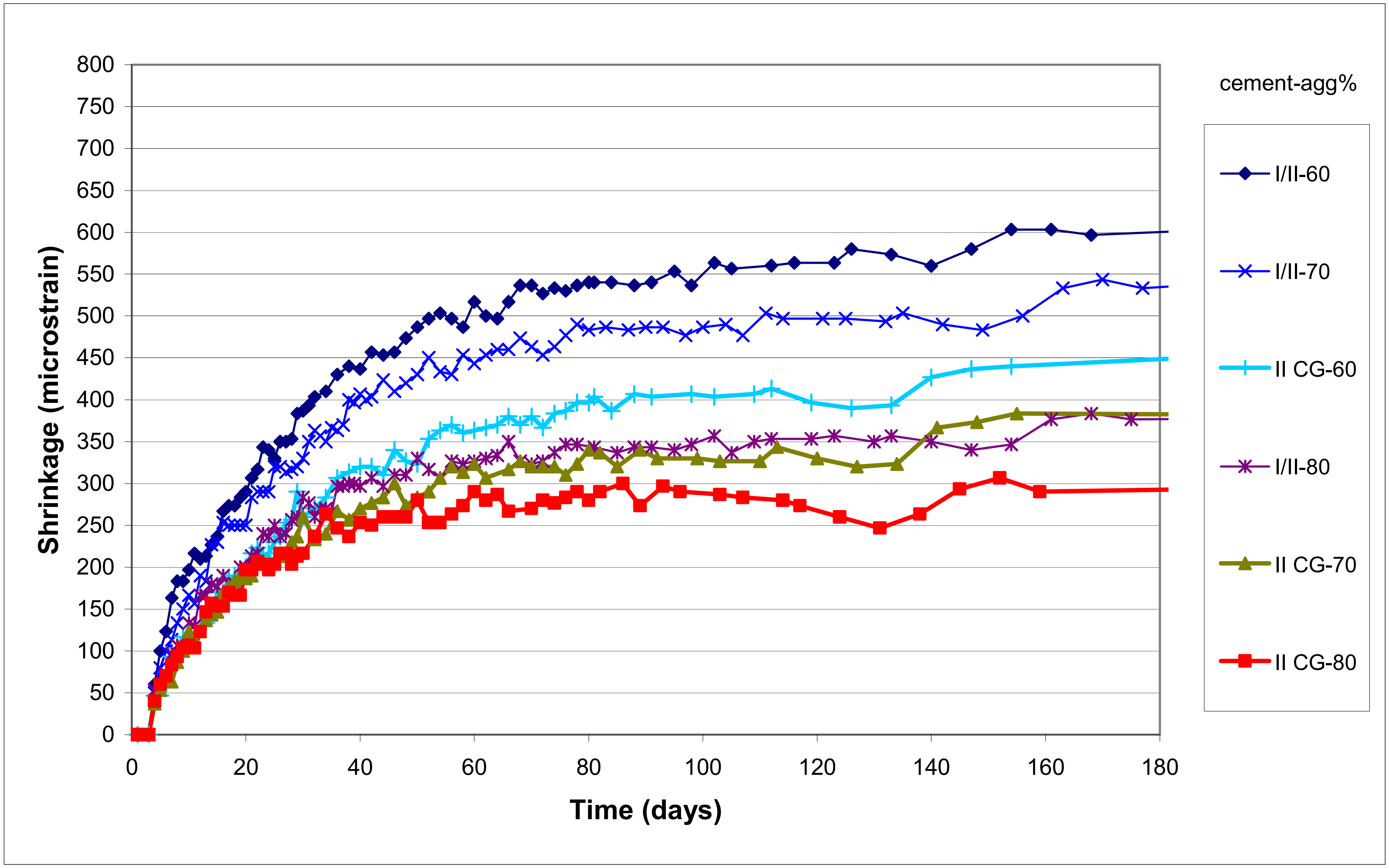

Figure 3.9 - Free Shrinkage Test, Program I. Average free shrinkage vs. time through 180 days. Type I/II and Type II Coarse-Ground Cement. w/c ratio = 0.45.

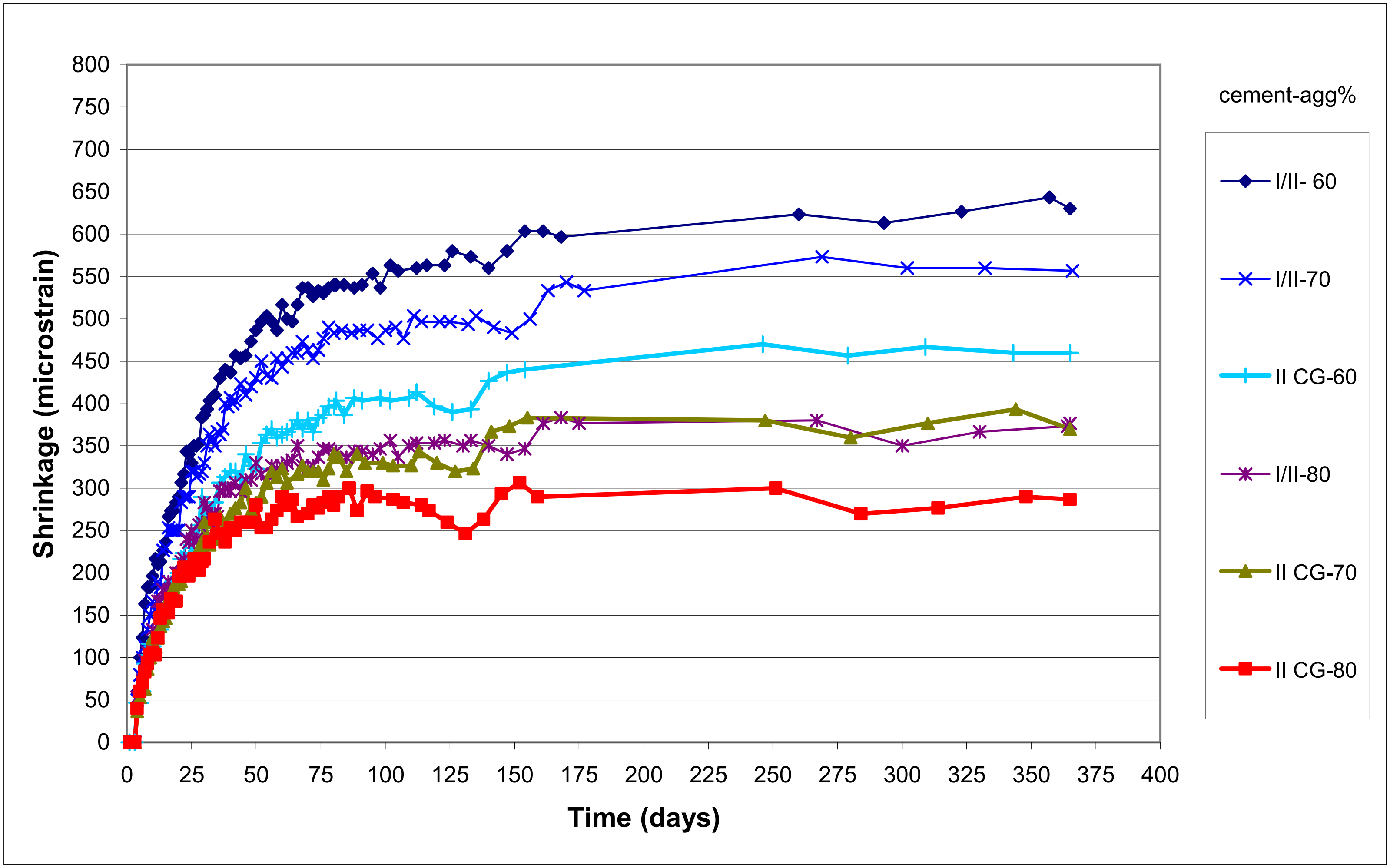

Figure 3.10 - Free Shrinkage Test, Program I. Average free shrinkage vs. time through 365 days. Type I/II and Type II Coarse-Ground Cement. w/c ratio = 0.45.

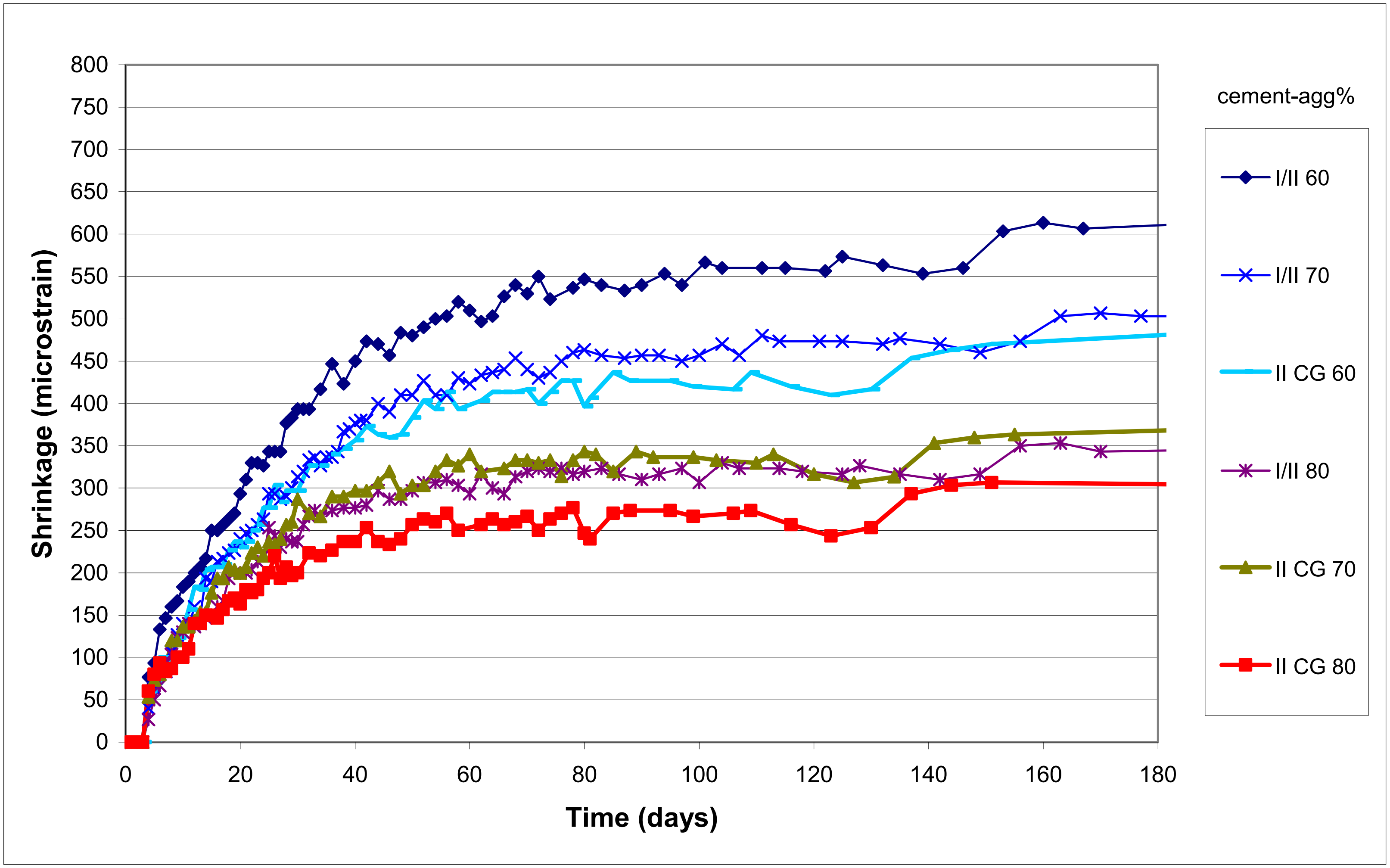

Figure 3.11 - Free Shrinkage Test, Program I. Average free shrinkage vs. time through 180 days. Type I/II and Type II Coarse-Ground Cement. w/c ratio = 0.50.

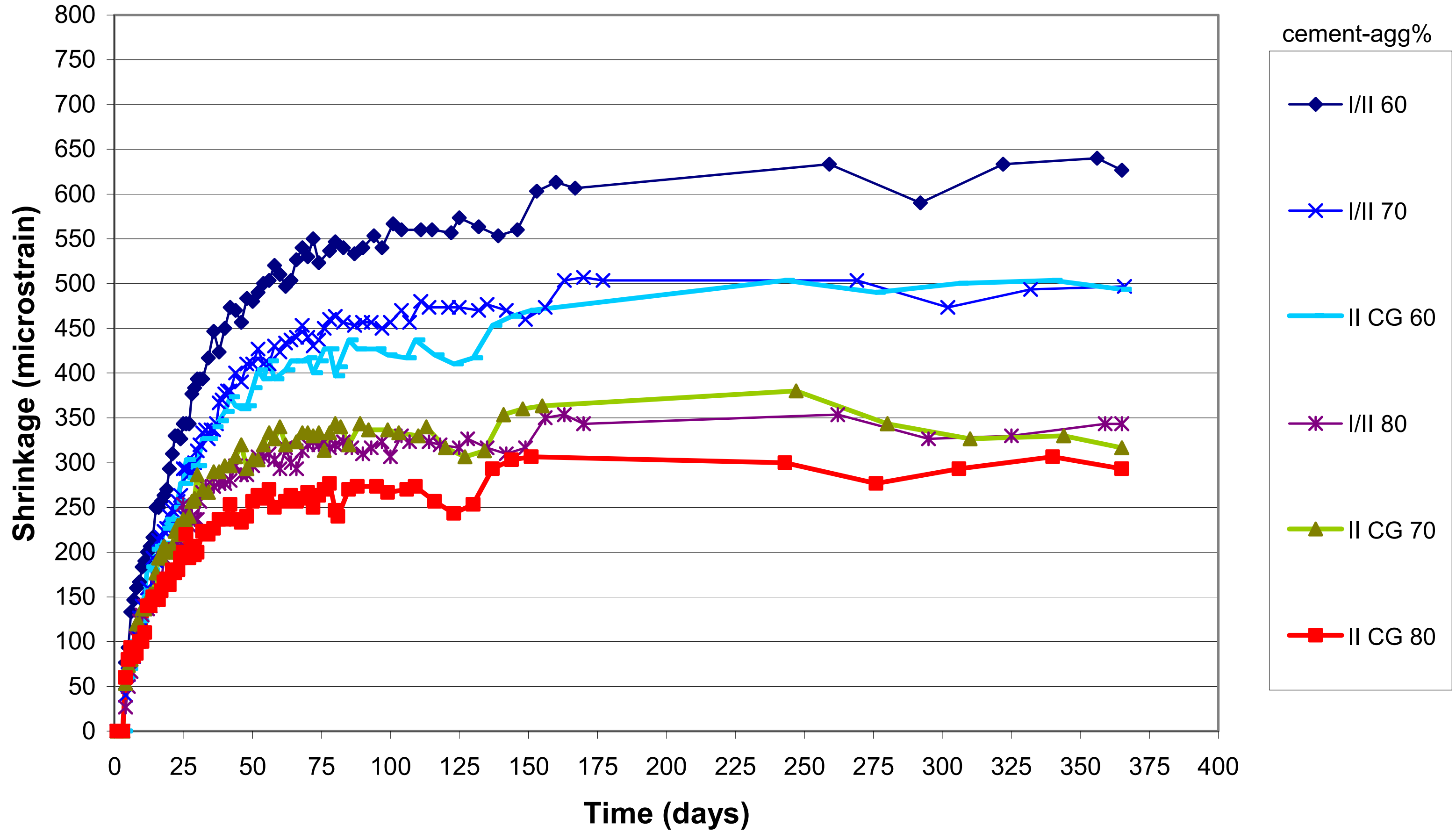

Figure 3.12 - Free Shrinkage Test, Program I. Average free shrinkage vs. time through 365 days. Type I/II and Type II Coarse-Ground Cement. w/c ratio = 0.50.

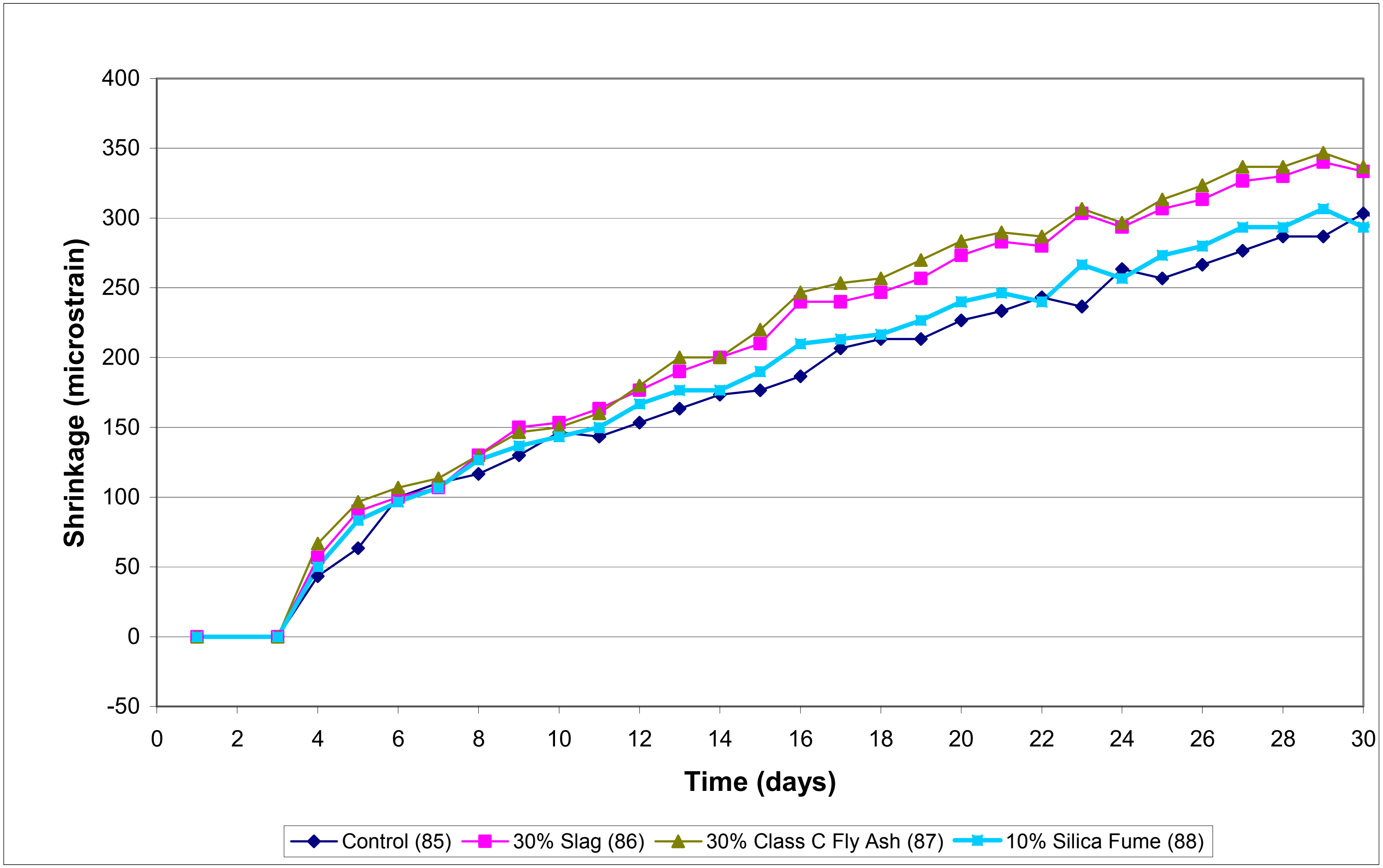

Figure 3.13 - Free Shrinkage Test, Program II. Average free shrinkage vs. time through 30 days. Comparing mineral admixtures.

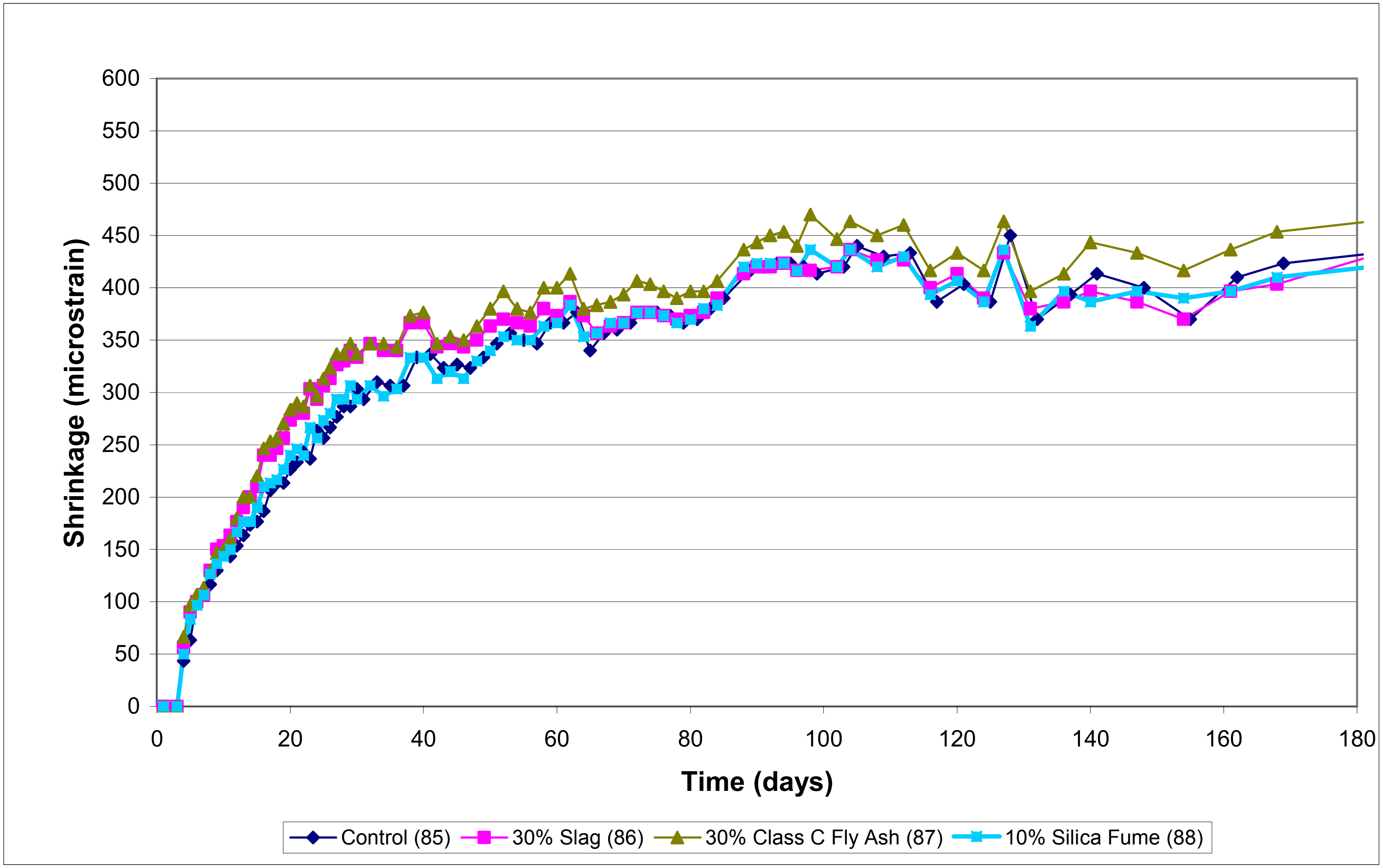

Figure 3.14 - Free Shrinkage Test, Program II. Average free shrinkage vs. time through 180 days. Comparing mineral admixtures.

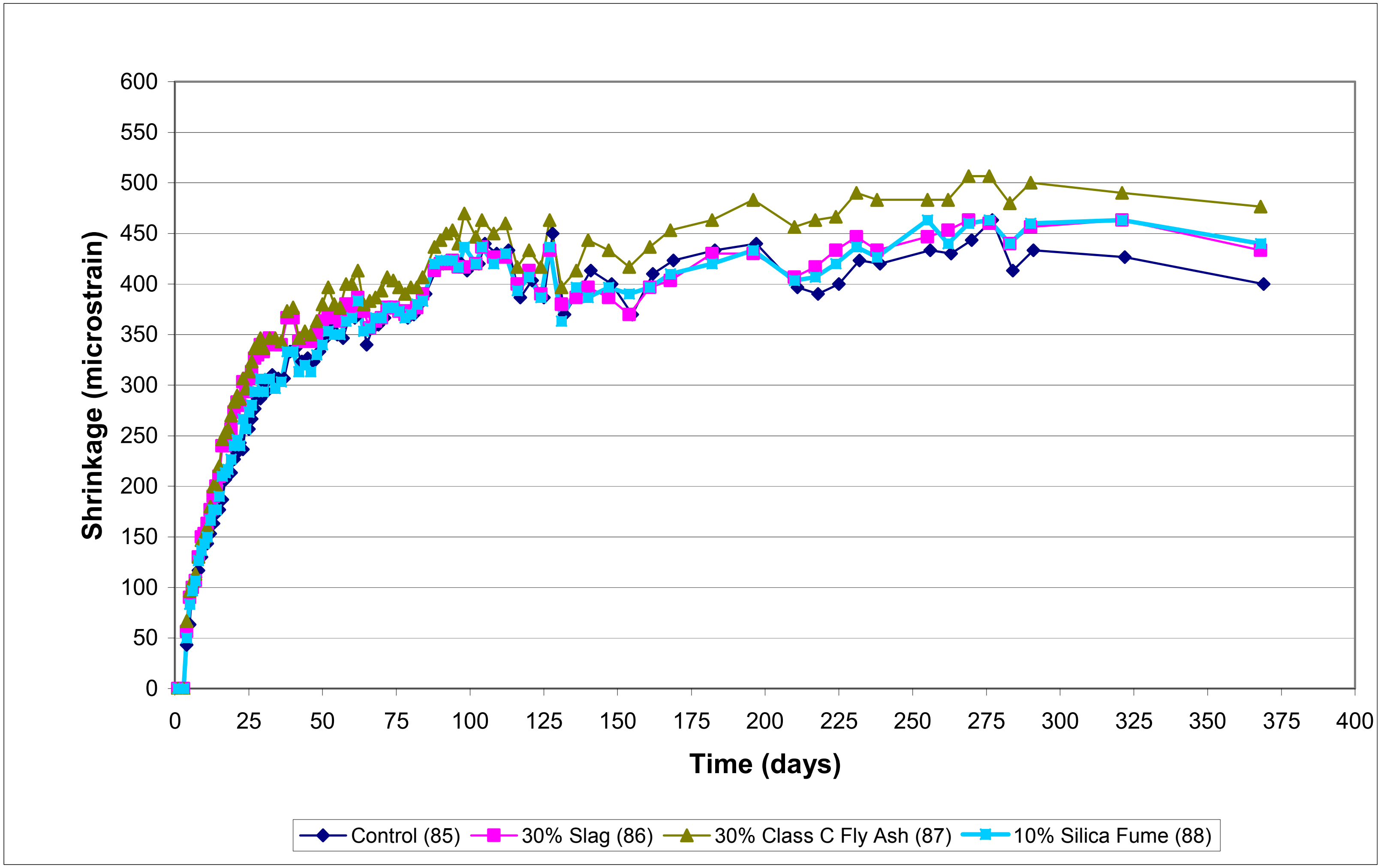

Figure 3.15 - Free Shrinkage Test, Program II. Average free shrinkage vs. time through 365 days. Comparing mineral admixtures.

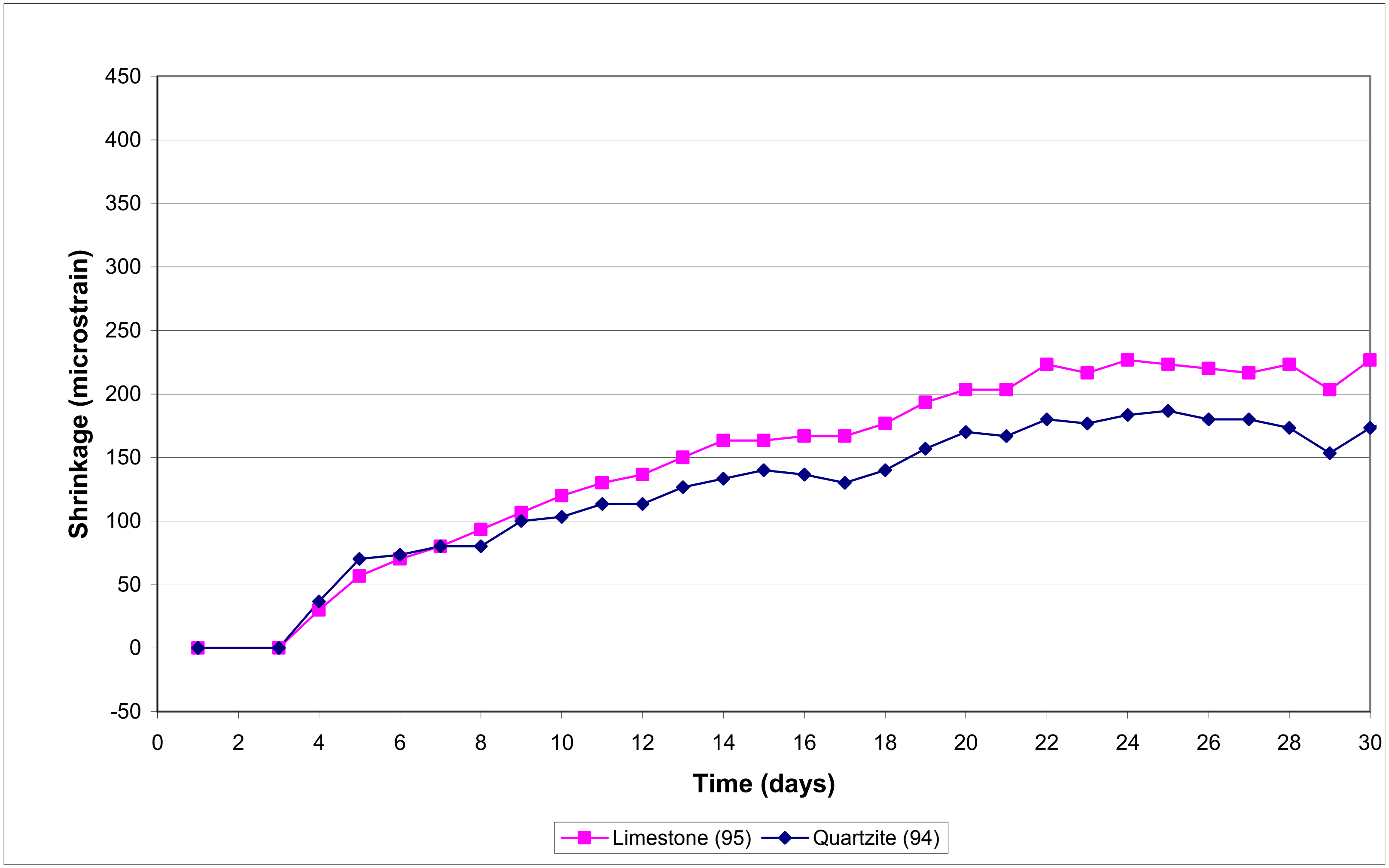

Figure 3.16 - Free Shrinkage Test, Program III, Batches 94 and 95. Average free shrinkage vs. time through 30 days. Comparing concretes made with limestone and quartzite coarse aggregates.

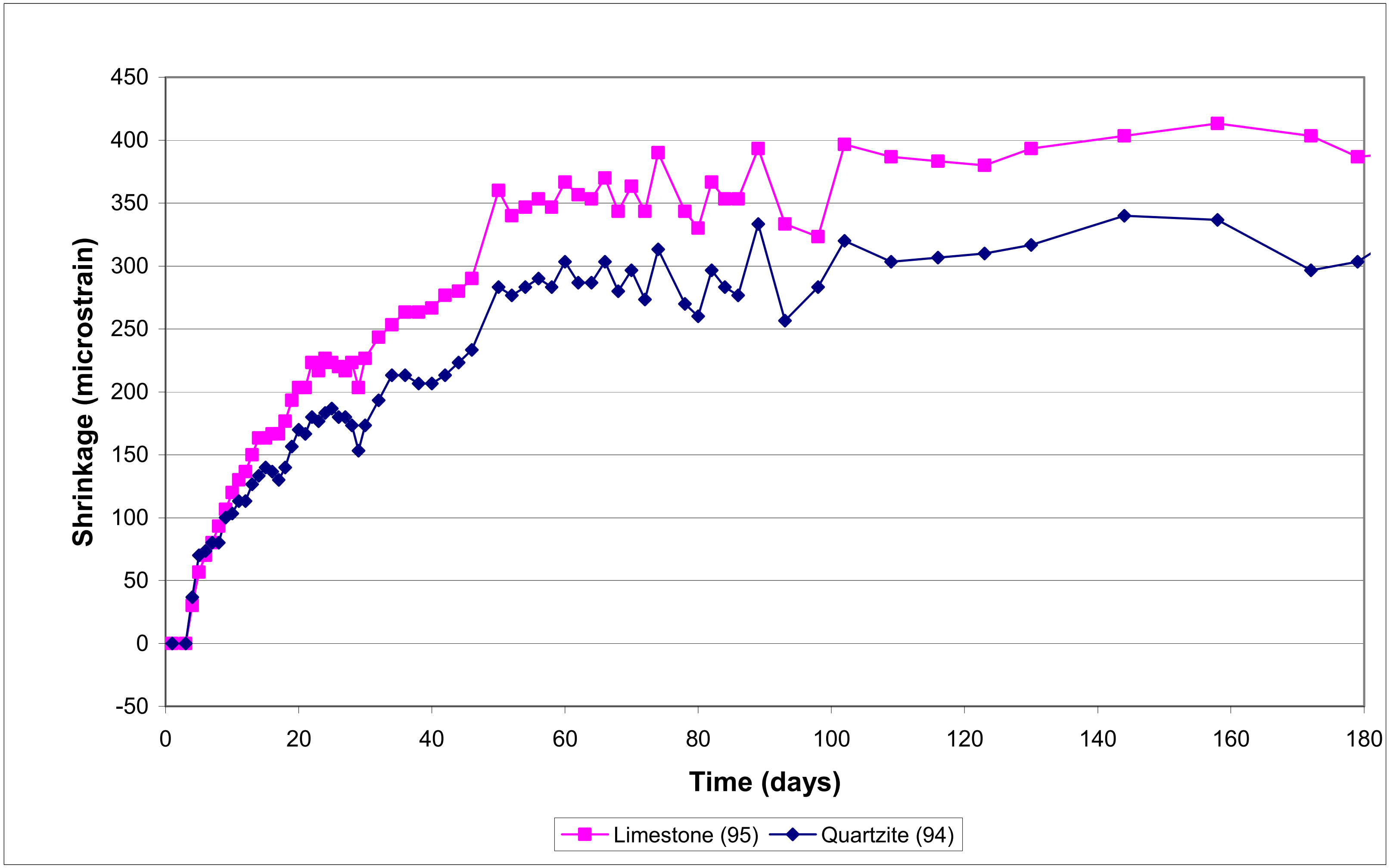

Figure 3.17 - Free Shrinkage Test, Program III, Batches 94 and 95. Average free shrinkage vs. time through 180 days. Comparing concretes made with limestone and quartzite coarse aggregates.

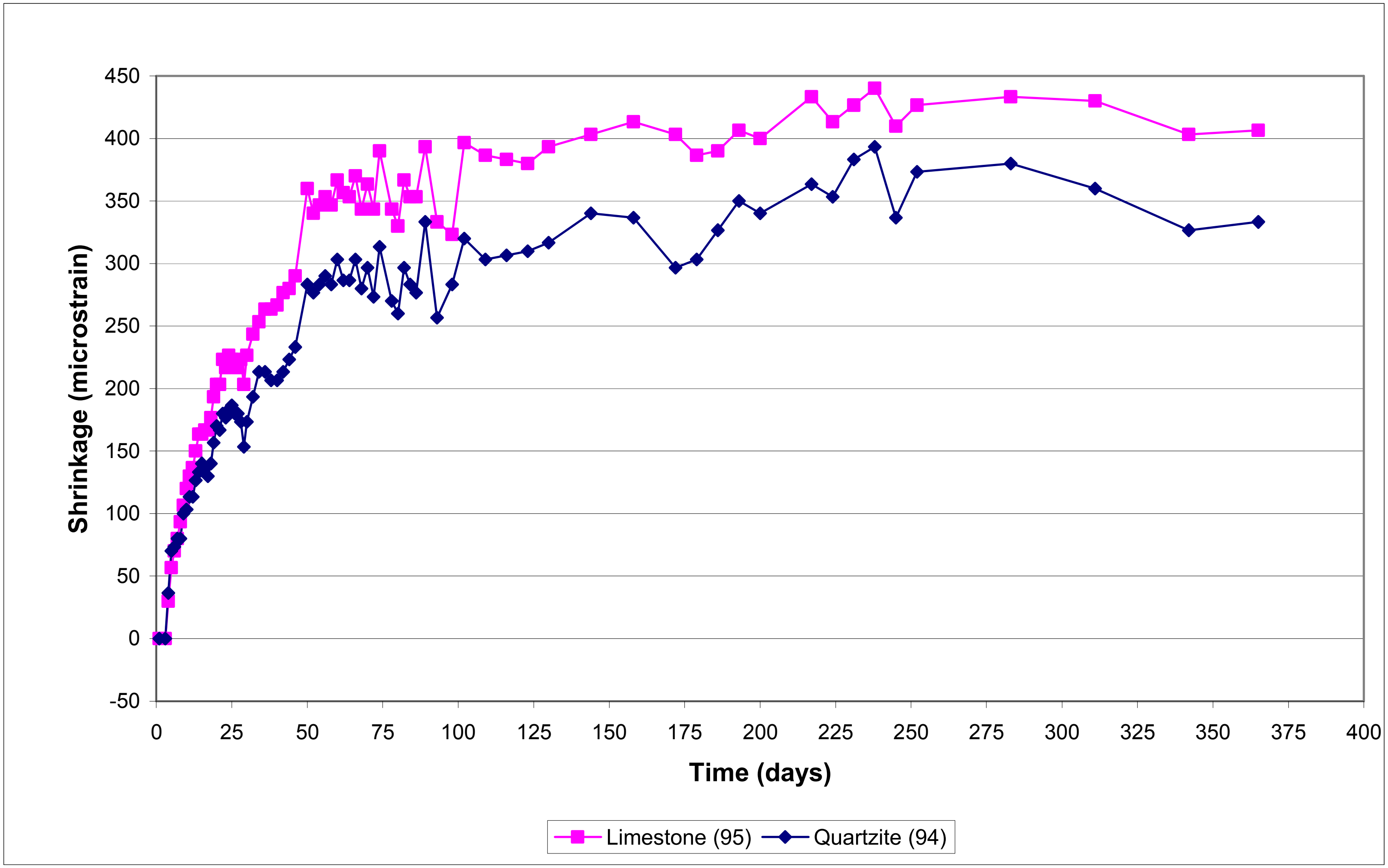

Figure 3.18 - Free Shrinkage Test, Program III, Batches 94 and 95. Average free shrinkage vs. time through 365 days. Comparing concretes made with limestone and quartzite coarse aggregates.

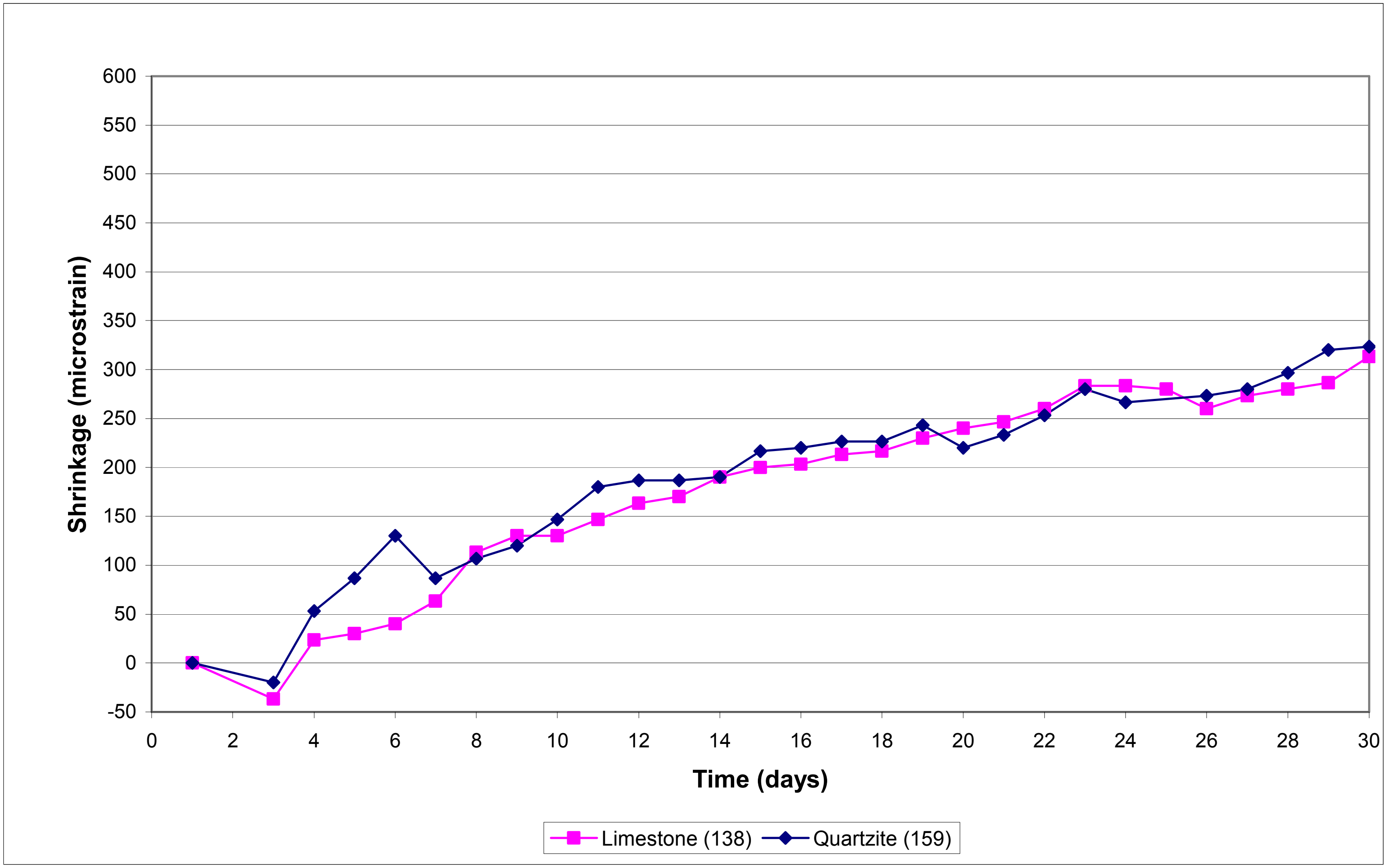

Figure 3.19 - Free Shrinkage Test, Program **III**, Batches 138 and 159. Average free shrinkage vs. time through 30 days. Comparing concretes made with limestone and quartzite coarse aggregates.

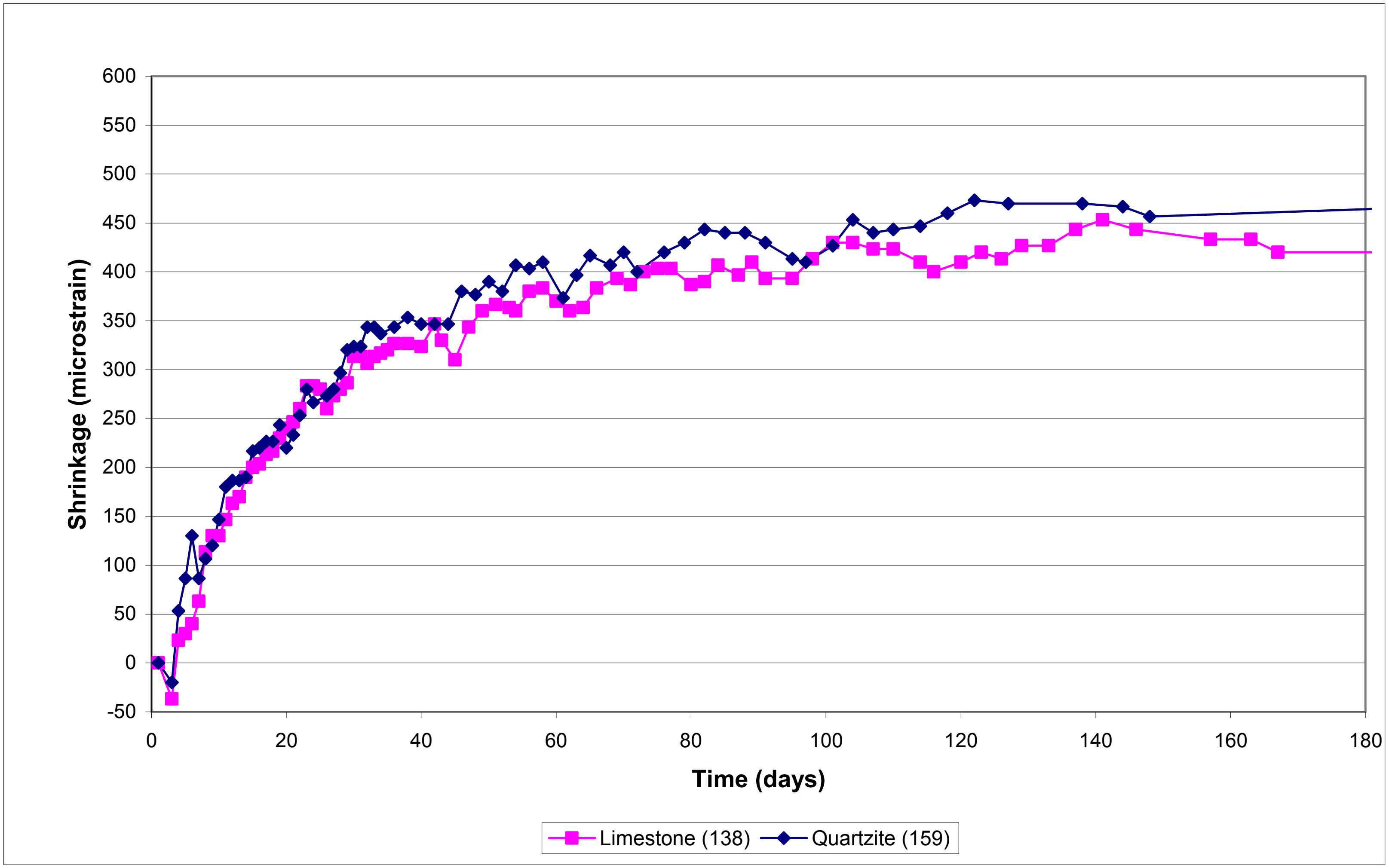

Figure 3.20 - Free Shrinkage Test, Program III, Batches 138 and 159. Average free shrinkage vs. time through 180 days. Comparing concretes made with limestone and quartzite coarse aggregates.

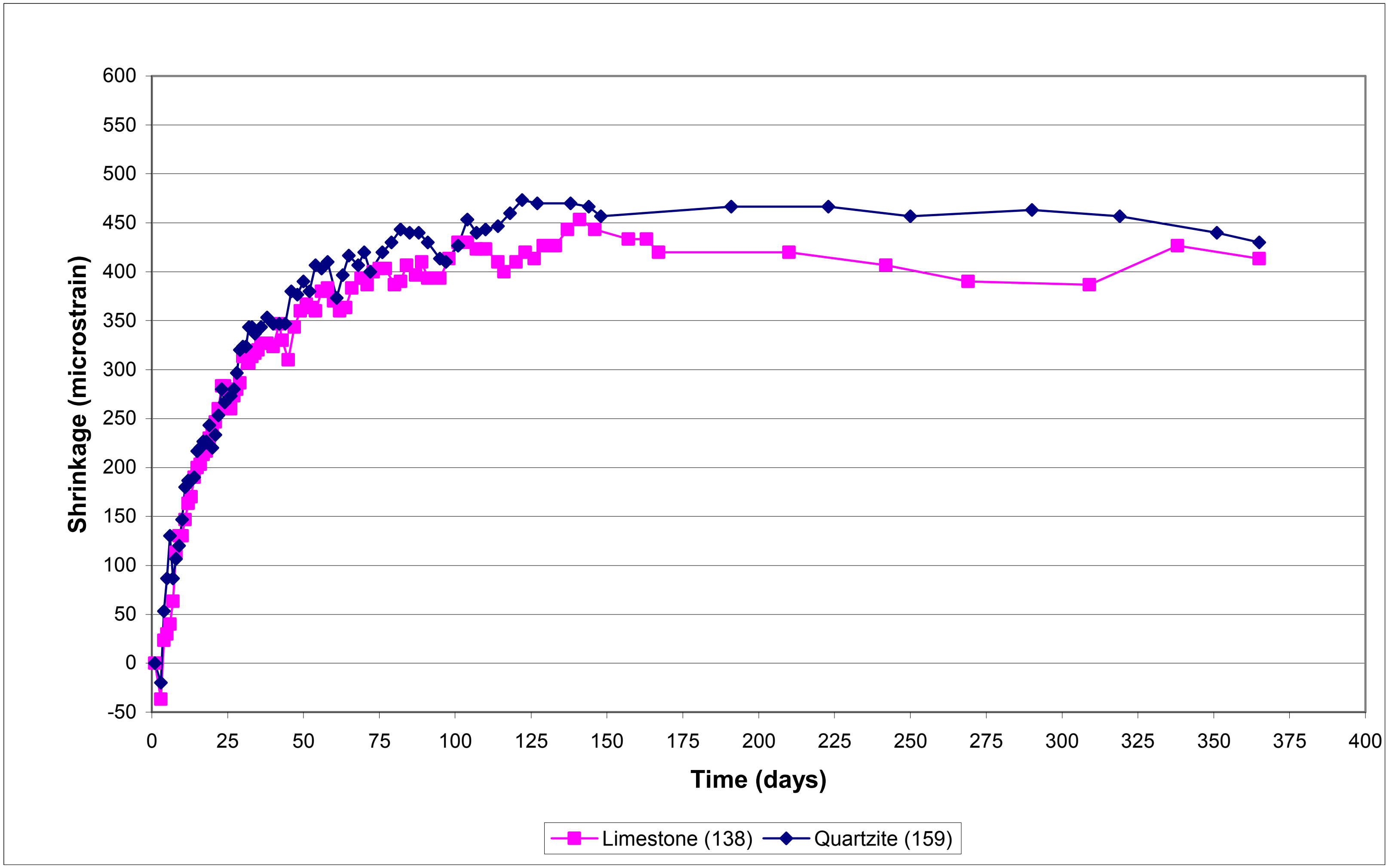

Figure 3.21 - Free Shrinkage Test, Program III, Batches 138 and 159. Average free shrinkage vs. time through 365 days. Comparing concretes made with limestone and quartzite coarse aggregates.

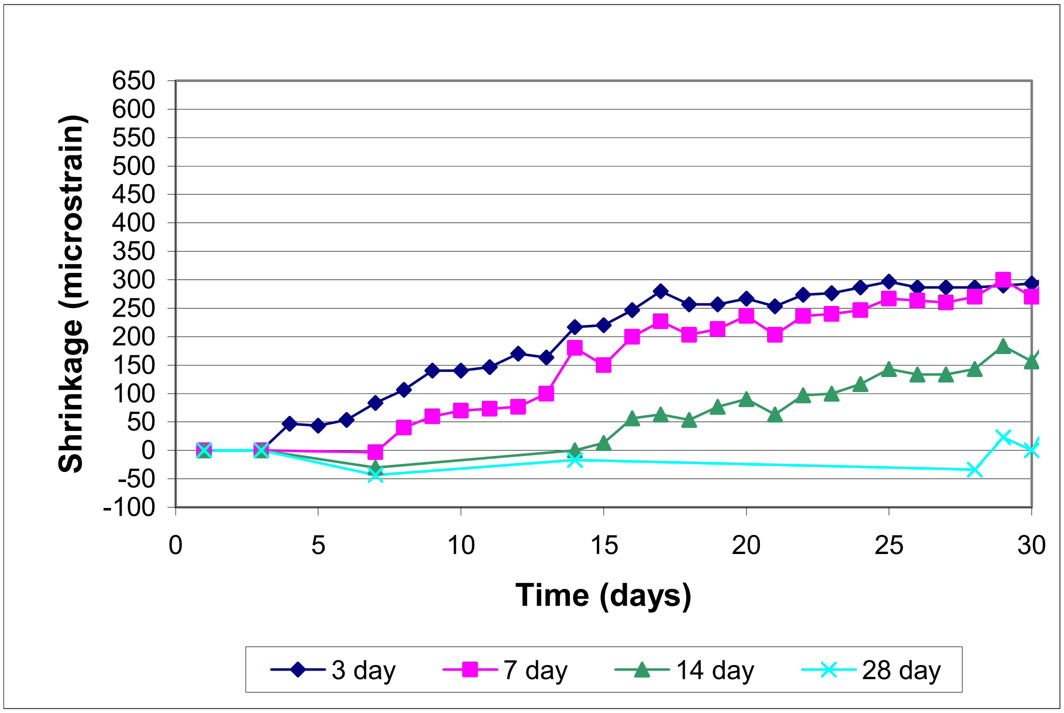

Figure 3.22a - Free Shrinkage,Program IV. Average free shrinkage vs. time through 30 days for different curing periods. Batch 165. Type I/II cement.

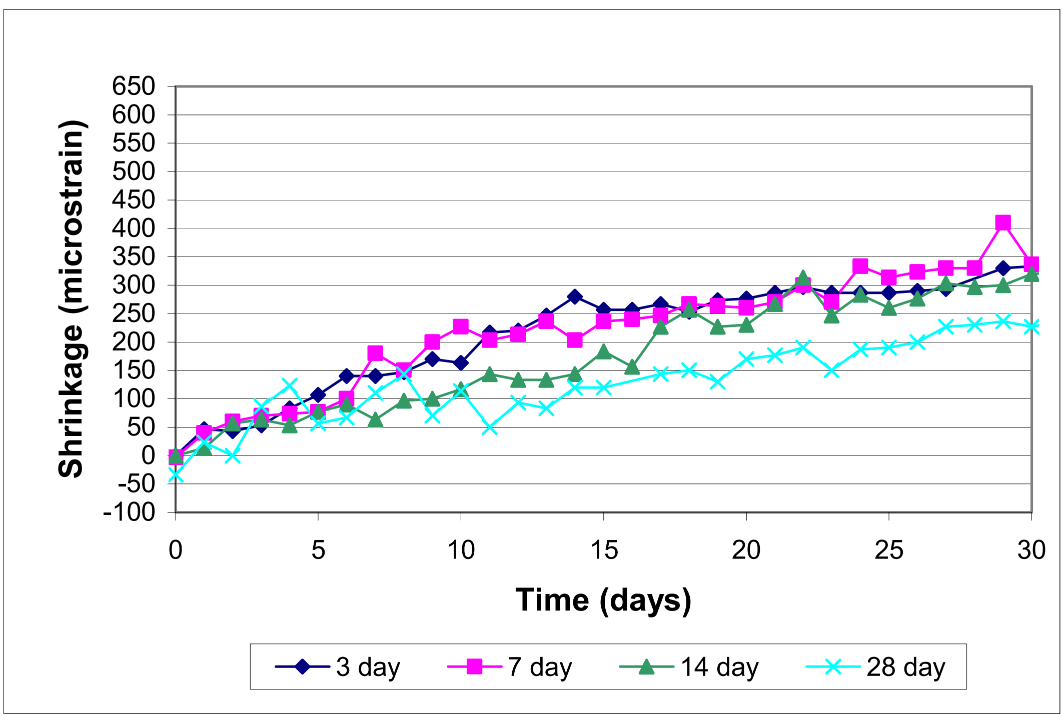

Figure 3.22b - Free Shrinkage,Program IV. Average free shrinkage vs. time through 30 days for different curing periods. Type I/II cement. Batch 165. Drying only.

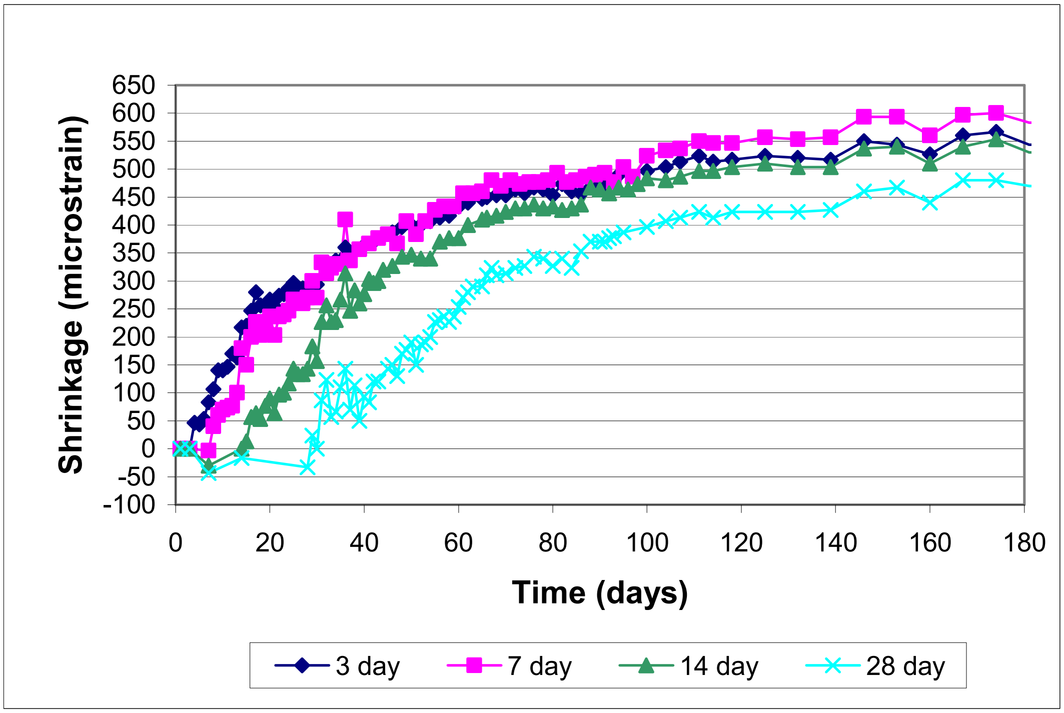

Figure 3.23a - Free Shrinkage,Program IV. Average free shrinkage vs. time through 180 days for different curing periods. Batch 165. Type I/II cement.

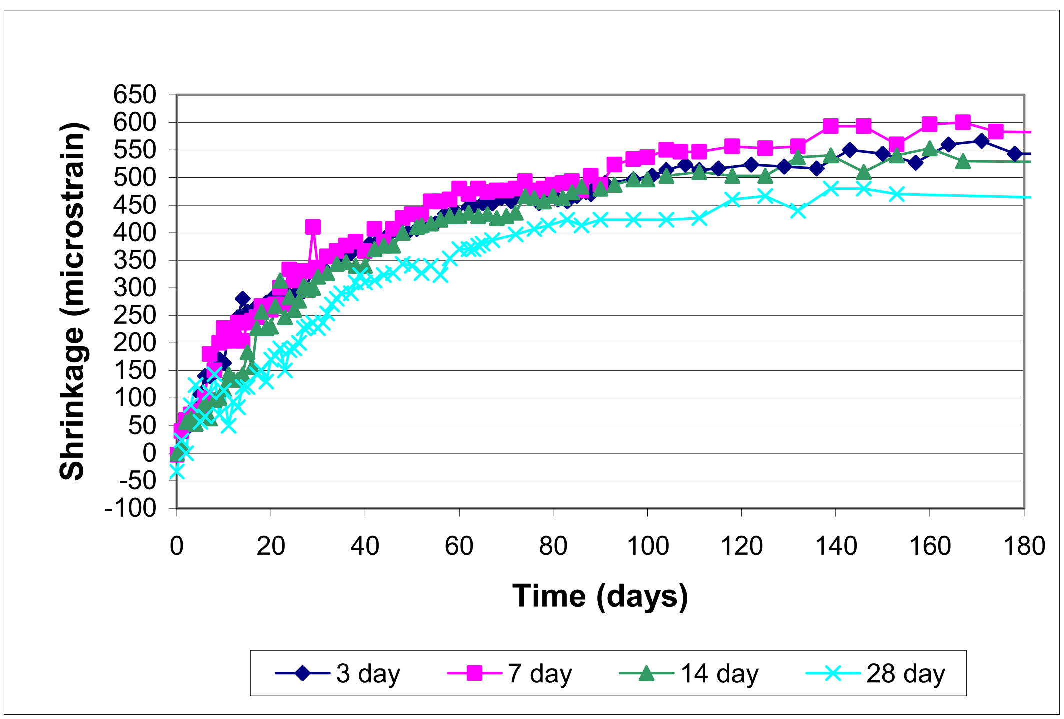

Figure 3.23b - Free Shrinkage,Program IV. Average free shrinkage vs. time through 180 days for different curing periods. Batch 165. Type I/II cement. Drying only.

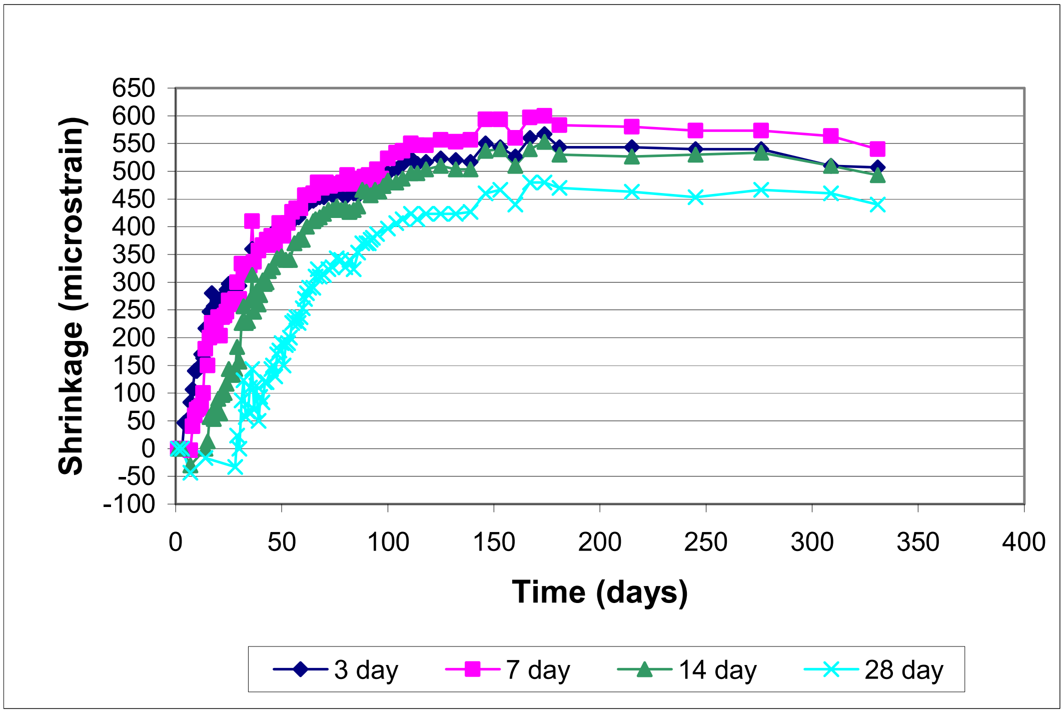

Figure 3.24a - Free Shrinkage,Program IV. Average free shrinkage vs. time through 365 days for different curing periods. Batch 165 Type I/II cement.

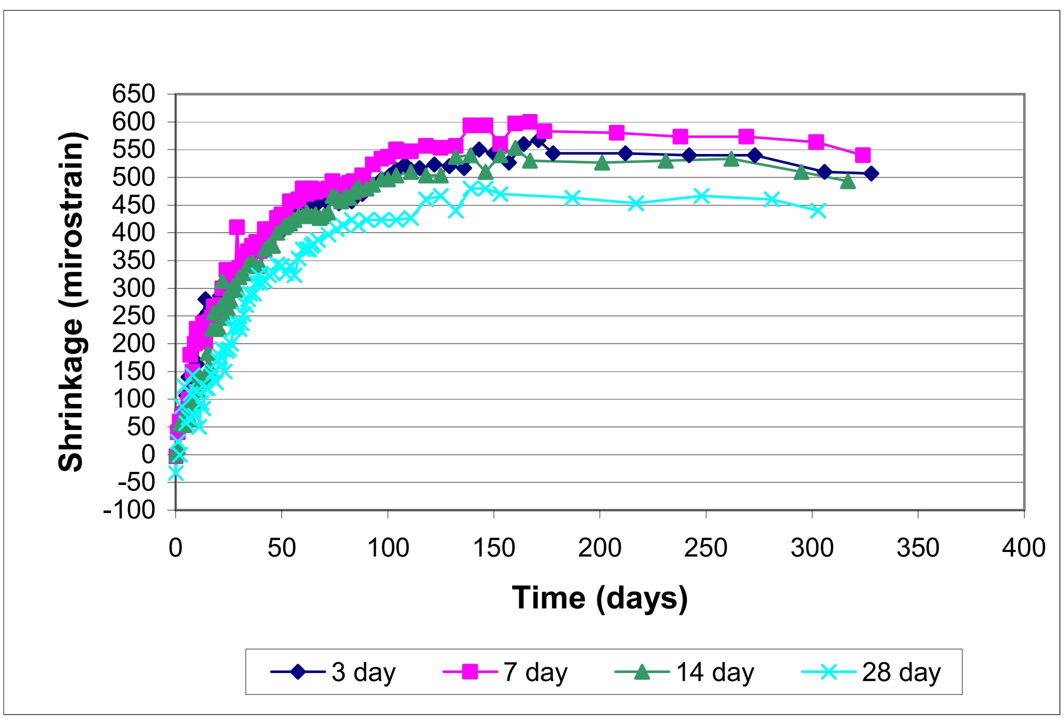

Figure 3.24b - Free Shrinkage,Program IV. Average free shrinkage vs. time through 365 days for different curing periods. Batch 165. Type I/II cement. Drying only.

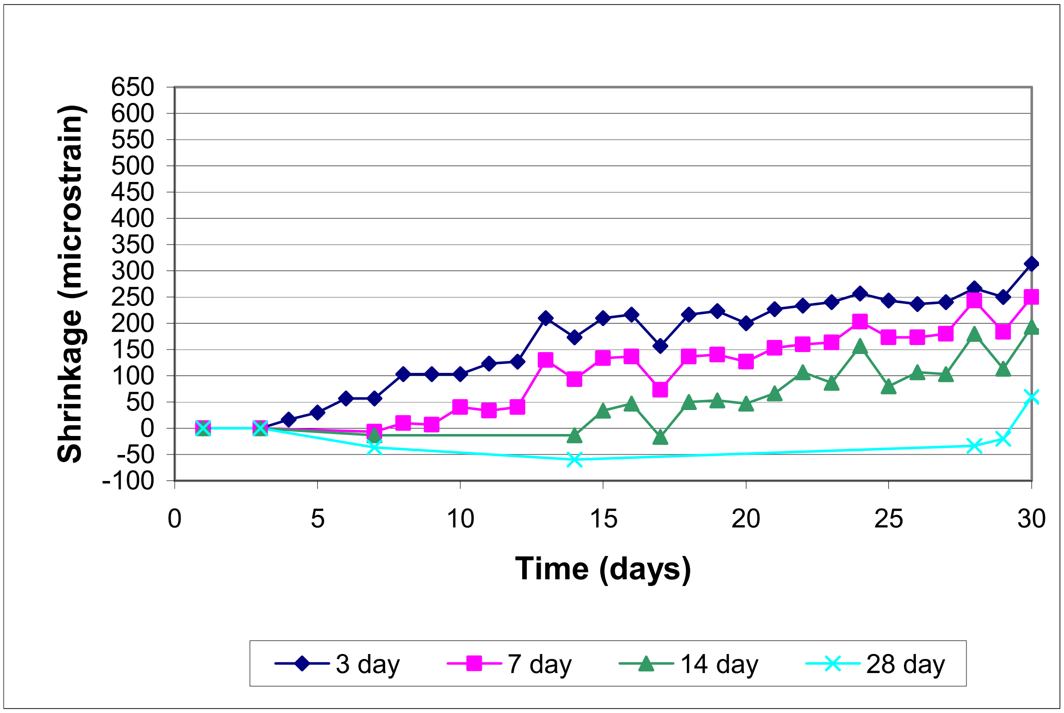

Figure 3.25a - Free Shrinkage,Program IV. Average free shrinkage vs. time through 30 days for different curing periods. Batch 166. Type II Coarse-Ground cement.

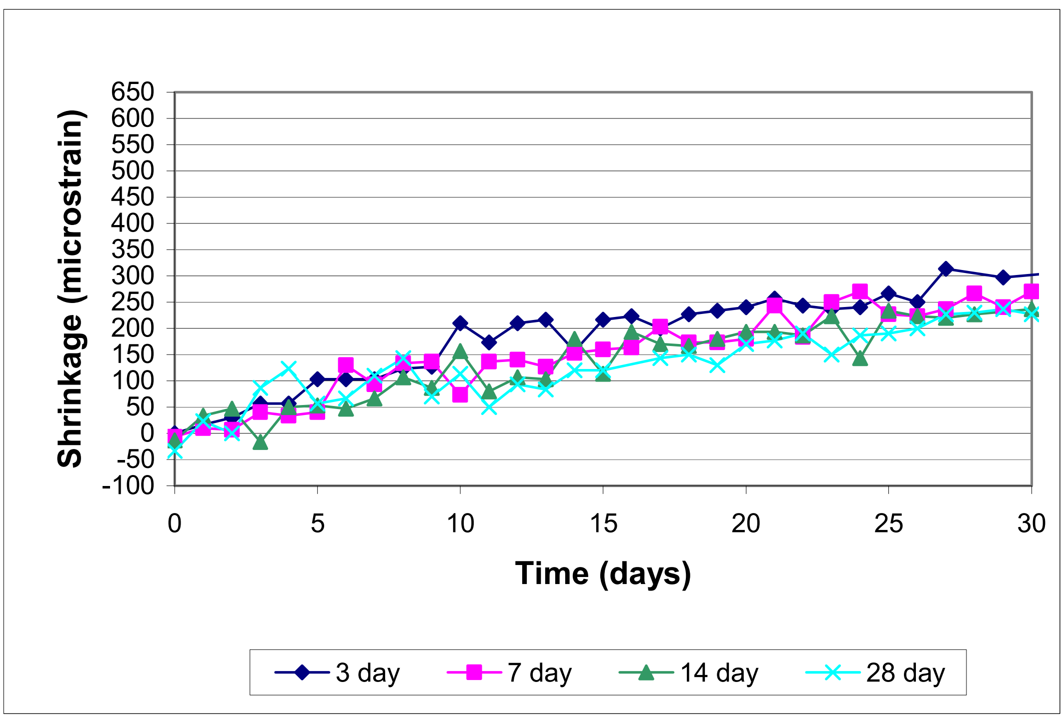

Figure 3.25b - Free Shrinkage,Program IV. Average free shrinkage vs. time through 30 days for different curing periods. Batch 166. Type II Coarse-Ground cement. Drying only.

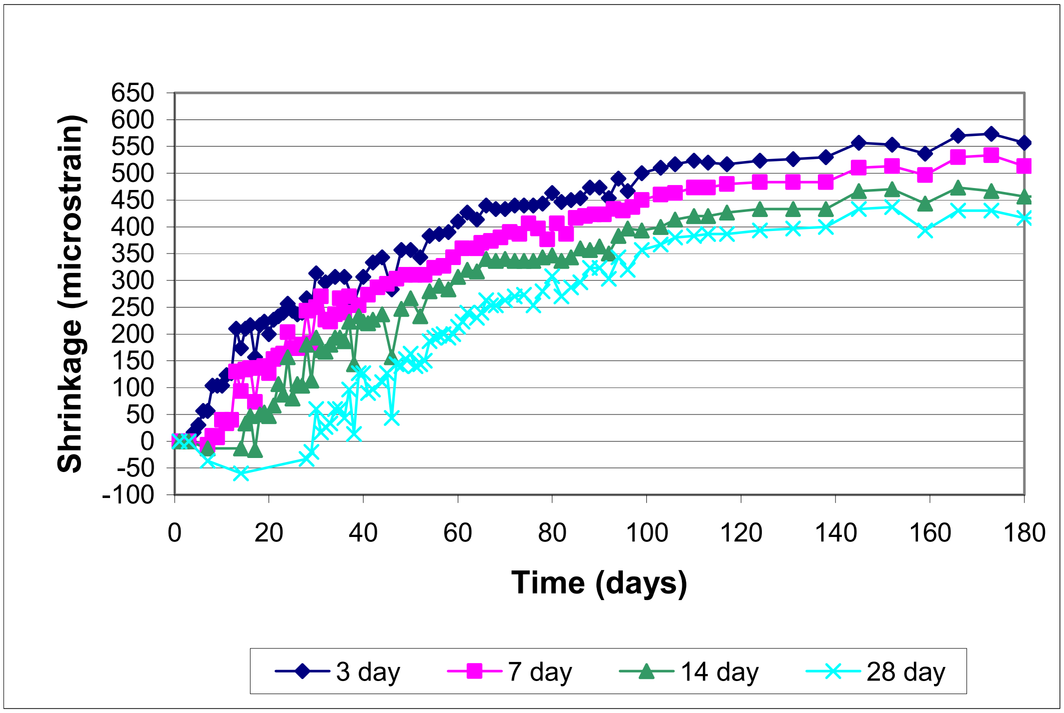

Figure 3.26a - Free Shrinkage,Program IV. Average free shrinkage vs. time through 180 days for different curing periods. Batch 166. Type II Coarse-Ground cement.

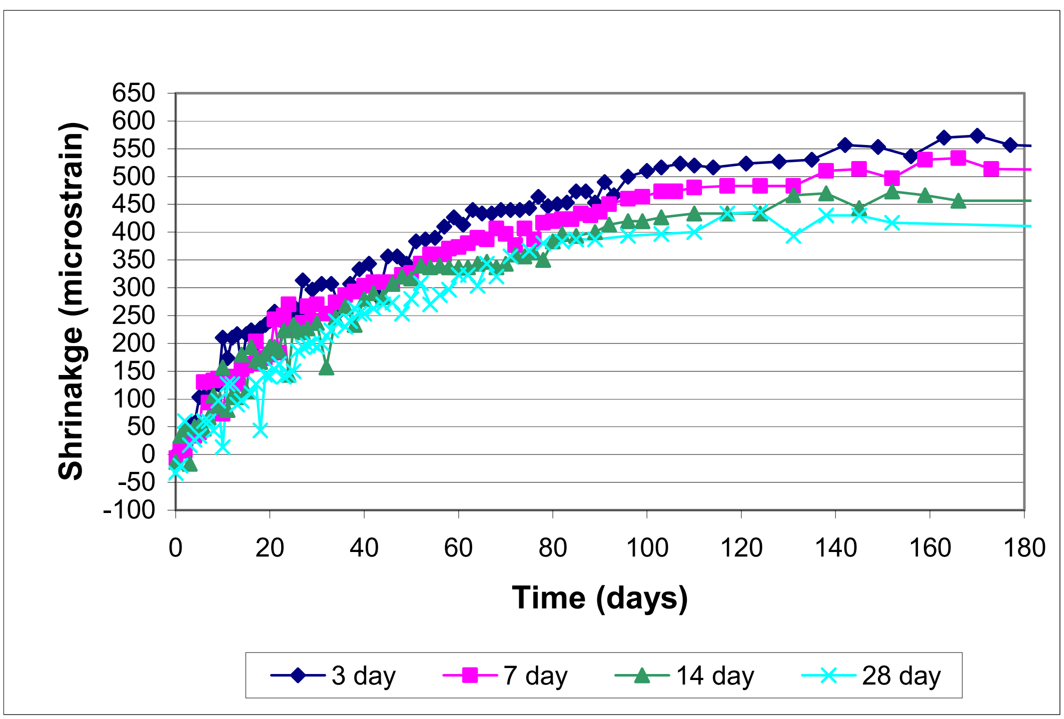

Figure 3.26b - Free Shrinkage,Program IV. Average free shrinkage vs. time through 180 days for different curing periods. Batch 166. Type II Coarse-Ground cement. Drying only.

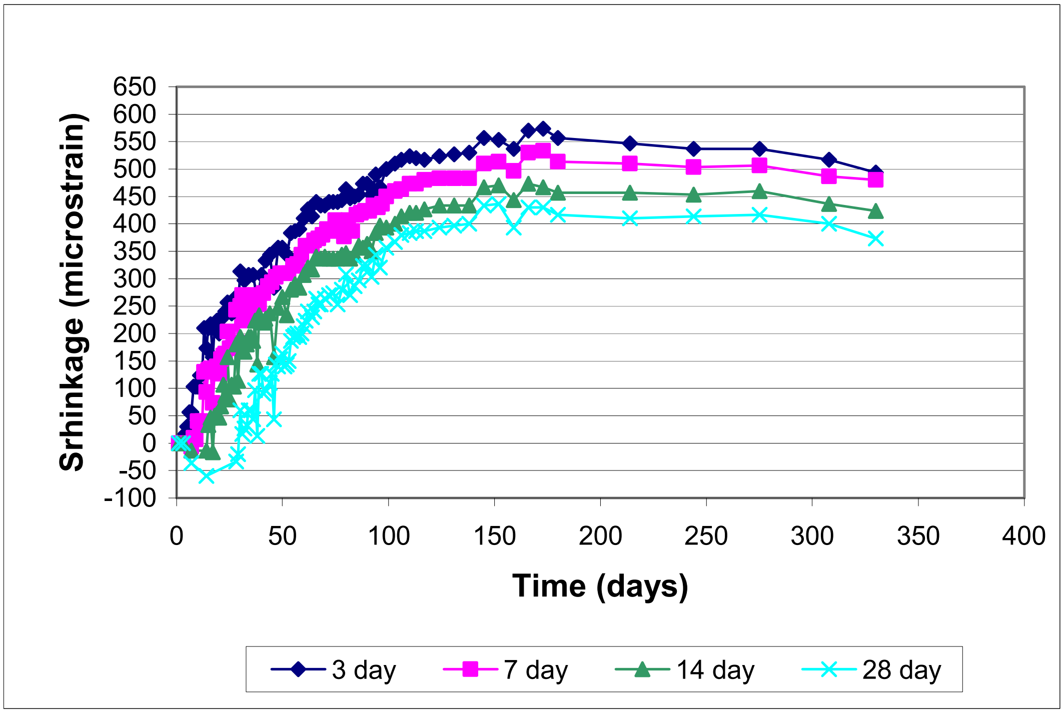

Figure 3.27a - Free Shrinkage,Program IV. Average free shrinkage vs. time through 365 days for different curing periods. Batch 166. Type II Coarse-Ground cement.

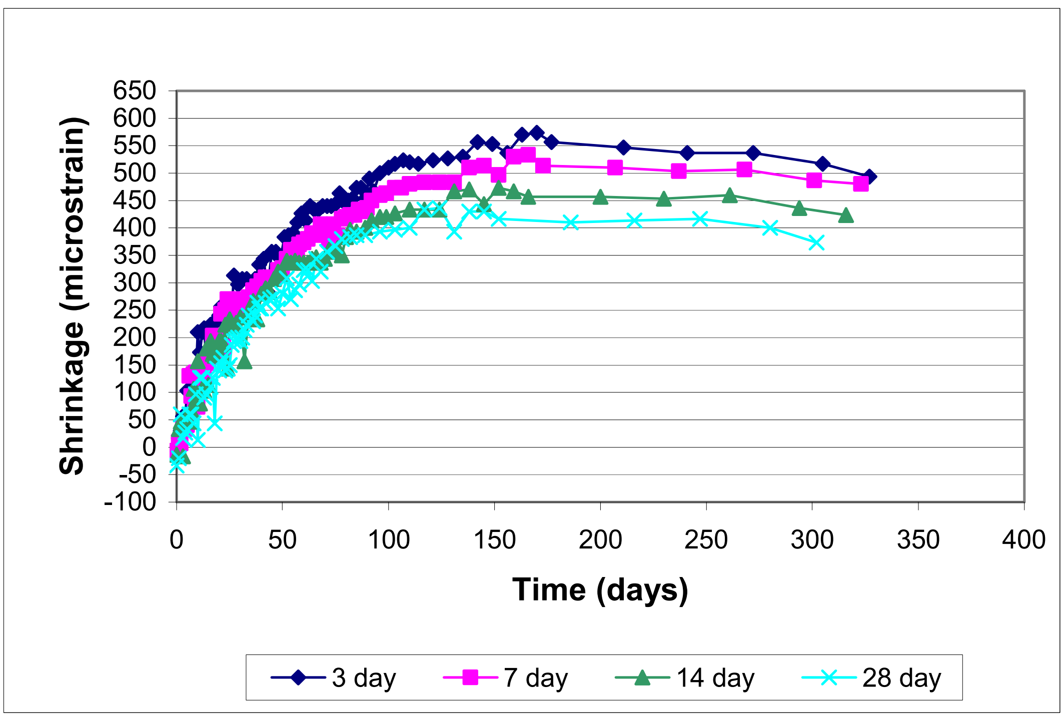

Figure 3.27b - Free Shrinkage,Program IV. Average free shrinkage vs. time through 300 days for different curing periods. Batch 166. Type II Coarse-Ground cement. Drying only.

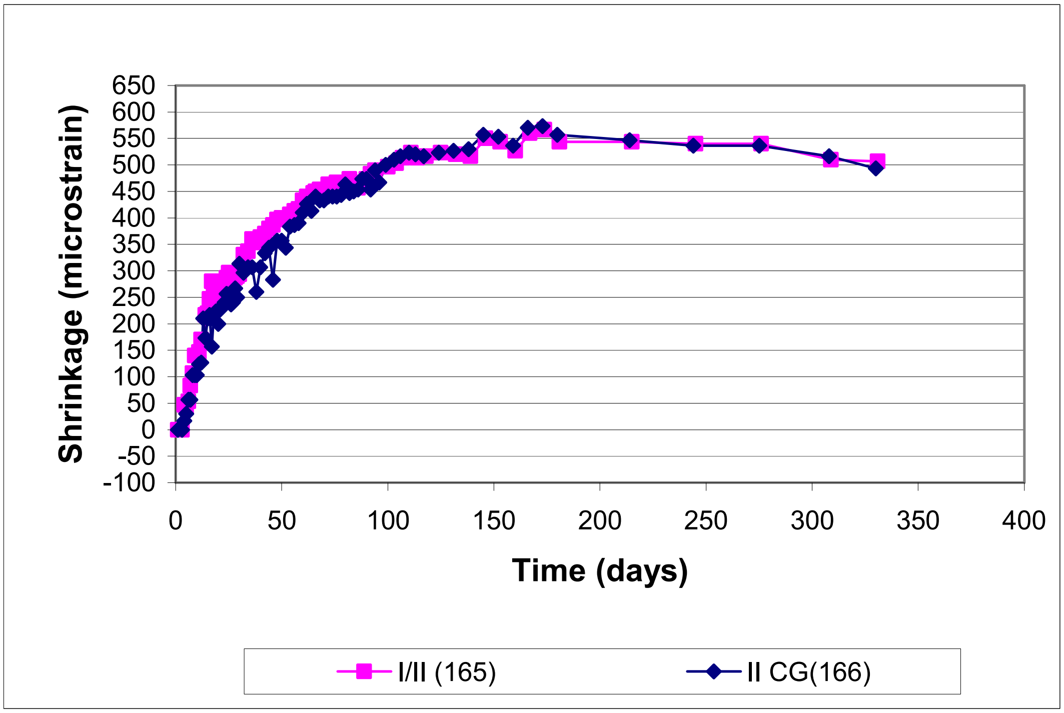

Figure 3.28a - Free Shrinkage,Program IV. Average free shrinkage vs. time through 330 days for 3 day cure period. Comparing cement type.

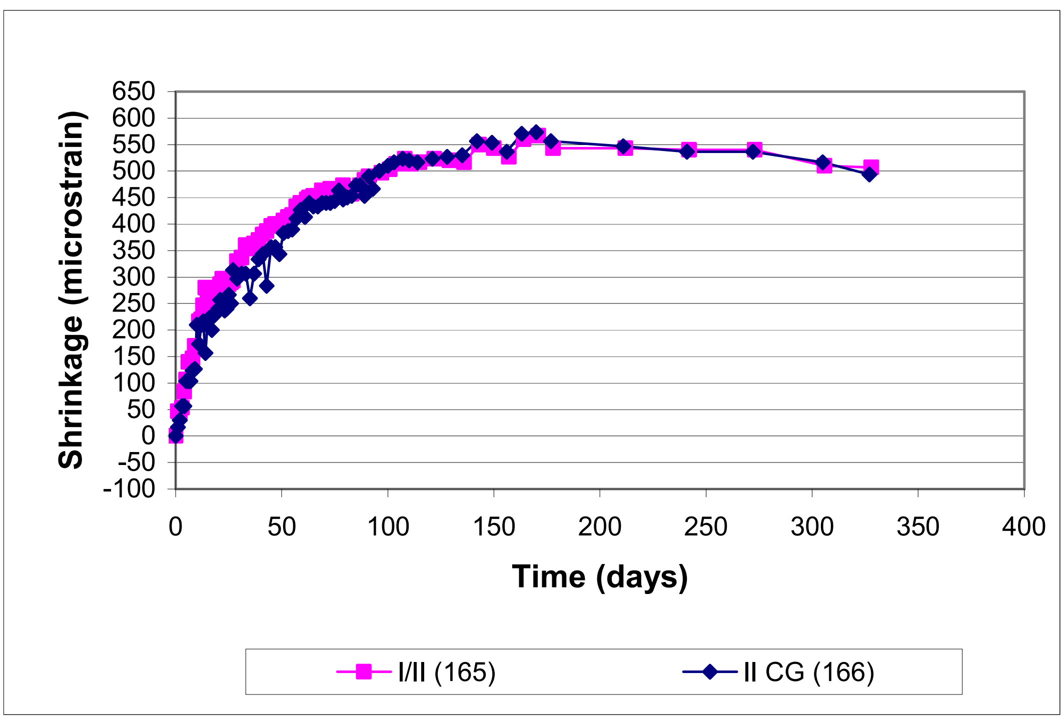

Figure 3.28b - Free Shrinkage,Program IV. Average free shrinkage vs. time through 330 days for 3 day cure period. Comparing cement type, drying only.

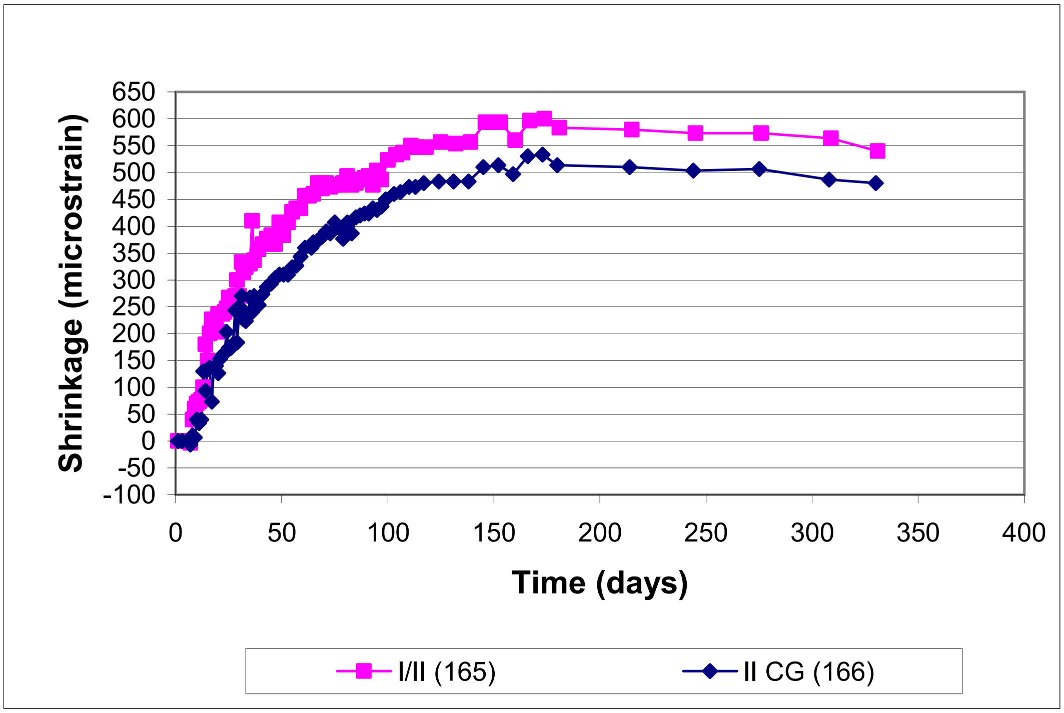

Figure 3.29a - Free Shrinkage,Program IV. Average free shrinkage vs. time through 330 days for 7 day cure period. Comparing cement type.

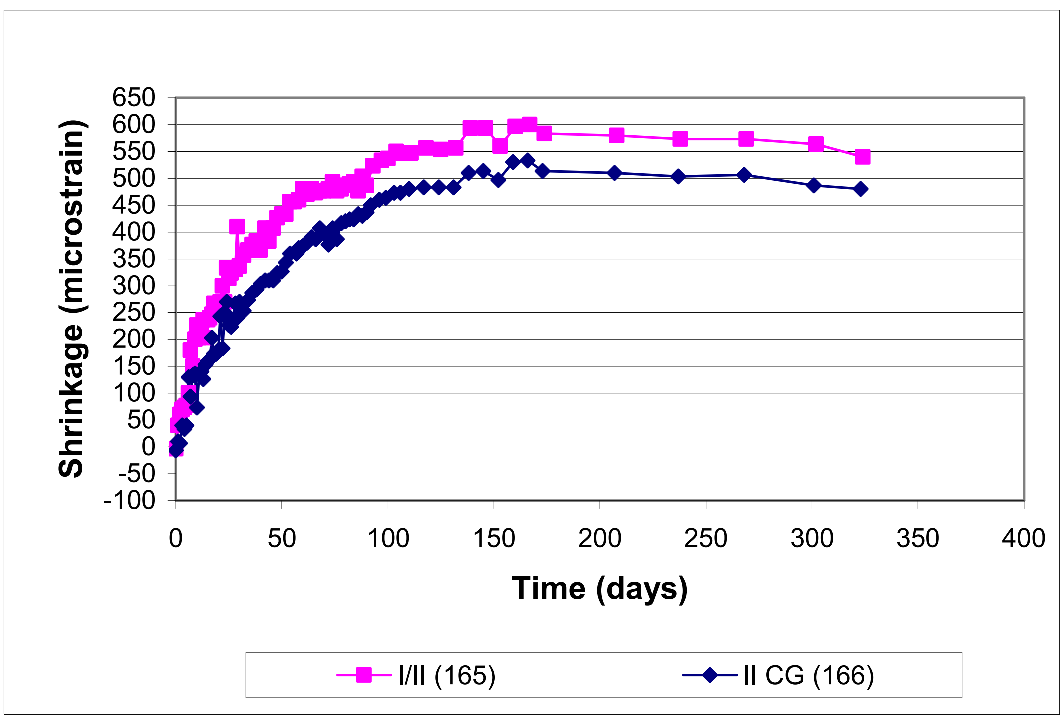

Figure 3.29b - Free Shrinkage,Program IV. Average free shrinkage vs. time through 330 days for 7 day cure period. Comparing cement type, drying only.

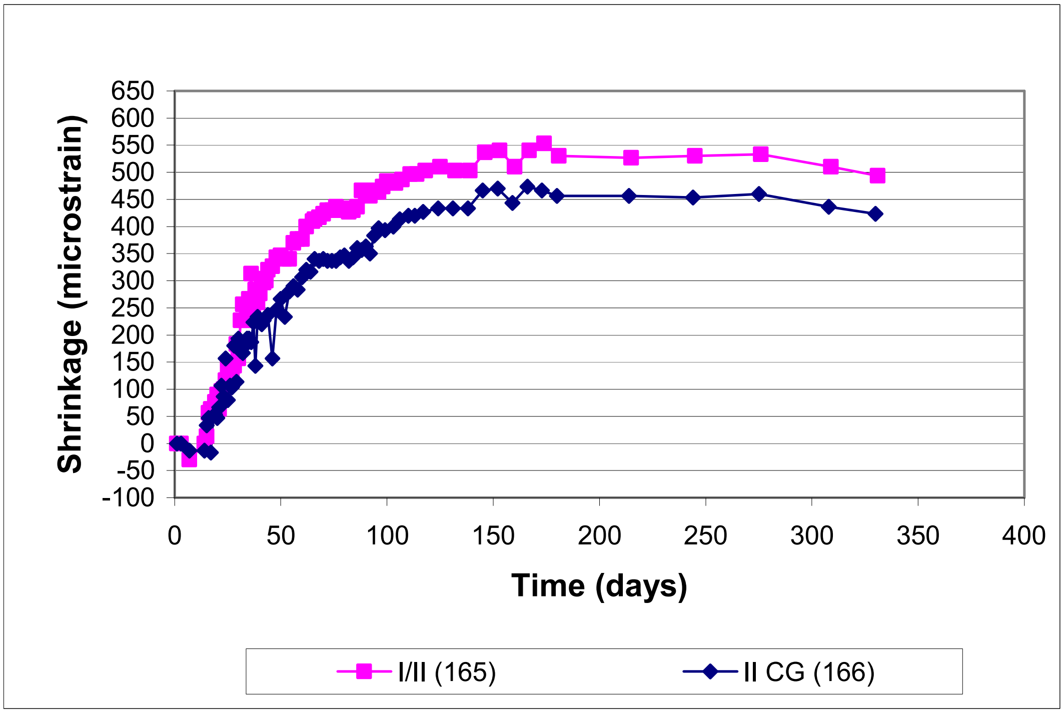

Figure 3.30a - Free Shrinkage,Program IV. Average free shrinkage vs. time through 330 days for 14 day cure period. Comparing cement type.

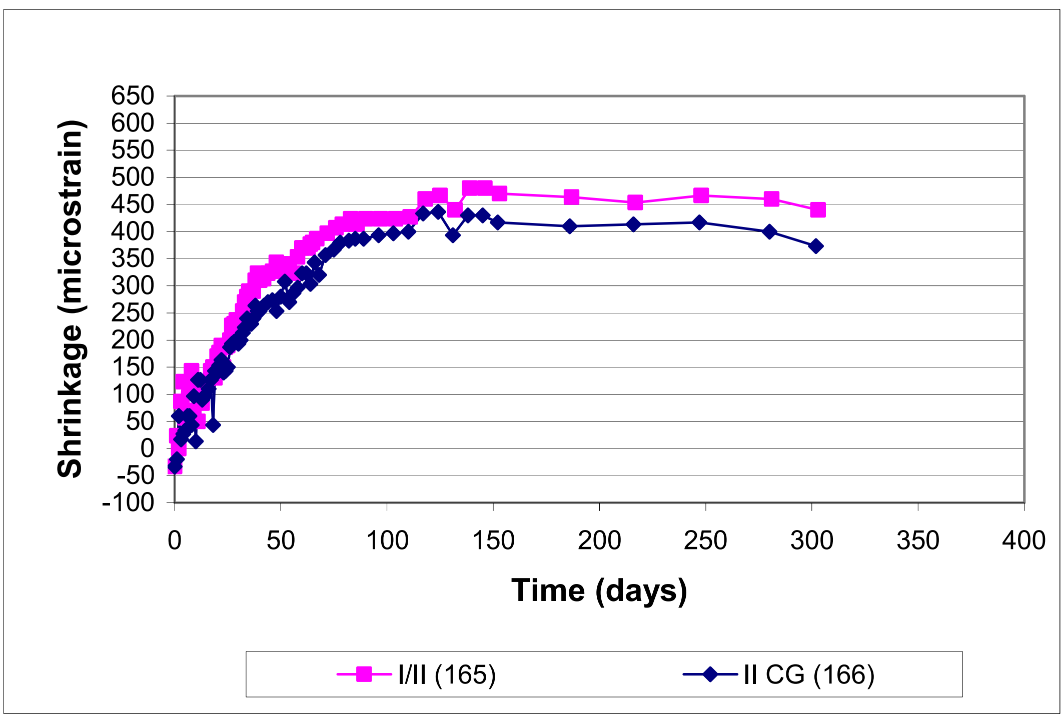

Figure 3.30b - Free Shrinkage,Program IV. Average free shrinkage vs. time through 300 days for 14 day cure period. Comparing cement type, drying only.

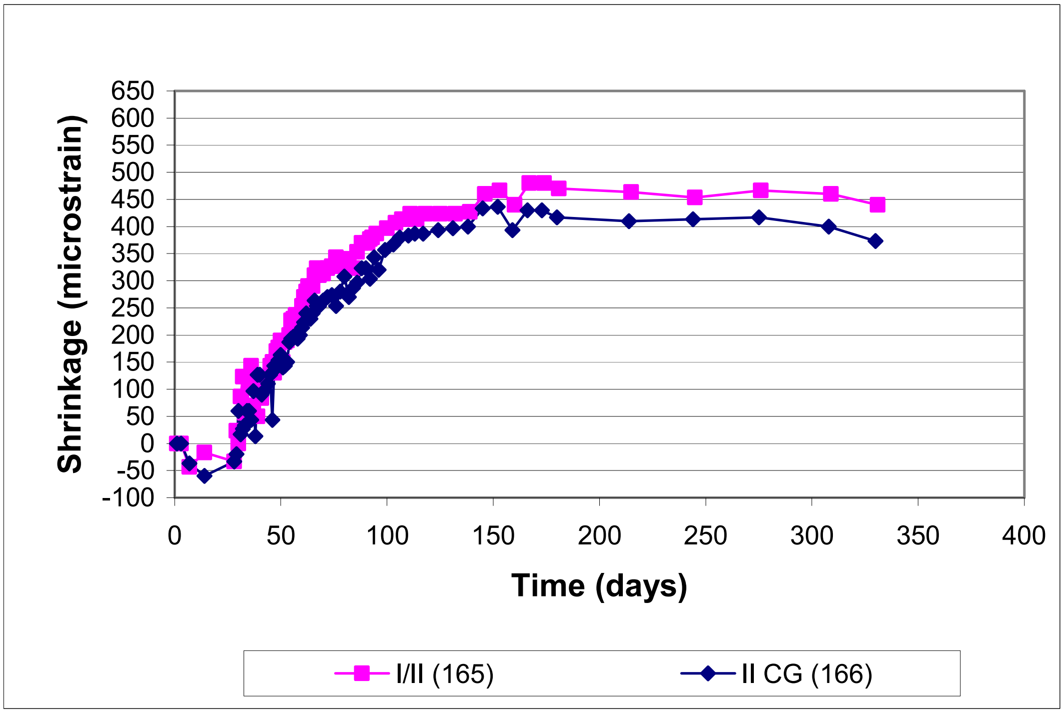

Figure 3.31a - Free Shrinkage,Program IV. Average free shrinkage vs. time through 330 days for 28 day cure period. Comparing cement type.

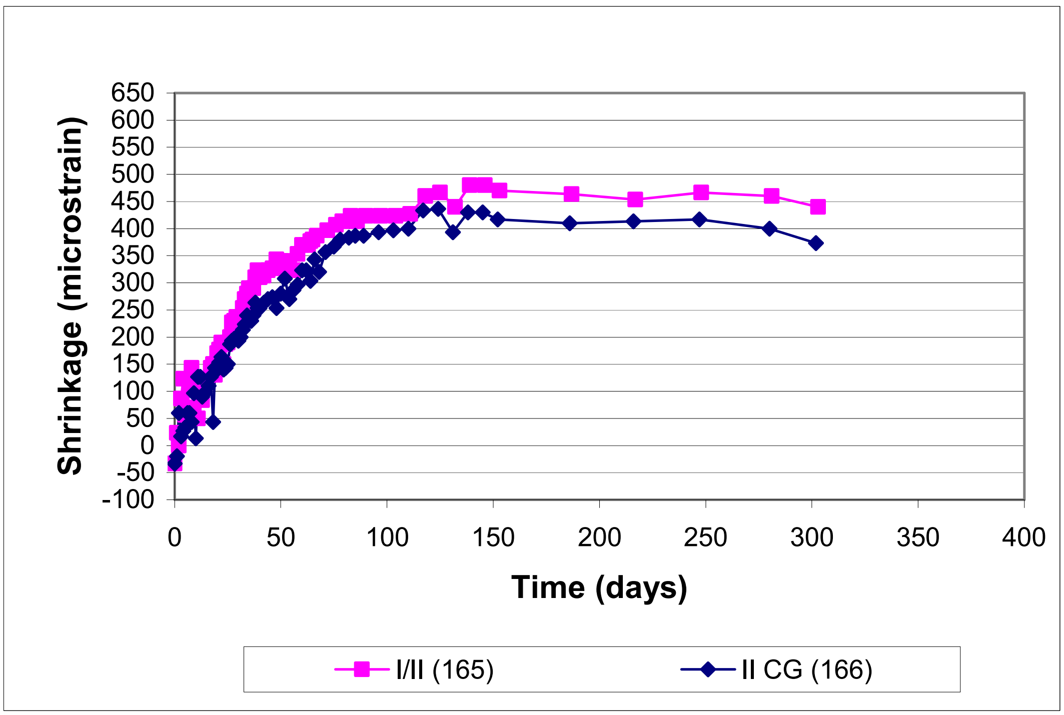

Figure 3.31b - Free Shrinkage,Program IV. Average free shrinkage vs. time through 300 days for 28 day cure period. Comparing cement type, drying only.

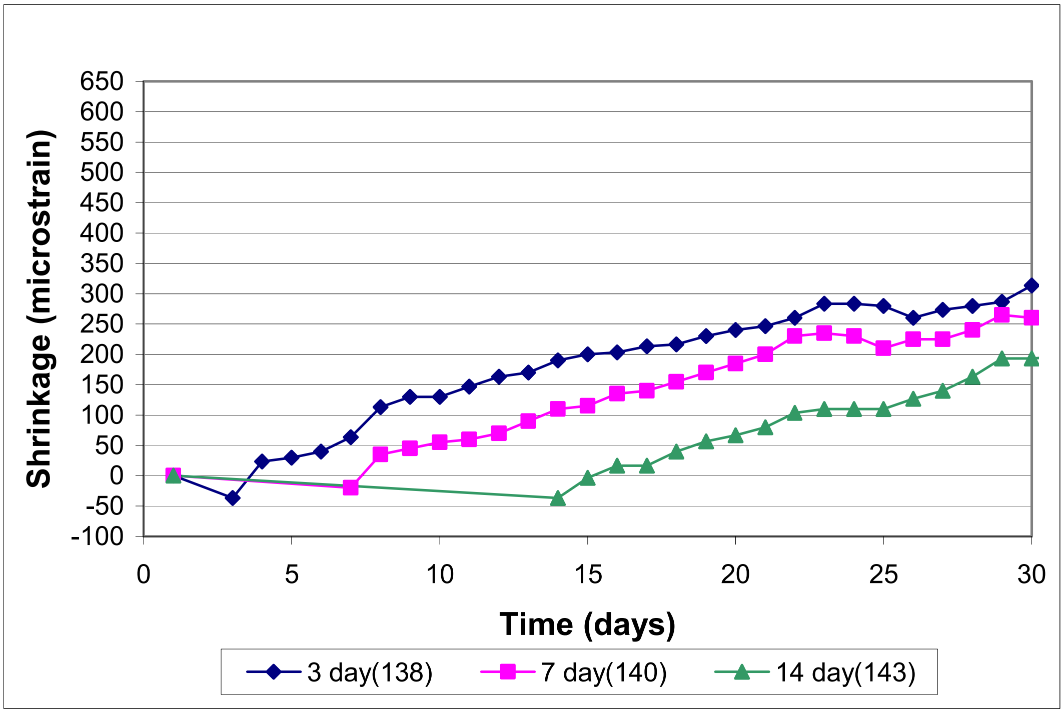

Figure 3.32a - Free Shrinkage,Program IV. Average free shrinkage vs. time through 30 days for different curing periods. Air-entrained concrete. Type I/II cement.

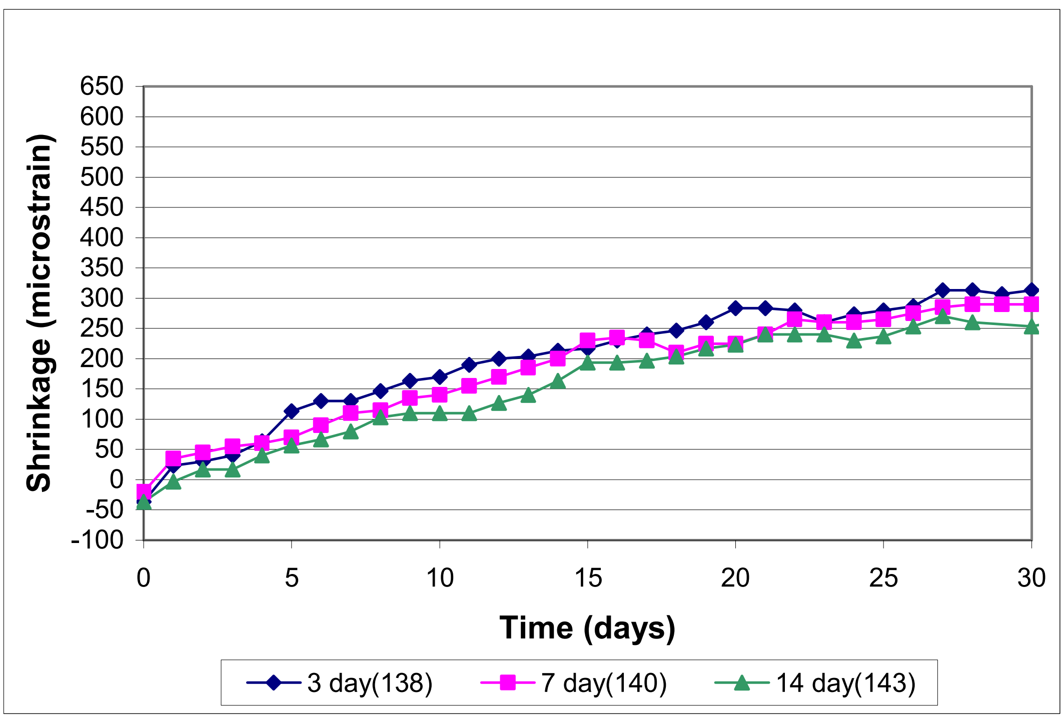

Figure 3.32b - Free Shrinkage,Program IV. Average free shrinkage vs. time through 30 days for different curing periods. Air-entrained concrete. Type I/II cement. Drying only.

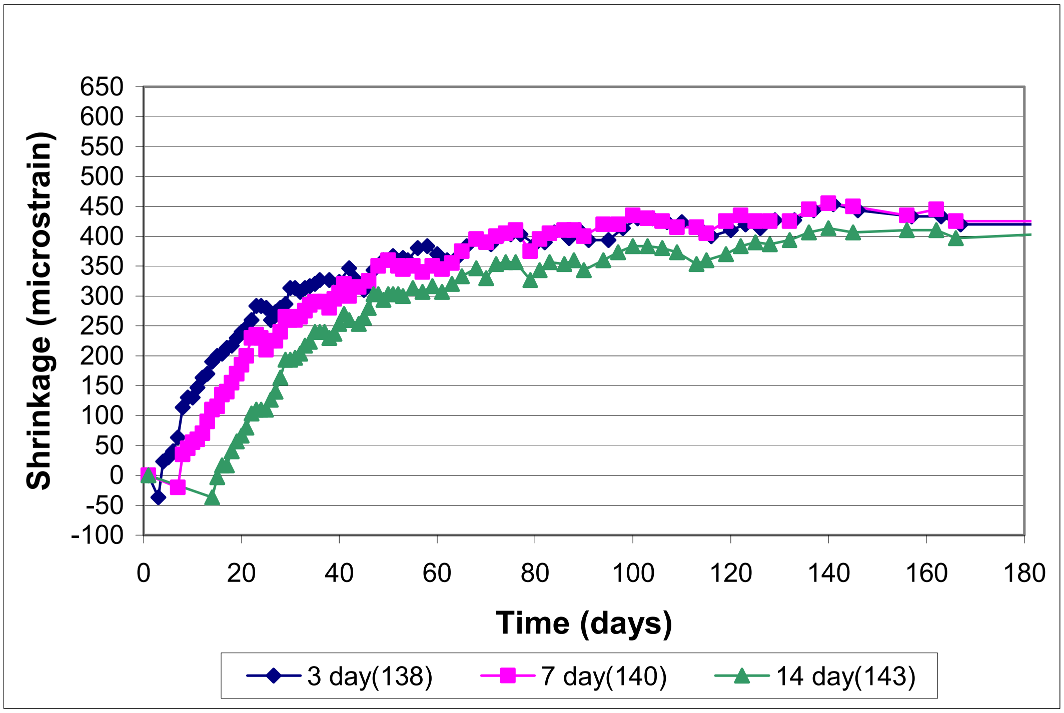

Figure 3.33a - Free Shrinkage,Program IV. Average free shrinkage vs. time through 180 days for different curing periods. Air-entrained concrete. Type I/II cement.

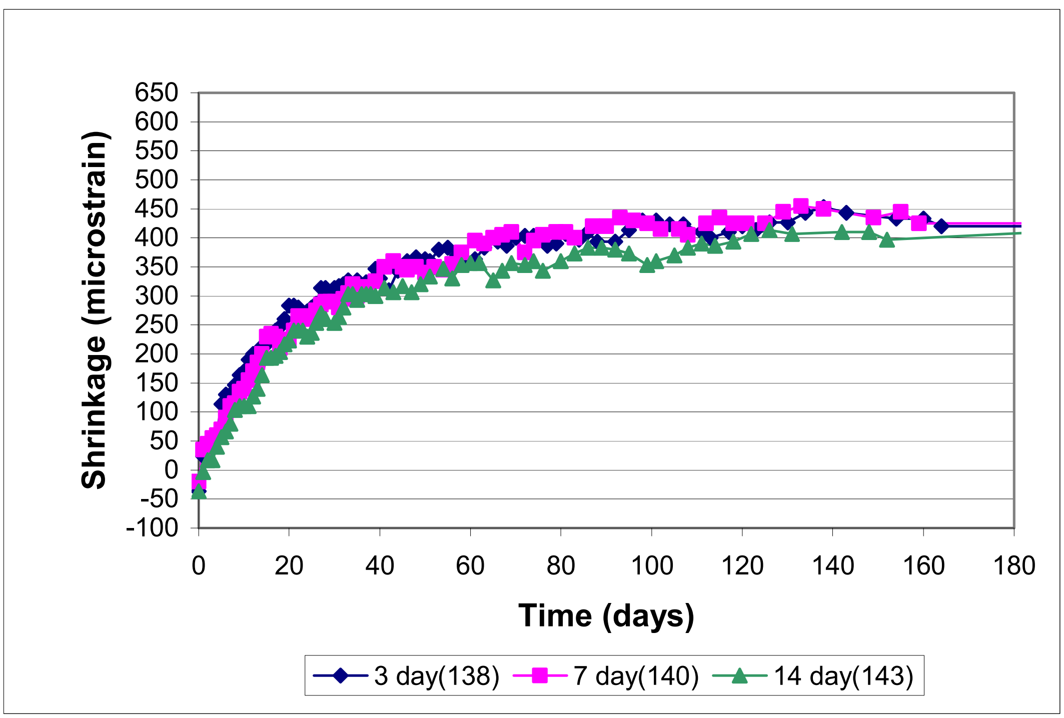

Figure 3.33b - Free Shrinkage,Program IV. Average free shrinkage vs. time through 180 days for different curing periods. Air-entrained concrete. Type I/II cement. Drying only.

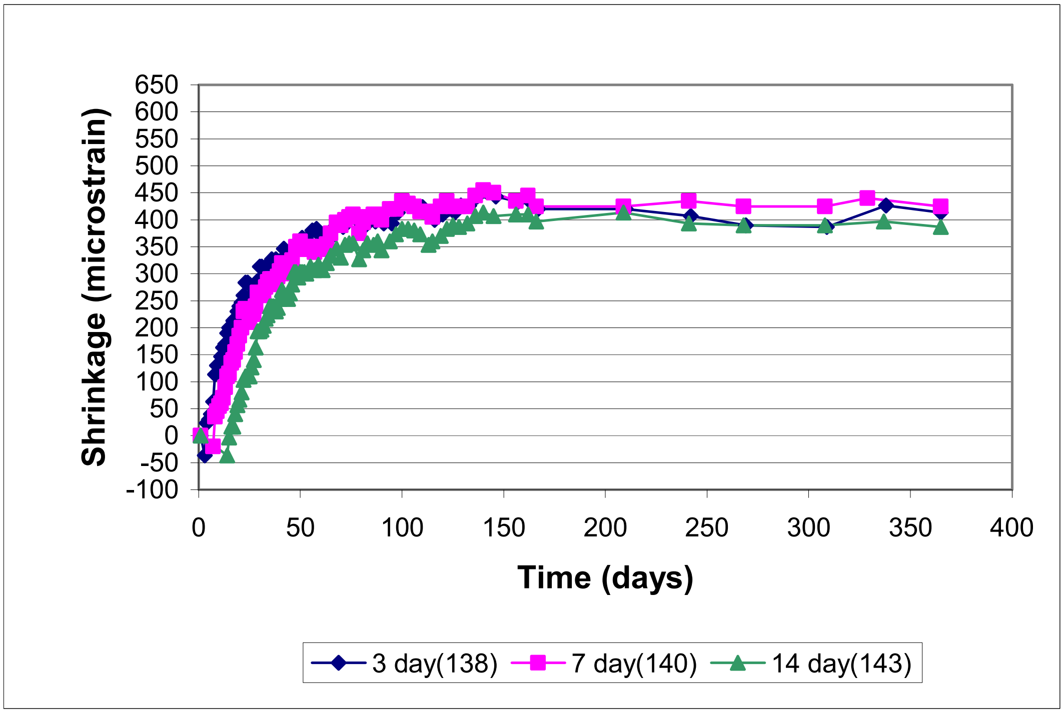

Figure 3.34a - Free Shrinkage,Program IV. Average free shrinkage vs. time through 365 days for different curing periods. Air-entrained concrete. Type I/II cement.

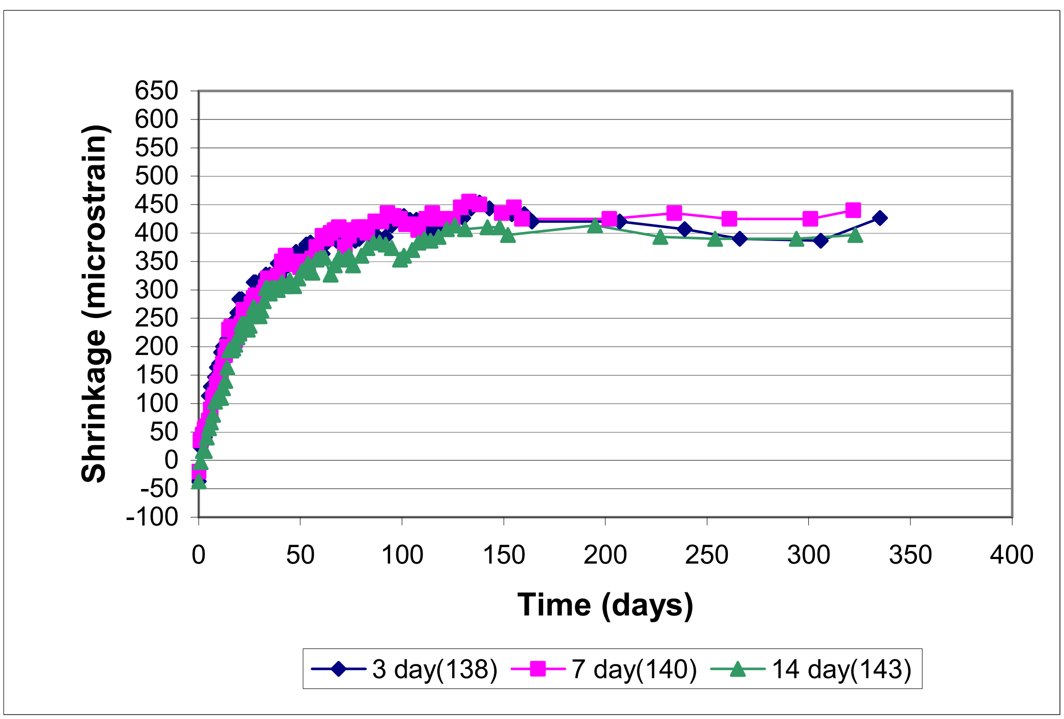

Figure 3.34b - Free Shrinkage,Program IV. Average free shrinkage vs. time through 330 days for different curing periods. Air-entrained concrete. Type I/II cement. Drying only.

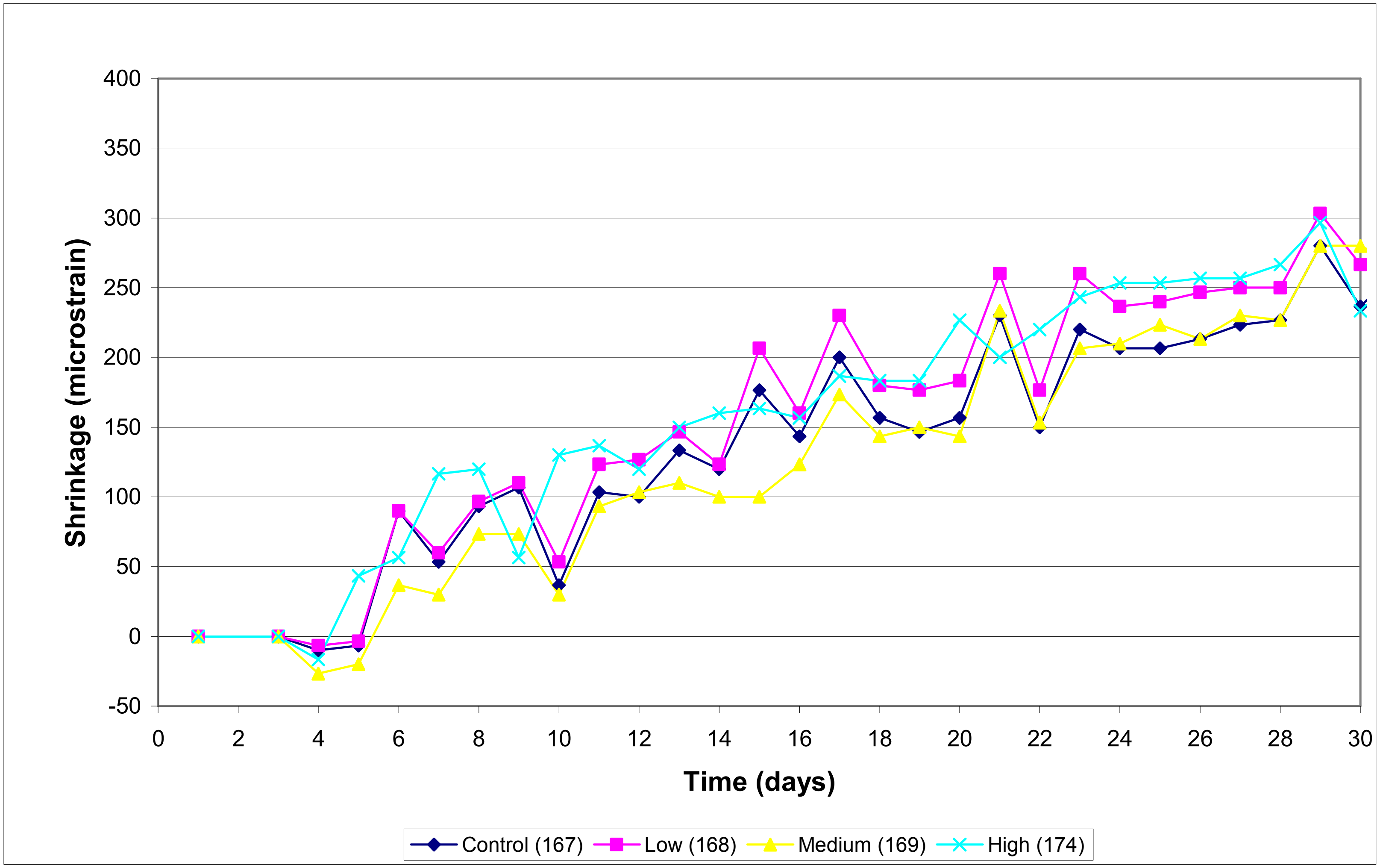

Figure 3.35 - Free Shrinkage Test, Program V. Average free shrinkage vs. time through 30 days. Comparing concretes with different dosage rates of Glenium 3000NS.

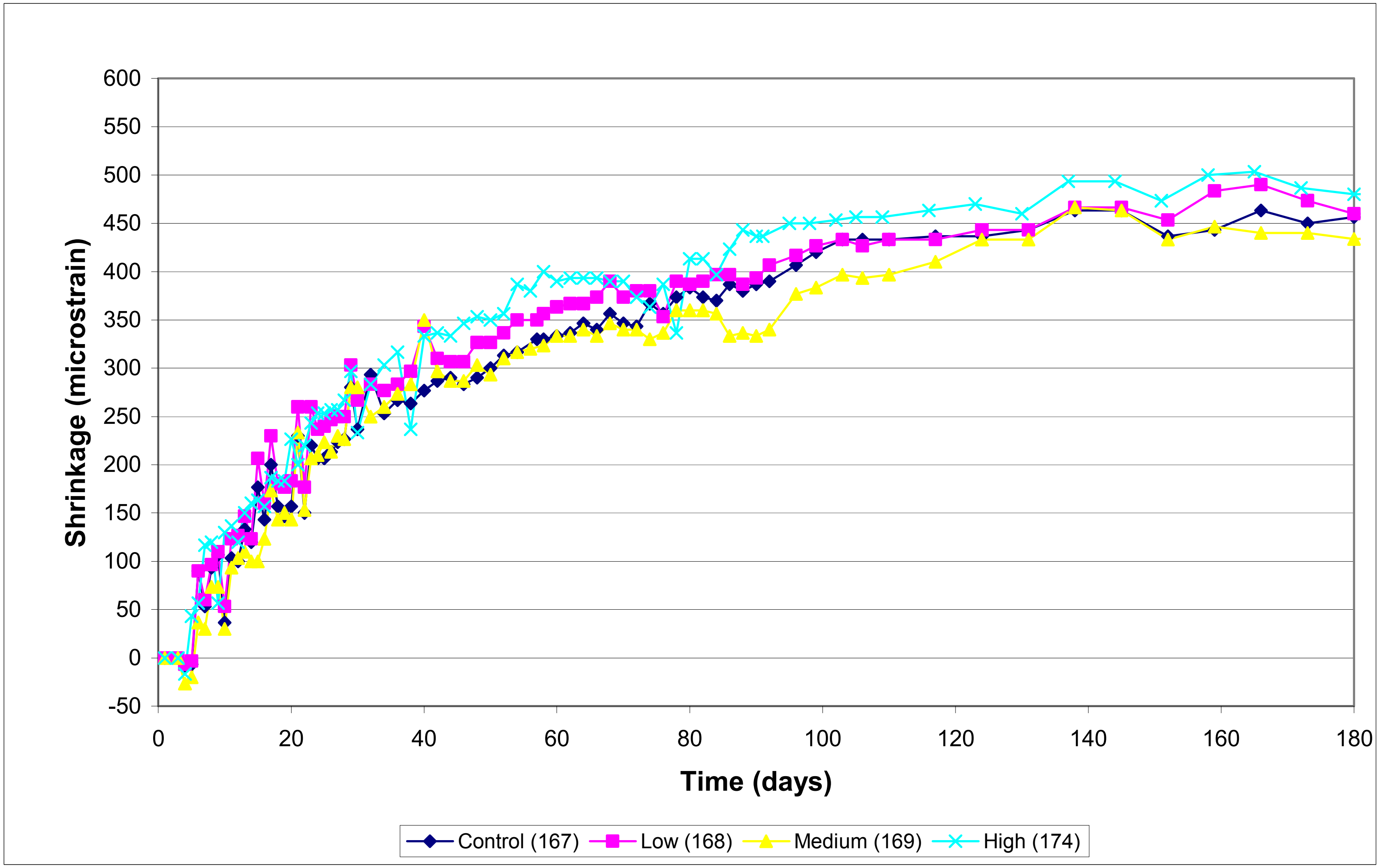

Figure 3.36 - Free Shrinkage Test, Program V. Average free shrinkage vs. time through 180 days. Comparing concretes with different dosage rates of Glenium 3000NS.

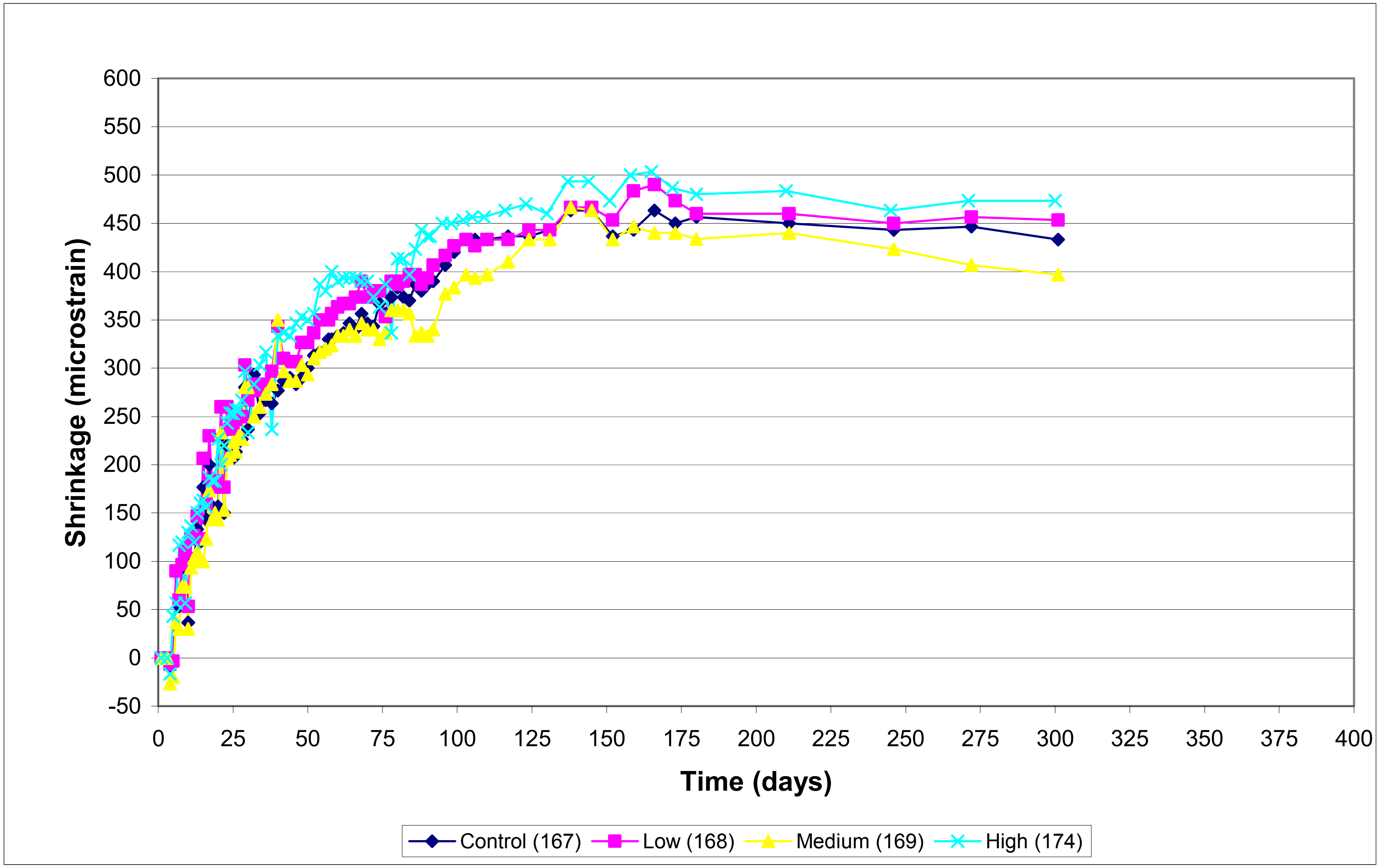

Figure 3.37 - Free Shrinkage Test, Program V. Average free shrinkage vs. time through 300 days. Comparing concretes with different dosage rates of Glenium 3000NS.

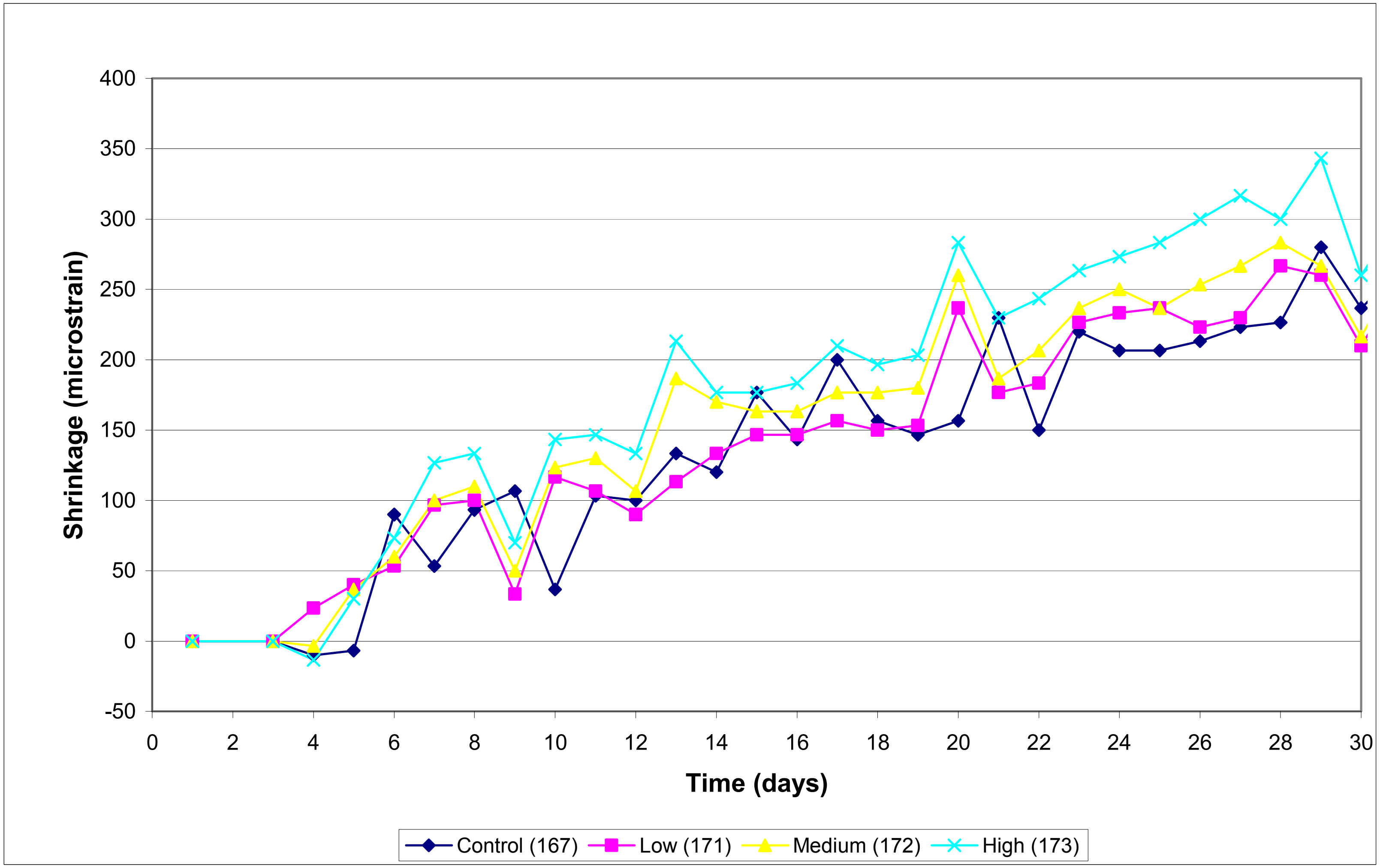

Figure 3.38 - Free Shrinkage Test, Program V. Average free shrinkage vs. time through 30 days. Comparing concretes with different dosage rates of Rheobuild 1000.

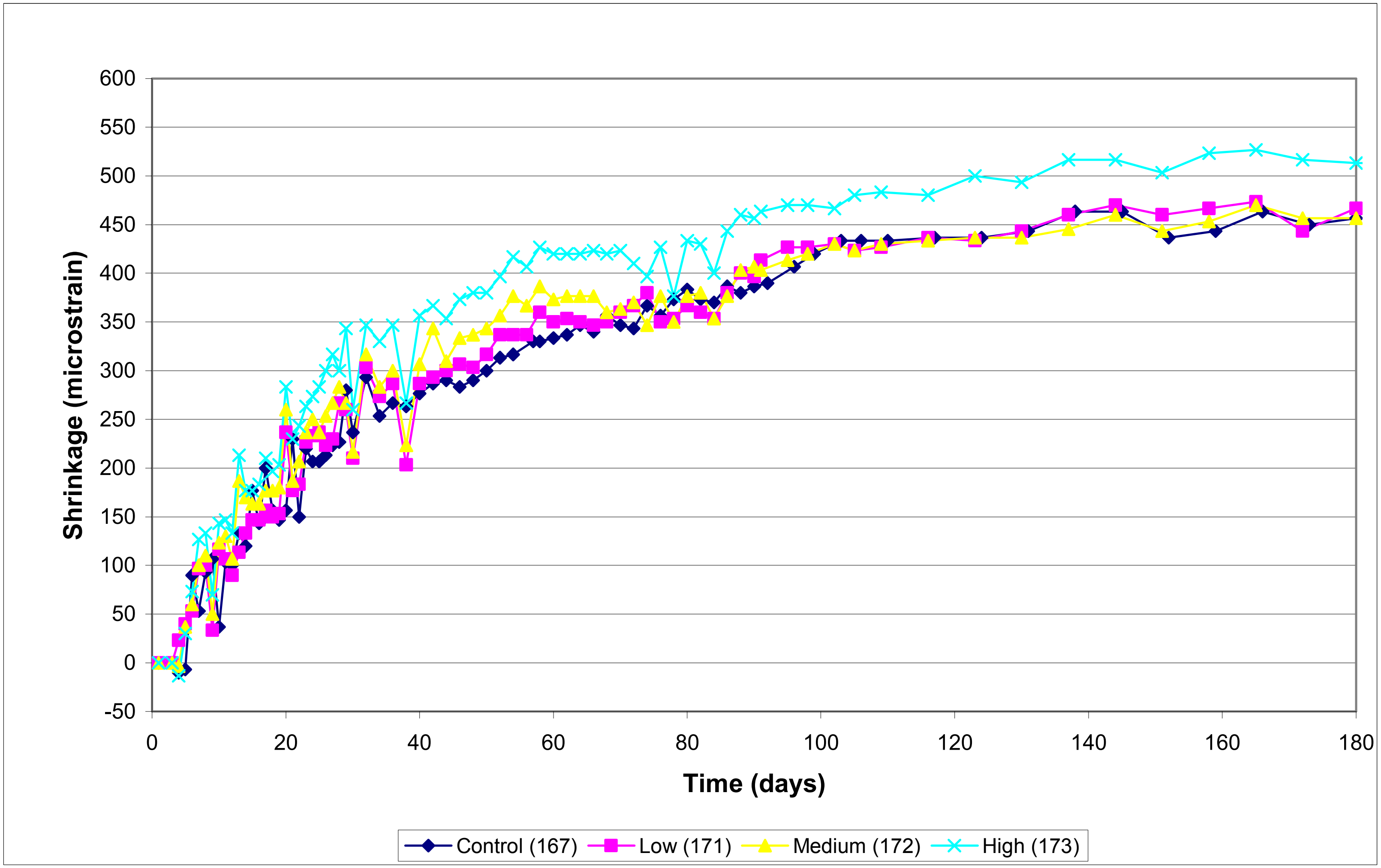

Figure 3.39 - Free Shrinkage Test, Program V. Average free shrinkage vs. time through 180 days. Comparing concretes with different dosage rates of Rheobuild 1000.

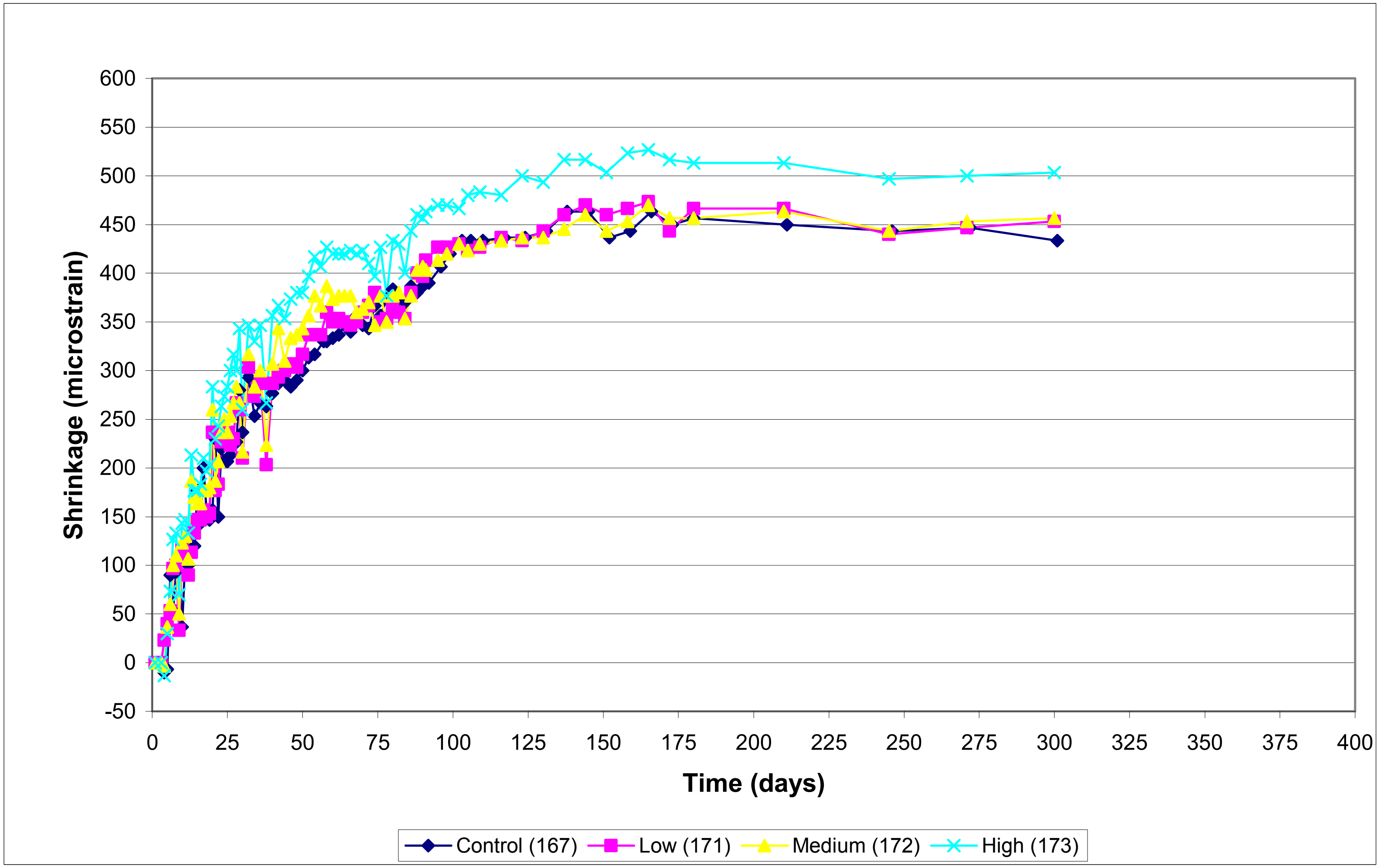

Figure 3.40 - Free Shrinkage Test, Program V. Average free shrinkage vs. time through 300 days. Comparing concretes with different dosage rates of Rheobuild 1000.

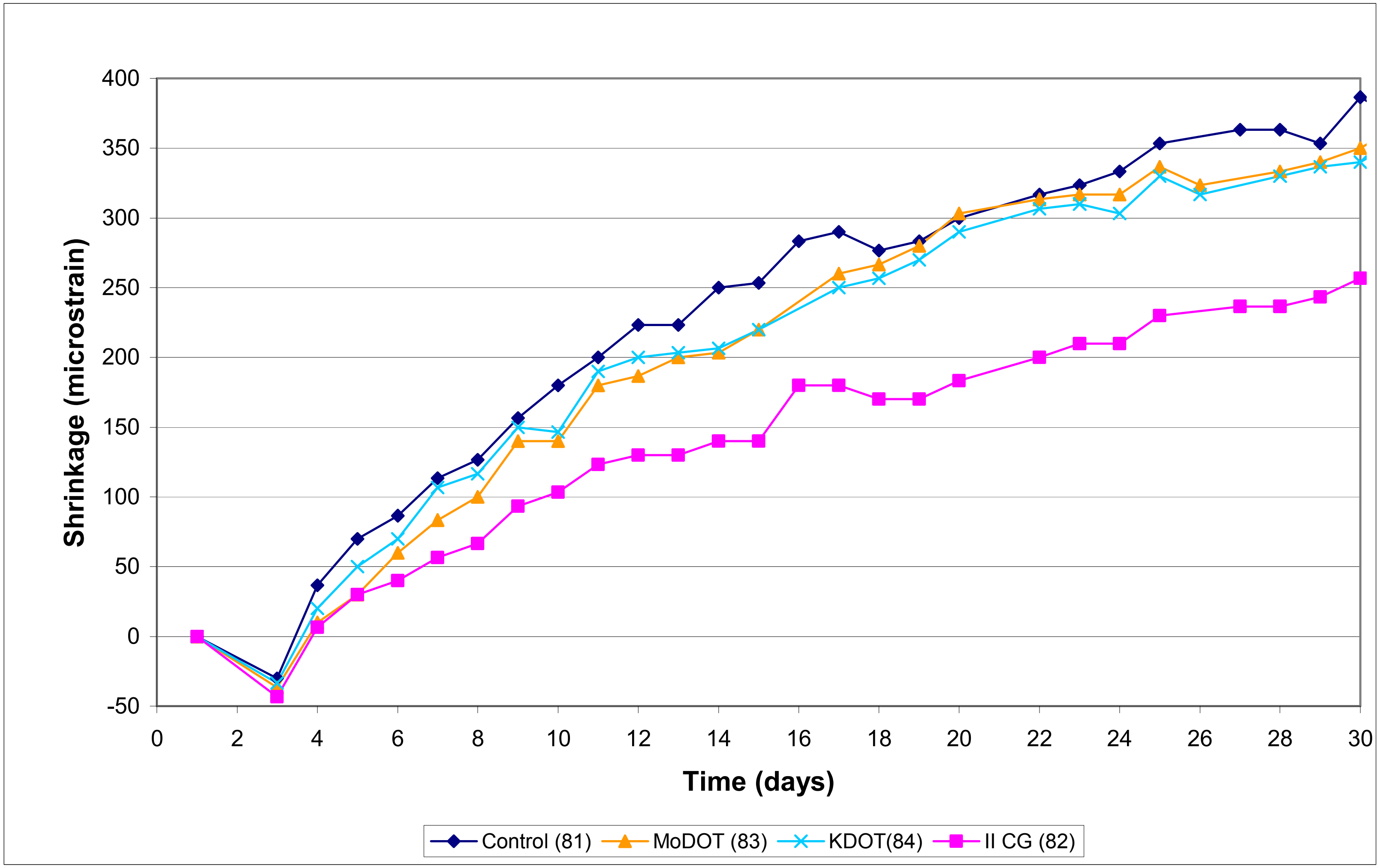

Figure 3.41 - Free Shrinkage Test, Program VI. Average free shrinkage vs. time through 30 days. Comparing bridge deck mixes.

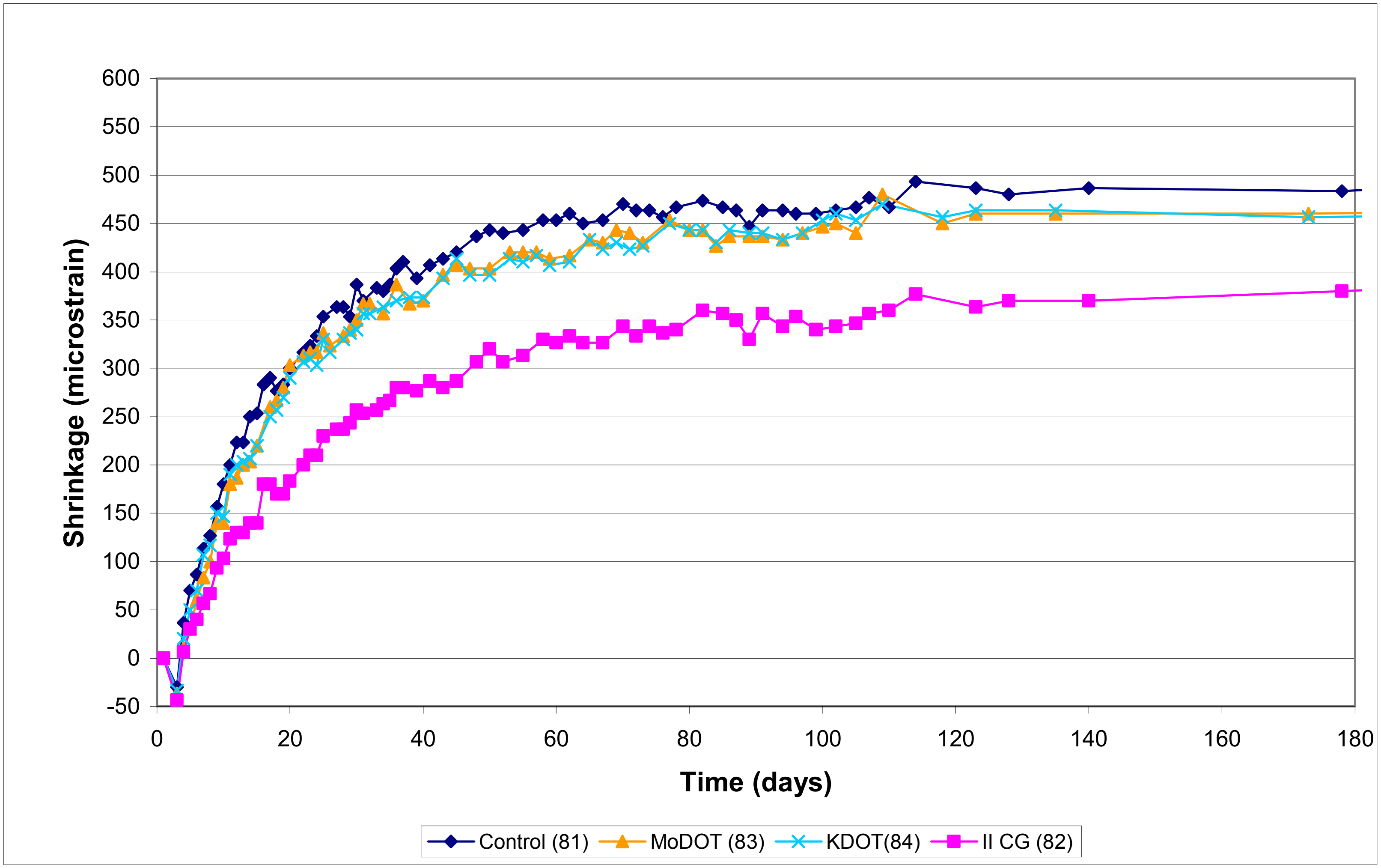

Figure 3.42 - Free Shrinkage Test, Program VI. Average free shrinkage vs. time through 180 days. Comparing bridge deck mixes.

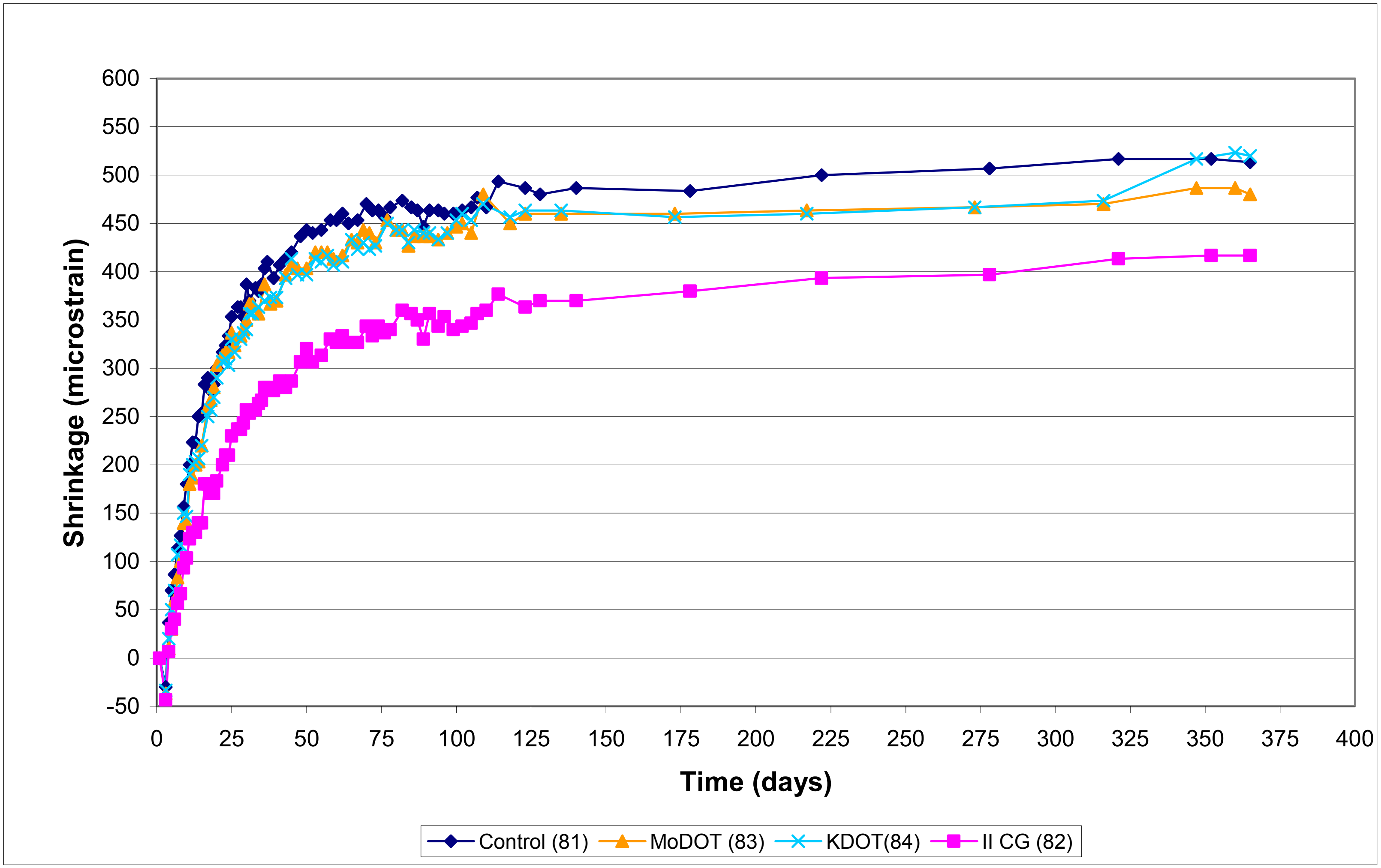

Figure 3.43 - Free Shrinkage Test, Program VI. Average free shrinkage vs. time through 365 days. Comparing bridge deck mixes.

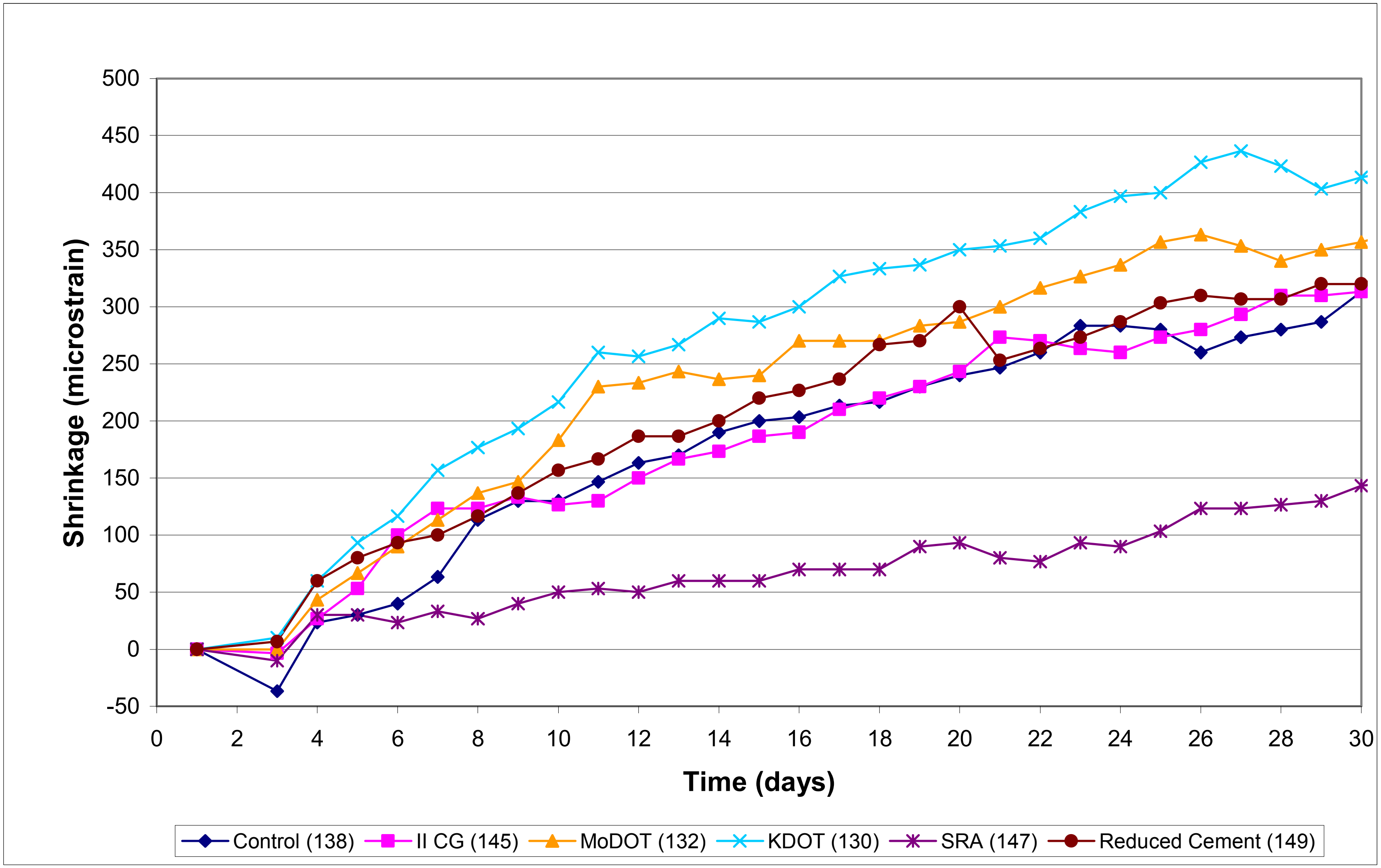

Figure 3.44 - Free Shrinkage Test, Program VII. Average free shrinkage vs. time through 30 days. Comparing bridge deck mixes.

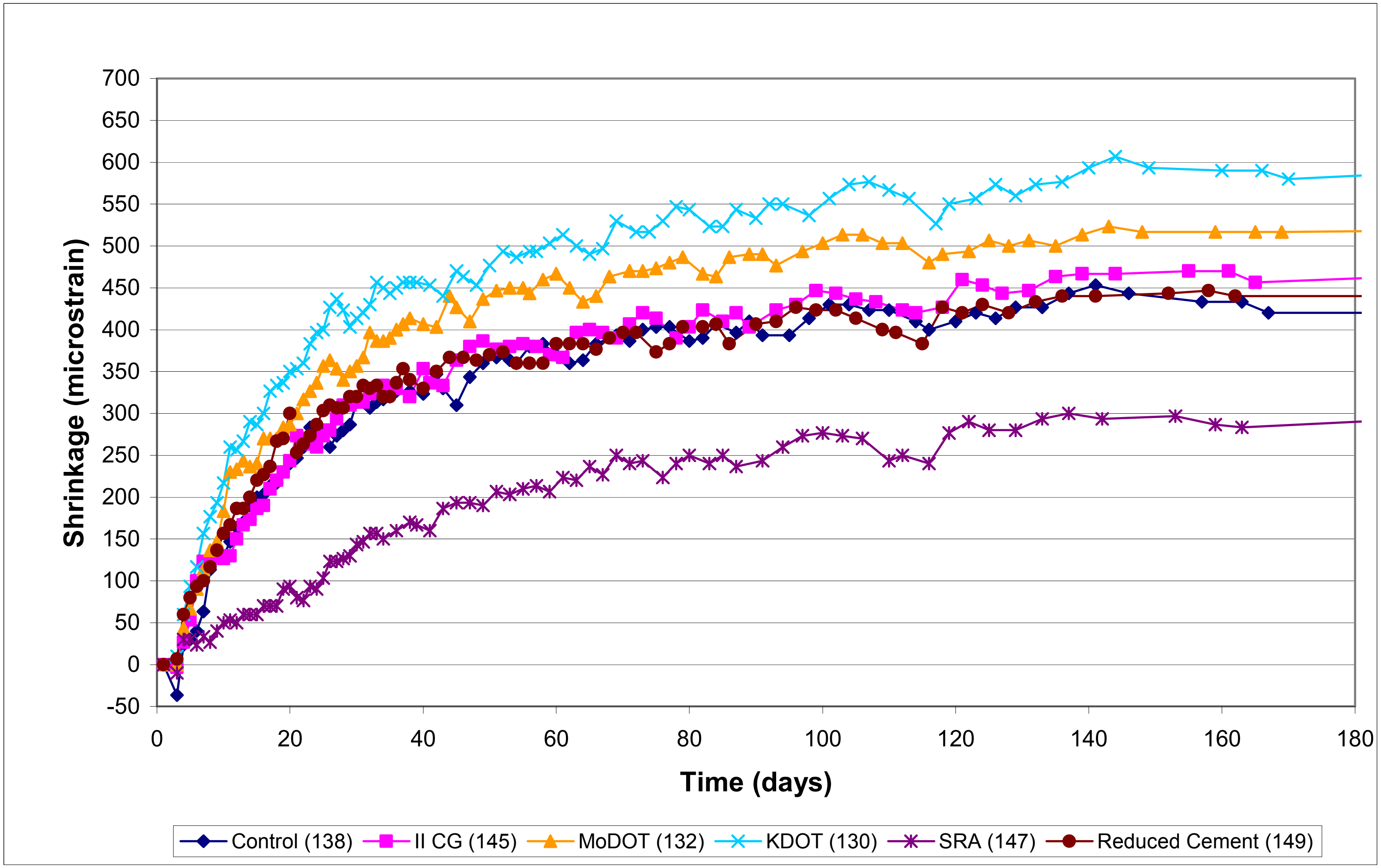

Figure 3.45 - Free Shrinkage Test, Program VII. Average free shrinkage vs. time through 180 days. Comparing bridge deck mixes.

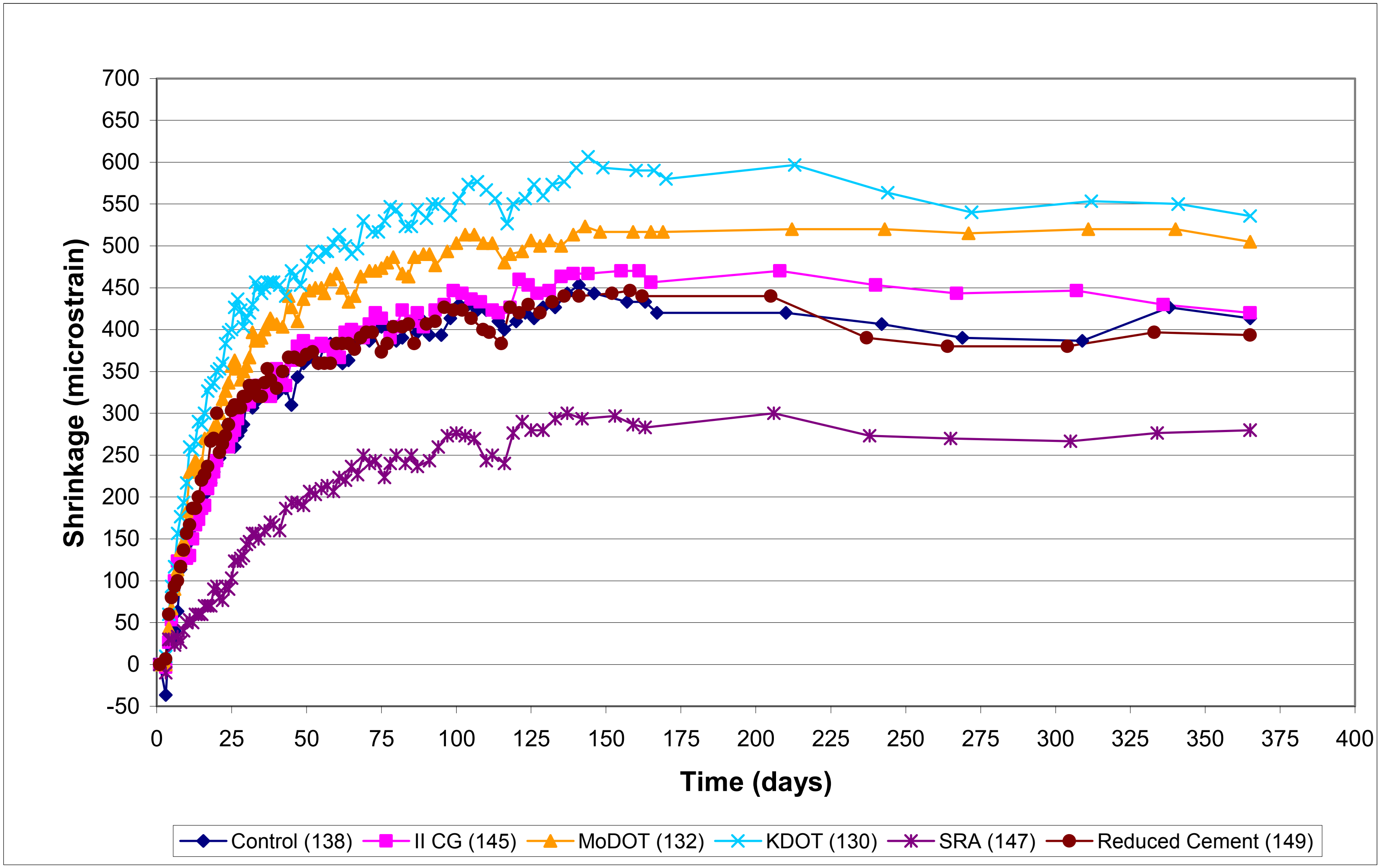

Figure 3.46 - Free Shrinkage Test, Program VII. Average free shrinkage vs. time through 365 days. Comparing bridge deck mixes.

APPENDIX A

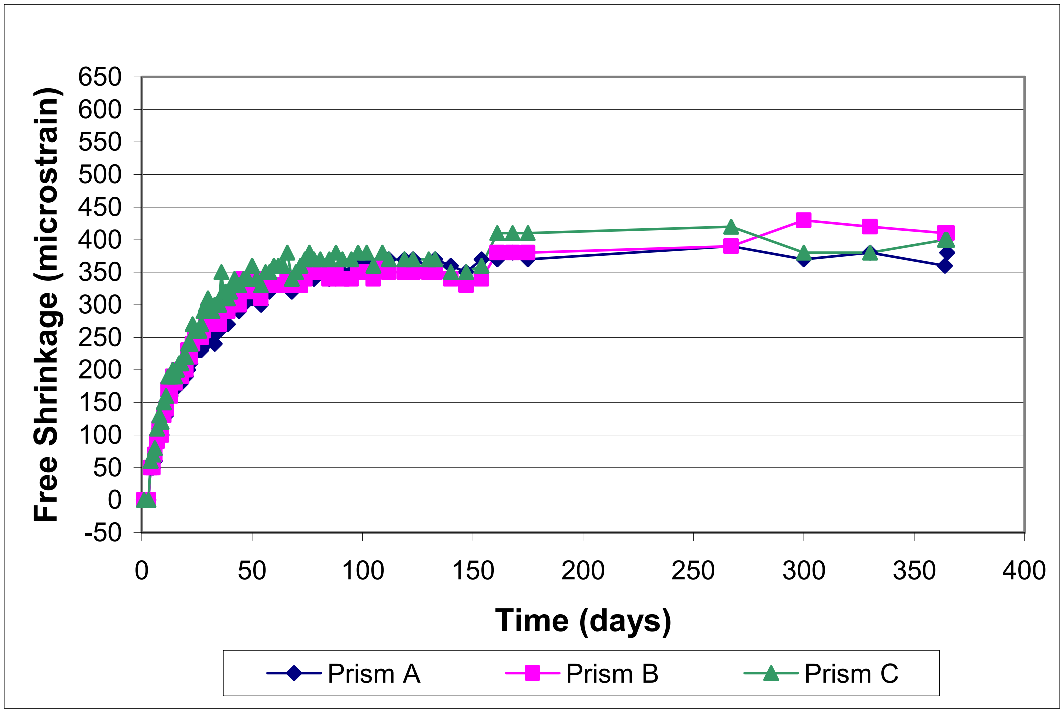

Figure A3.1 - Free Shrinkage, Batch 62. 80% Agg., 0.40 w/c., Type I/II cement. Drying begins at 3 days.

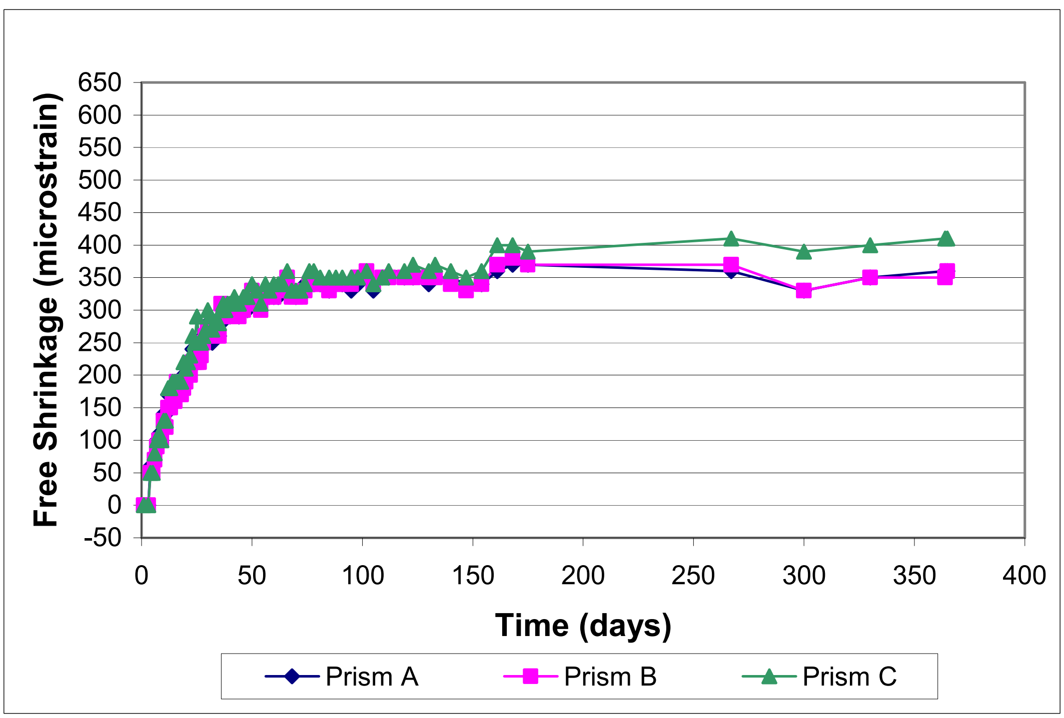

Figure A3.2 - Free Shrinkage, Batch 63. 80% Agg., 0.45 w/c., Type I/II cement. Drying begins at 3 days.

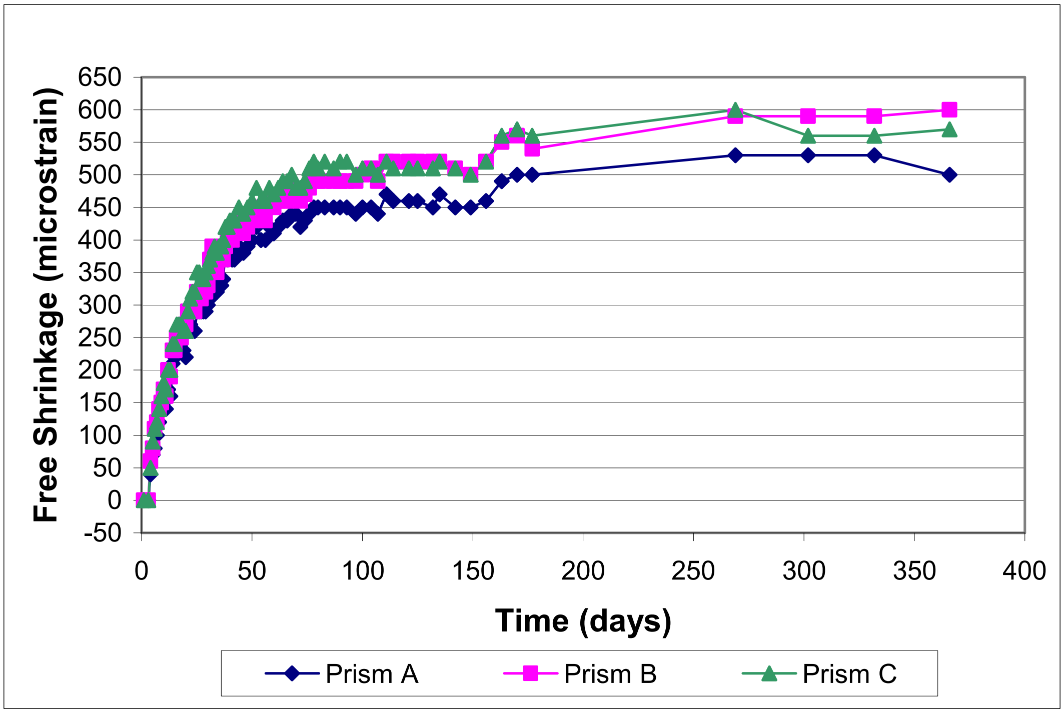

Figure A3.3 - Free Shrinkage, Batch 64. 70% Agg., 0.45 w/c., Type I/II cement. Drying begins at 3 day.

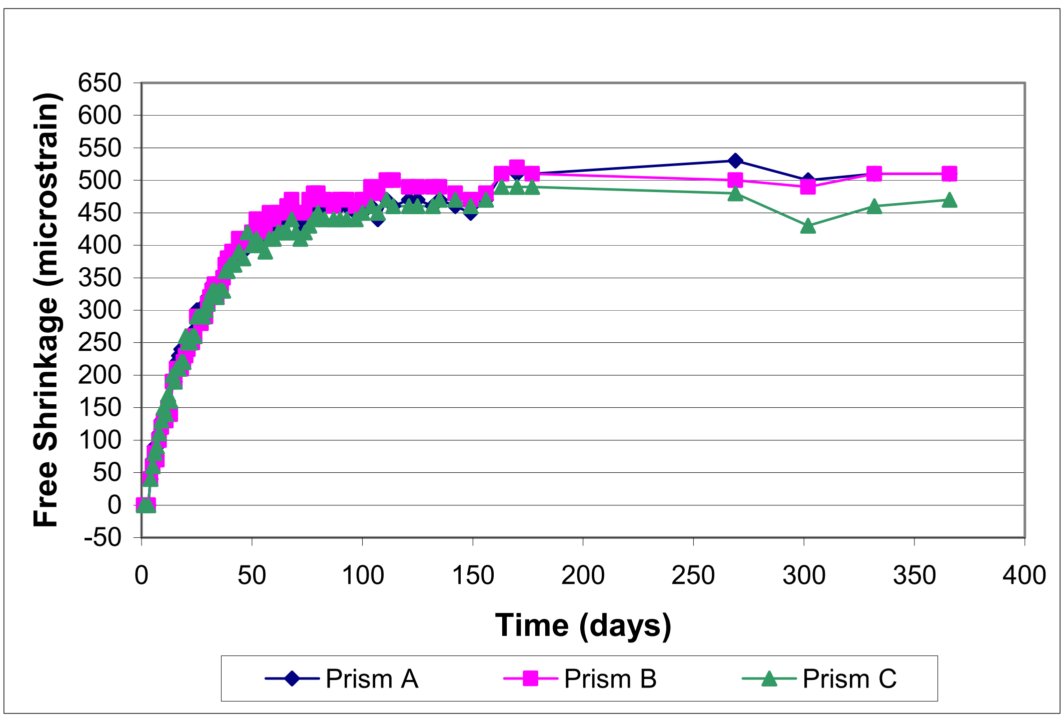

Figure A3.4 - Free Shrinkage, Batch 65. 70% Agg., 0.50 w/c., Type I/II cement. Drying begins on day 3.

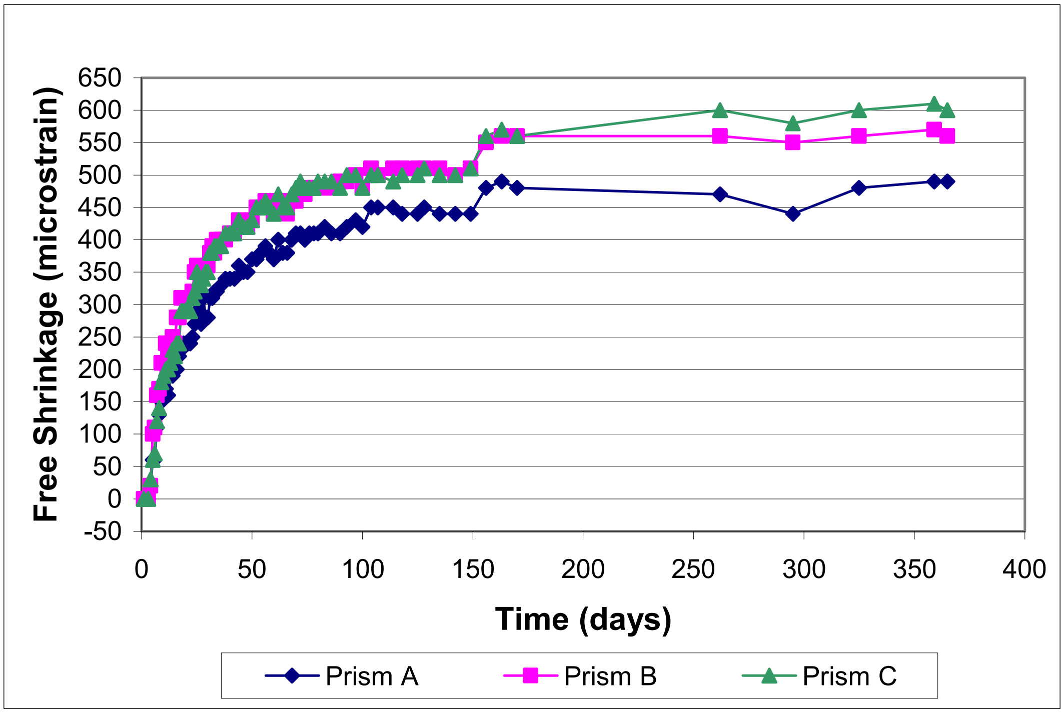

Figure A3.5 - Free Shrinkage, Batch 66. 70% Agg., 0.40 w/c., Type I/II cement. Drying begins on day 3.

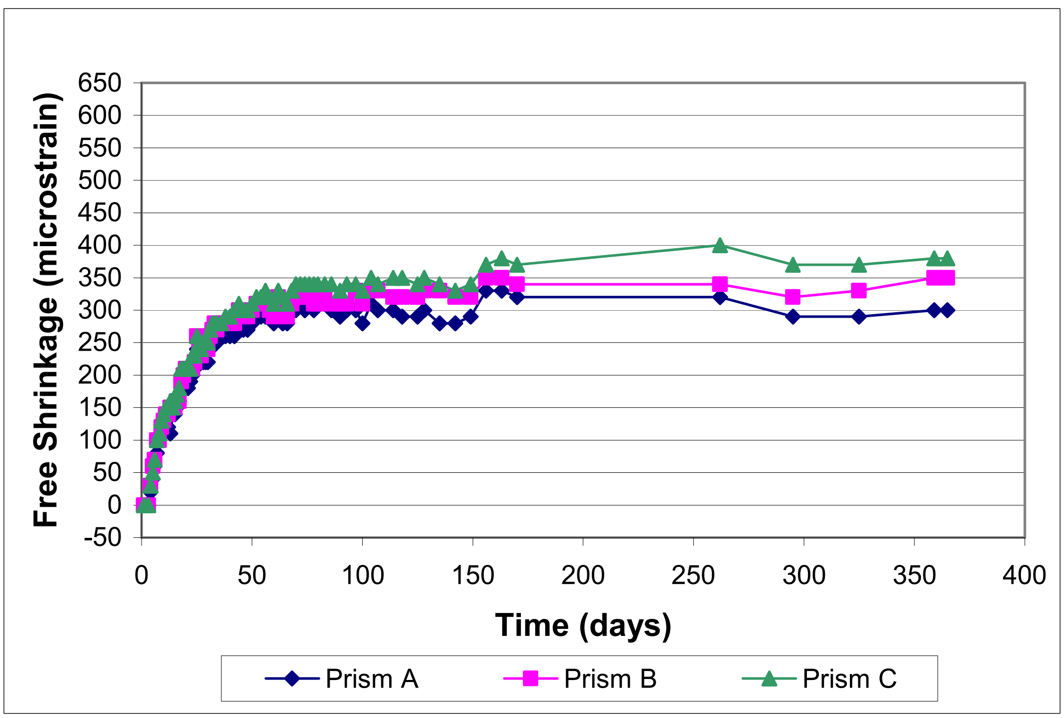

Figure A3.6 - Free Shrinkage, Batch 67. 80% Agg., 0.50 w/c., Type I/II cement. Drying begins on day 3.

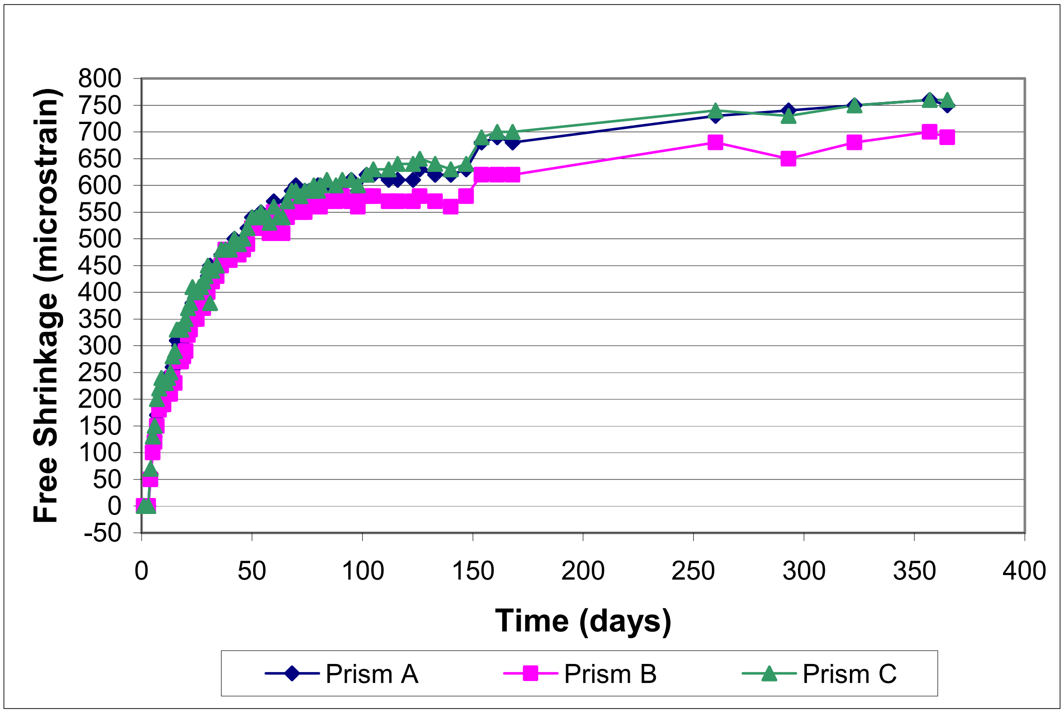

Figure A3.7 - Free Shrinkage, Batch 68. 60% Agg., 0.40 w/c., Type I/II cement. Drying begins on day 3.

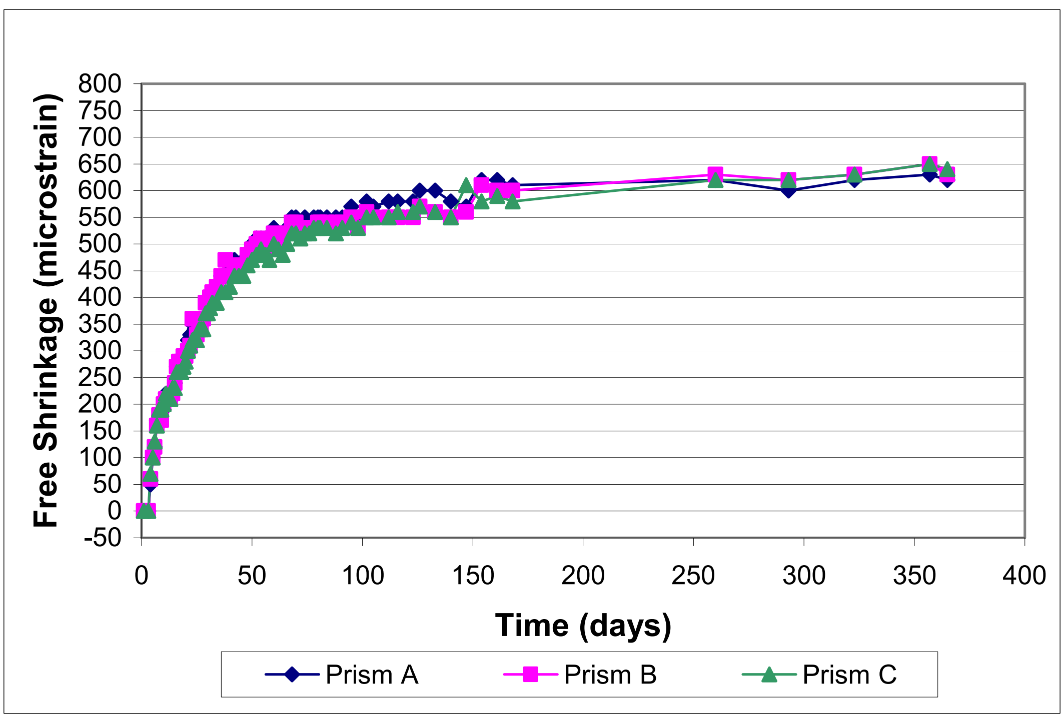

Figure A3.8 - Free Shrinkage, Batch 69. 60% Agg., 0.45 w/c., Type I/II cement. Drying begins on day 3.

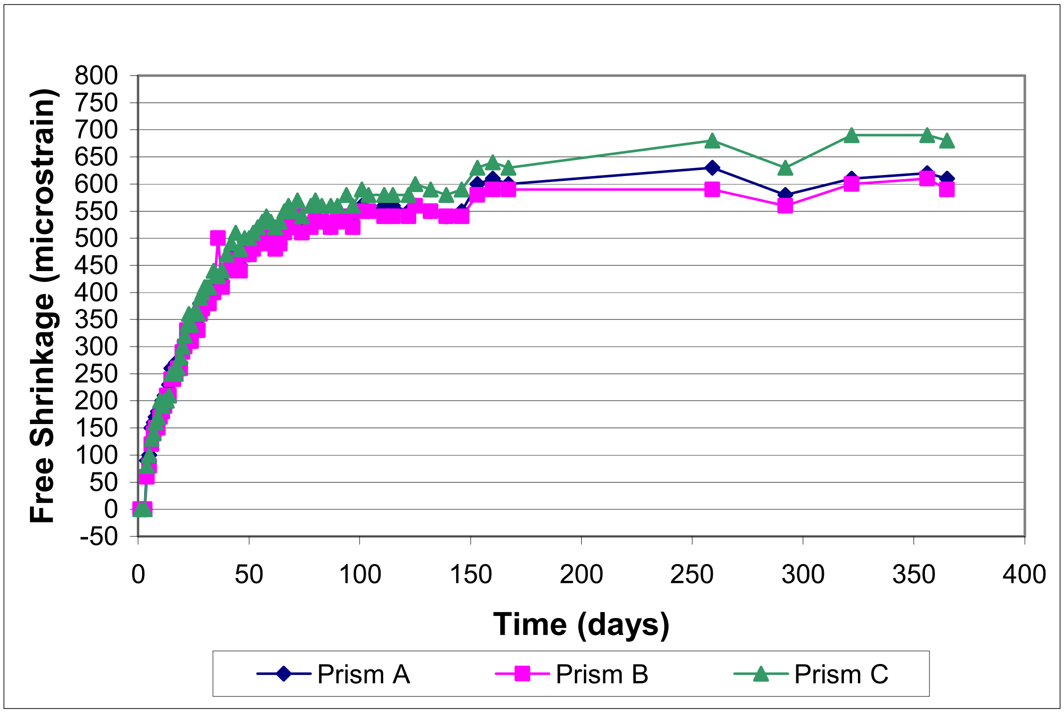

Figure A3.9 - Free Shrinkage, Batch 70. 60% Agg., 0.50 w/c., Type I/II cement. Drying begins on day 3.

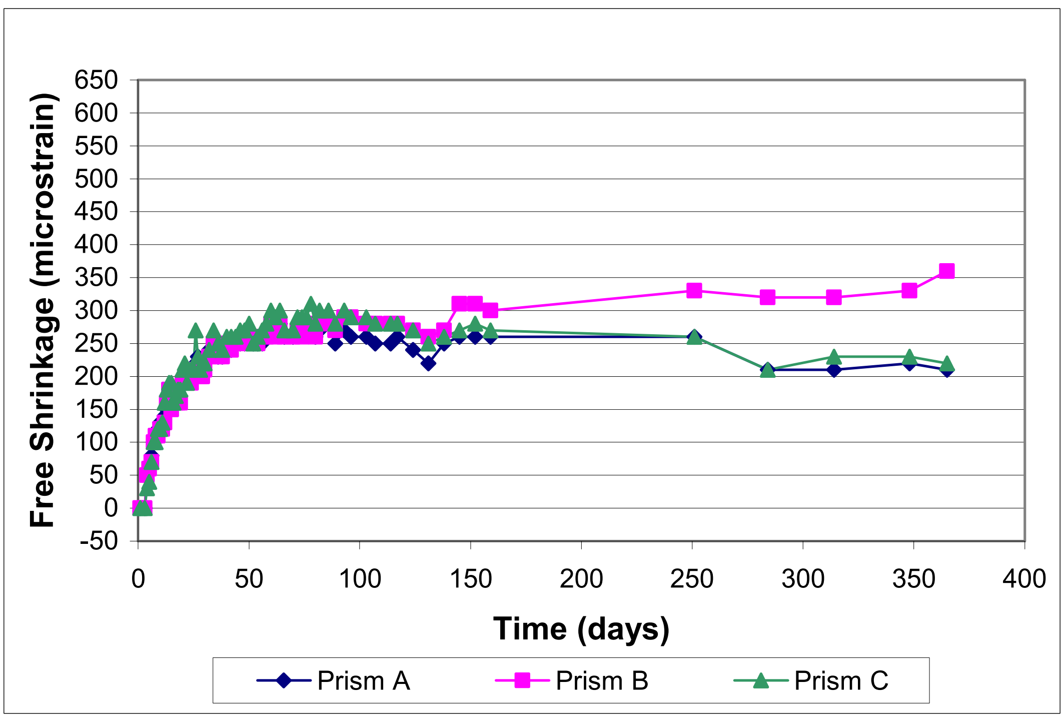

Figure A3.10 - Free Shrinkage, Batch 71. 80% Agg., 0.40 w/c., Type II Coarse-Ground cement. Drying begins on day 3.

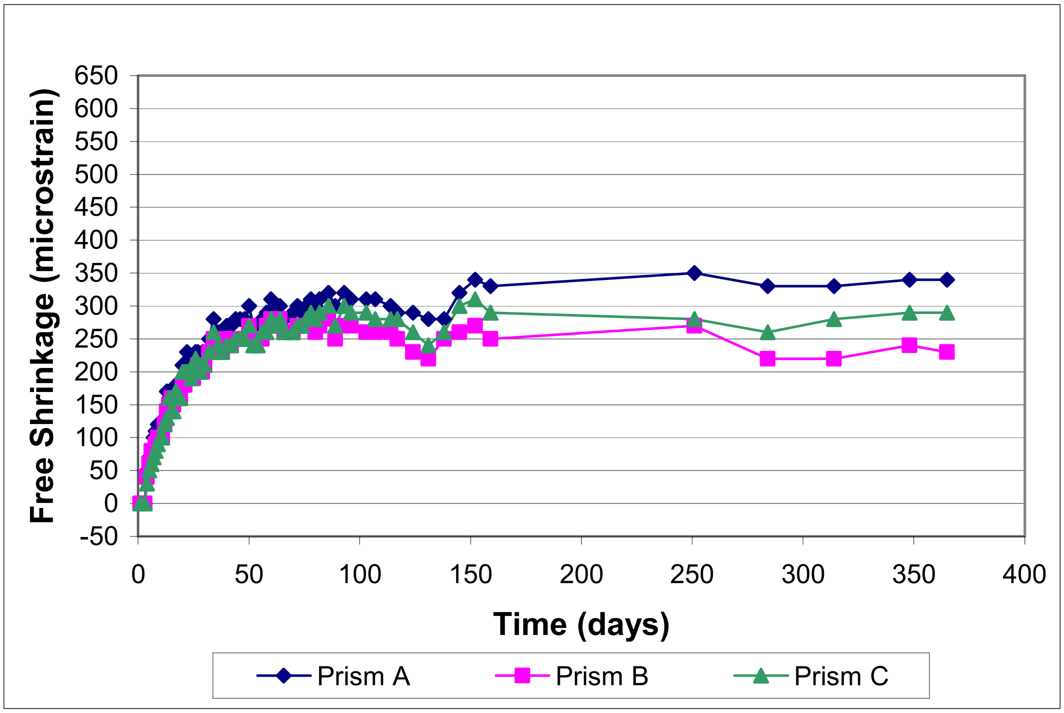

Figure A3.11 - Free Shrinkage, Batch 72. 80% Agg., 0.45 w/c., Type II Coarse-Ground cement. Drying begins on day 3.

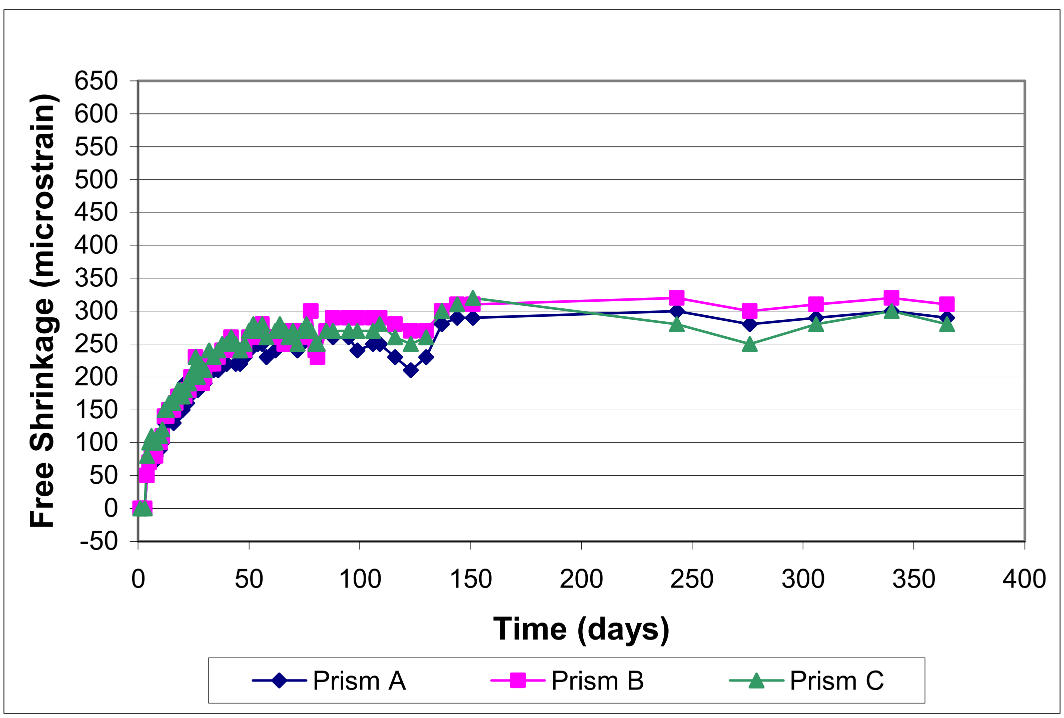

Figure A3.12 - Free Shrinkage, Batch 73. 80% Agg., 0.50 w/c., Type II Coarse-Ground cement. Drying begins on day 3.

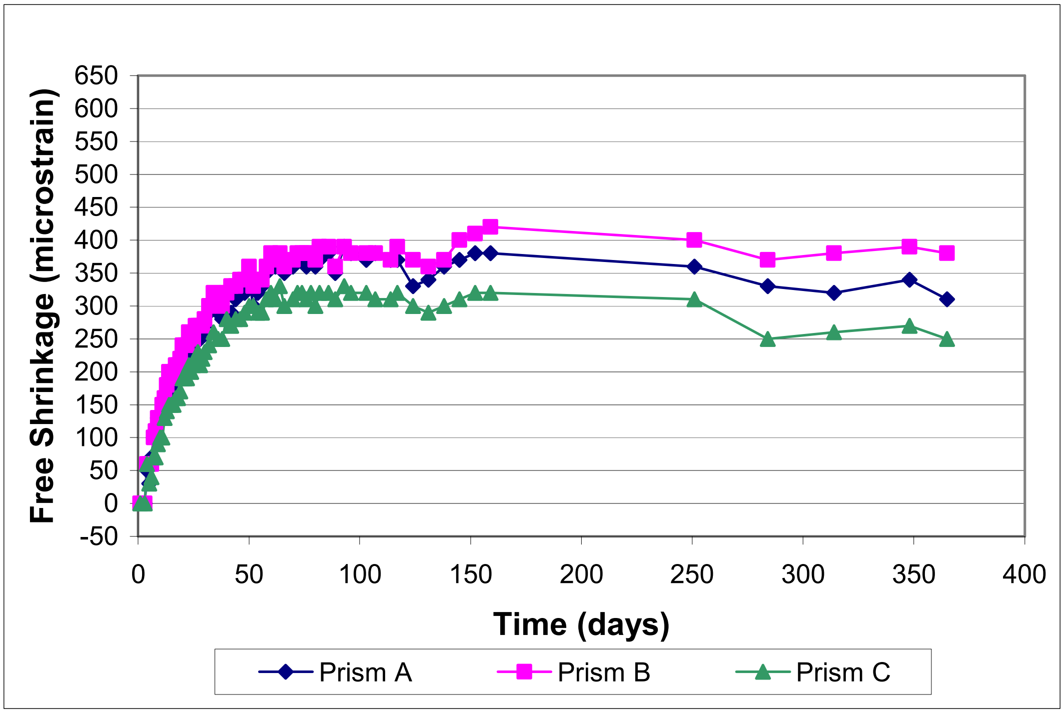

Figure A3.13 - Free Shrinkage, Batch 74. 70% Agg., 0.40 w/c., Type II Coarse-Ground cement. Drying begins on day 3.

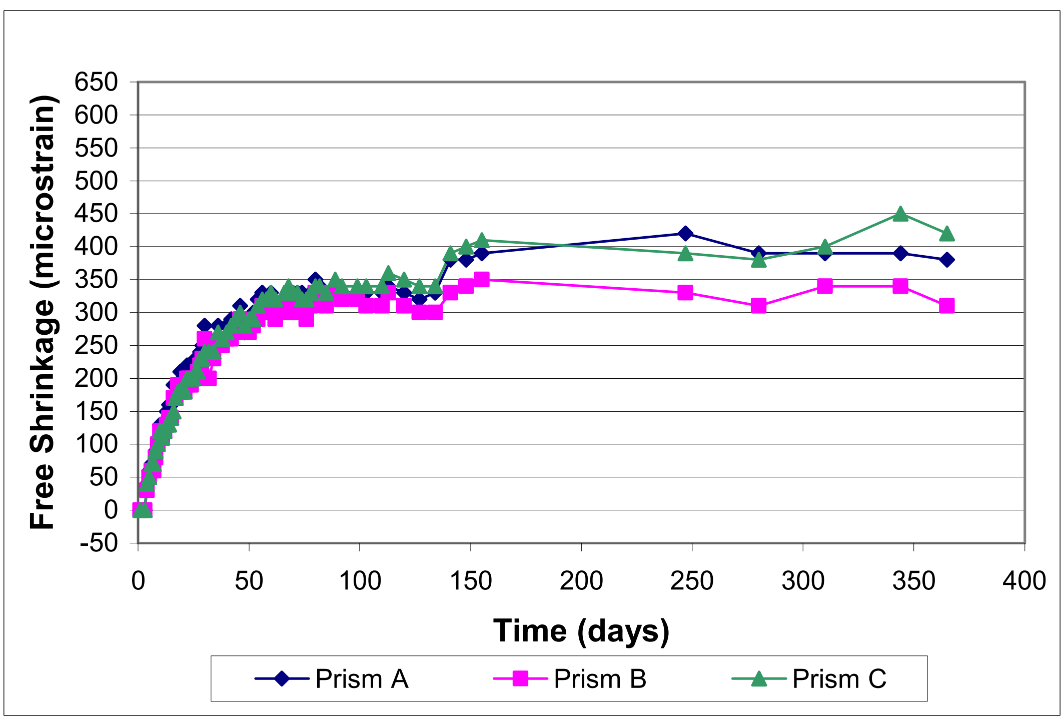

Figure A3.14 - Free Shrinkage, Batch 75. 70% Agg., 0.45 w/c., Type II Coares-Ground cement. Drying begins on day 3.

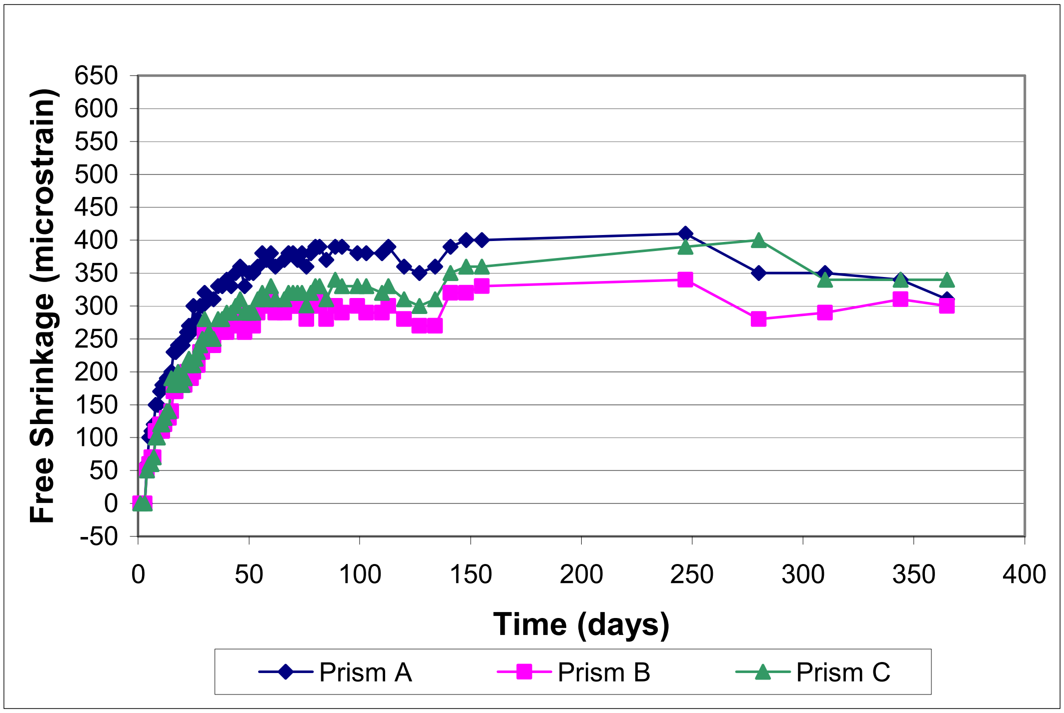

Figure A3.15 - Free Shrinkage, Batch 76. 70% Agg., 0.50 w/c., Type II Coarse-Ground cement. Drying begins on day 3.

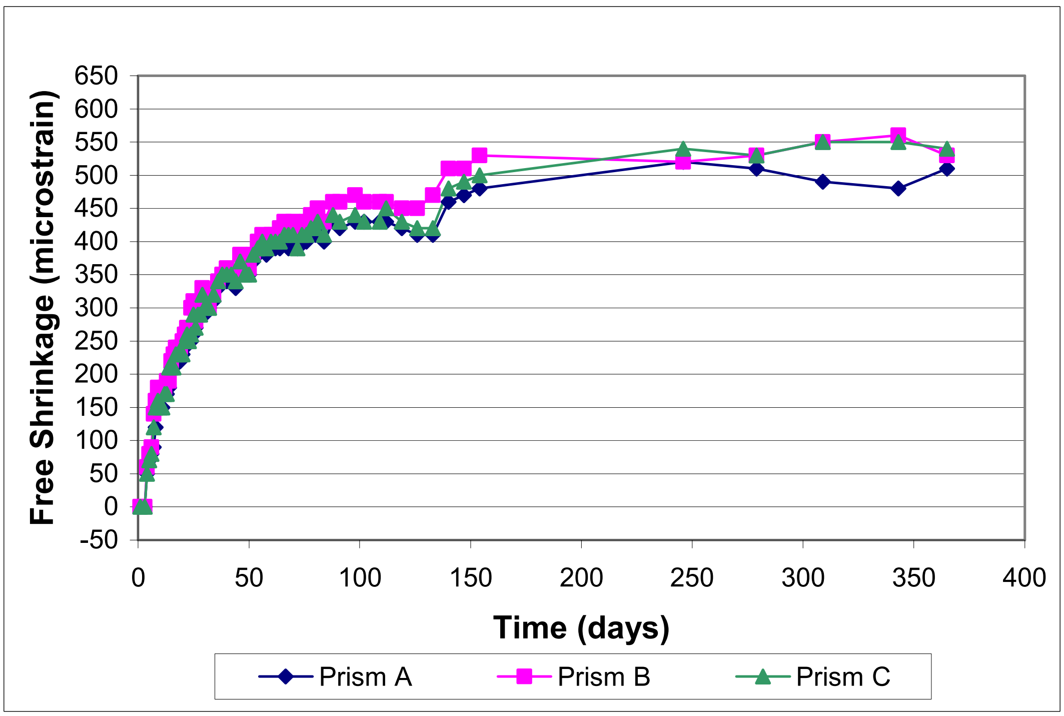

Figure A3.16 - Free Shrinkage, Batch 77. 60% Agg., 0.40 w/c., Type II Coarse-Ground cement. Drying begins on day 3.

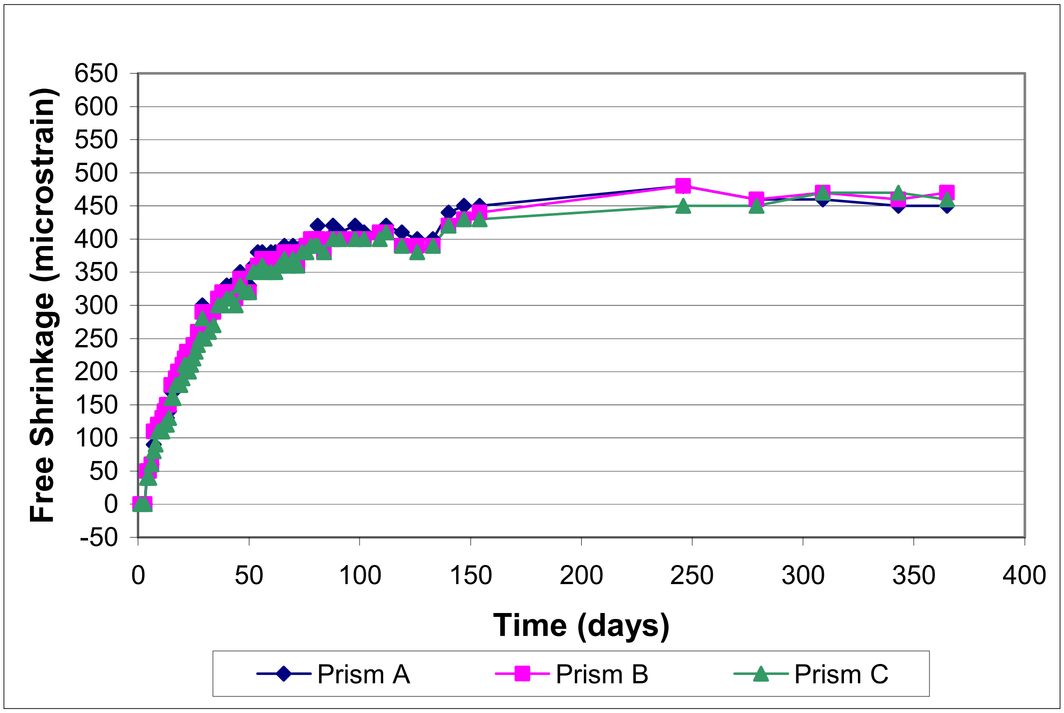

Figure A3.17 - Free Shrinkage, Batch 78. 60% Agg., 0.45 w/c., Type II Coarse-Ground cement. Drying begins on day 3.

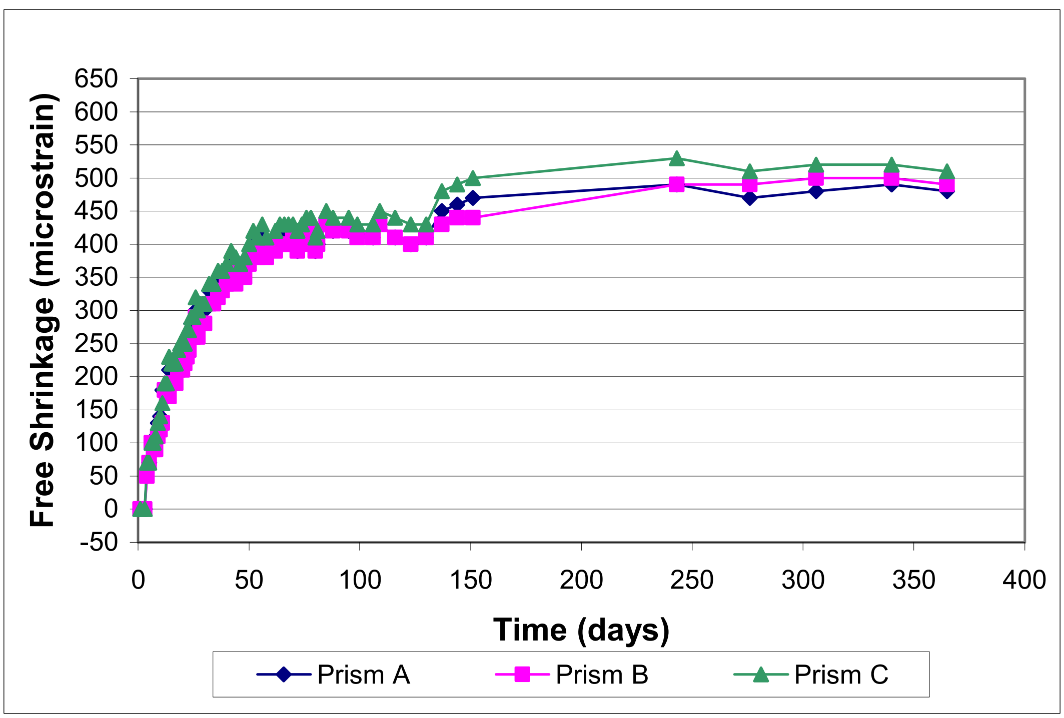

Figure A3.18 - Free Shrinkage, Batch 79. 60% Agg., 0.50 w/c., Type II Coarse-Ground cement. Drying begins on day 3.

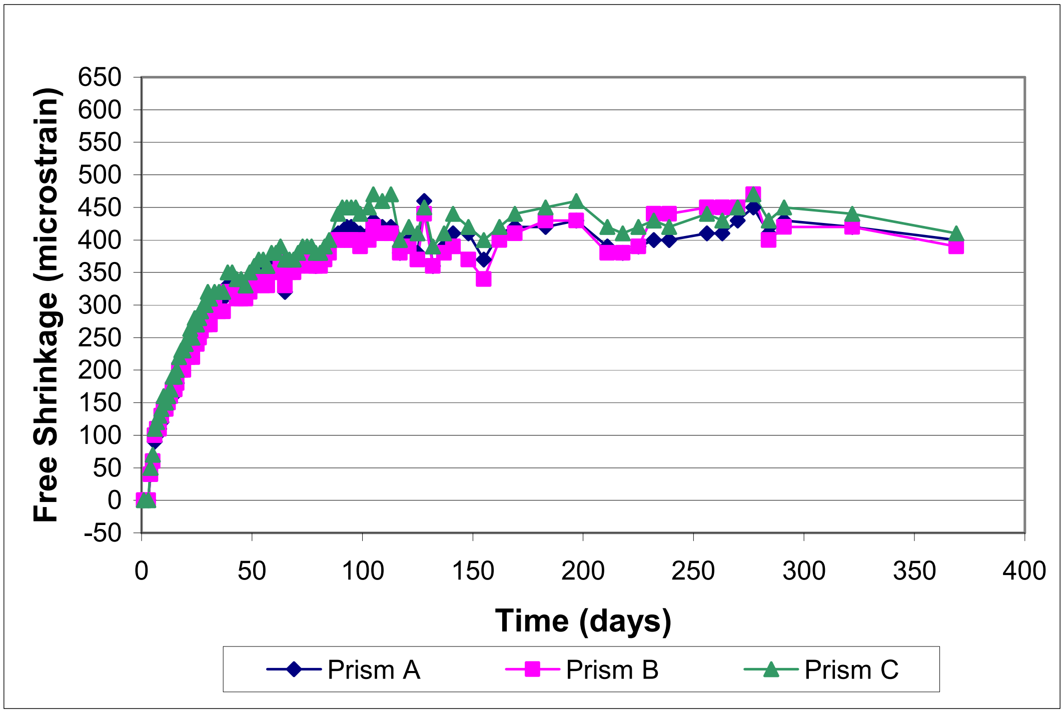

Figure A3.19 - Free Shrinkage, Batch 85. 70% Agg., 0.45 w/c., Type I/II cement. Drying begins at 3 days. Control, no mineral admixtures.

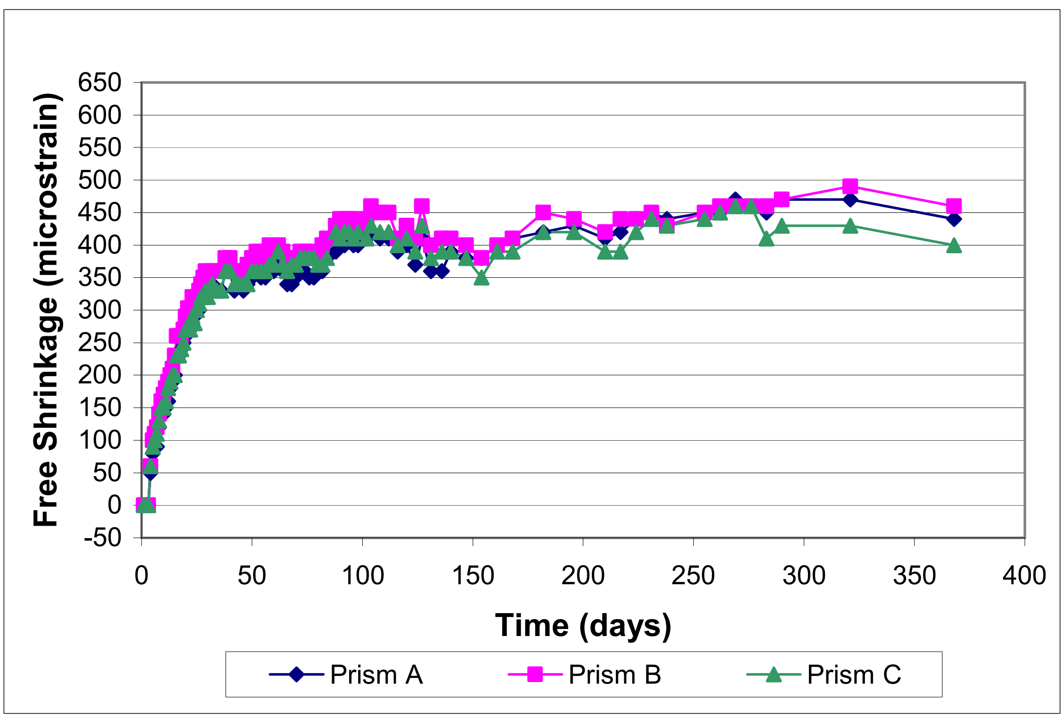

Figure A3.20 - Free Shrinkage, Batch 86. 70% Agg., 0.45 w/c., Type I/II cement. Drying begins at 3 days. 30% slag replacement.

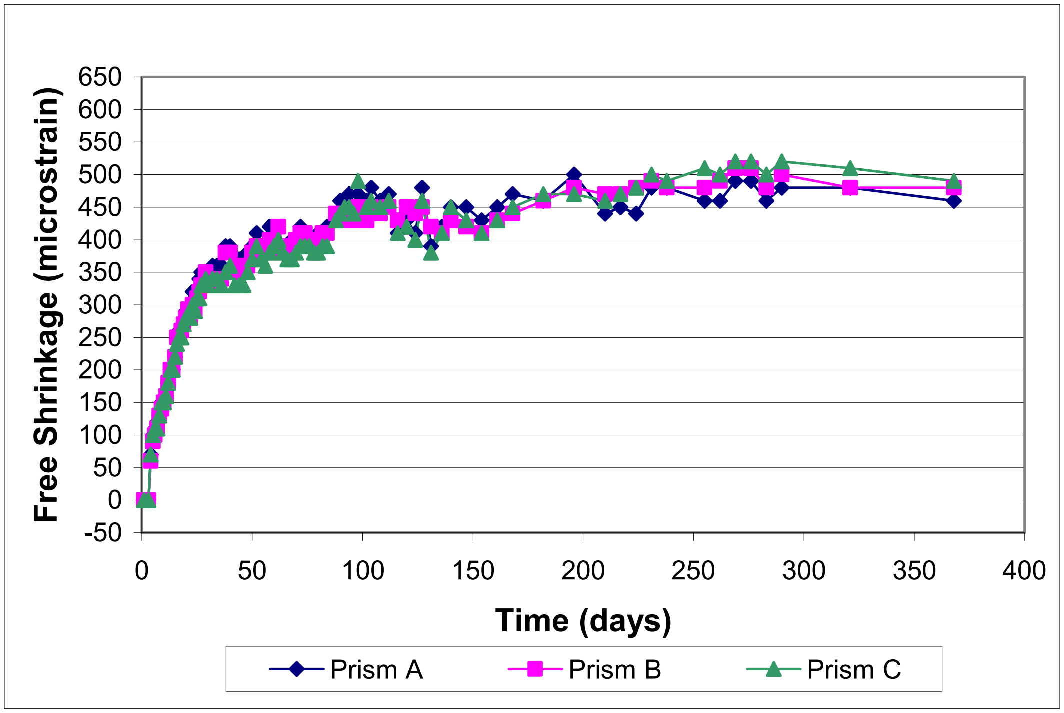

Figure A3.21 - Free Shrinkage, Batch 87. 70% Agg., 0.45 w/c., Type I/II cement. Drying begins at 3 days. 30% Class C fly ash replacement.

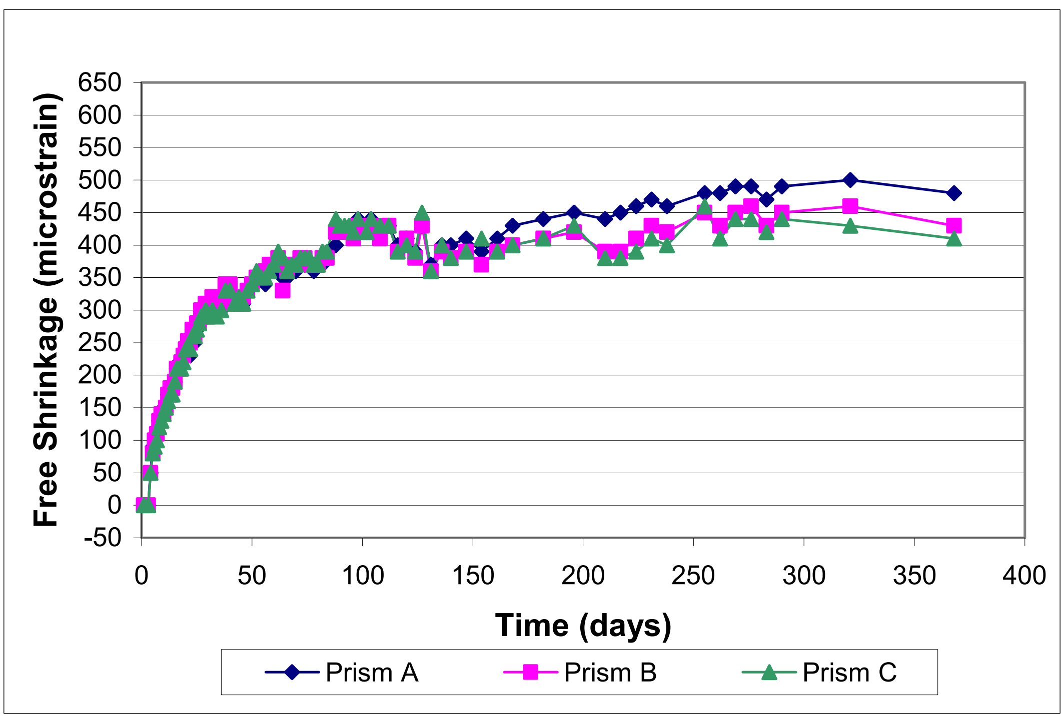

Figure A3.22 - Free Shrinkage, Batch 88. 70% Agg., 0.45 w/c., Type I/II cement. Drying begins at 3 days. 10% silica fume replacement.

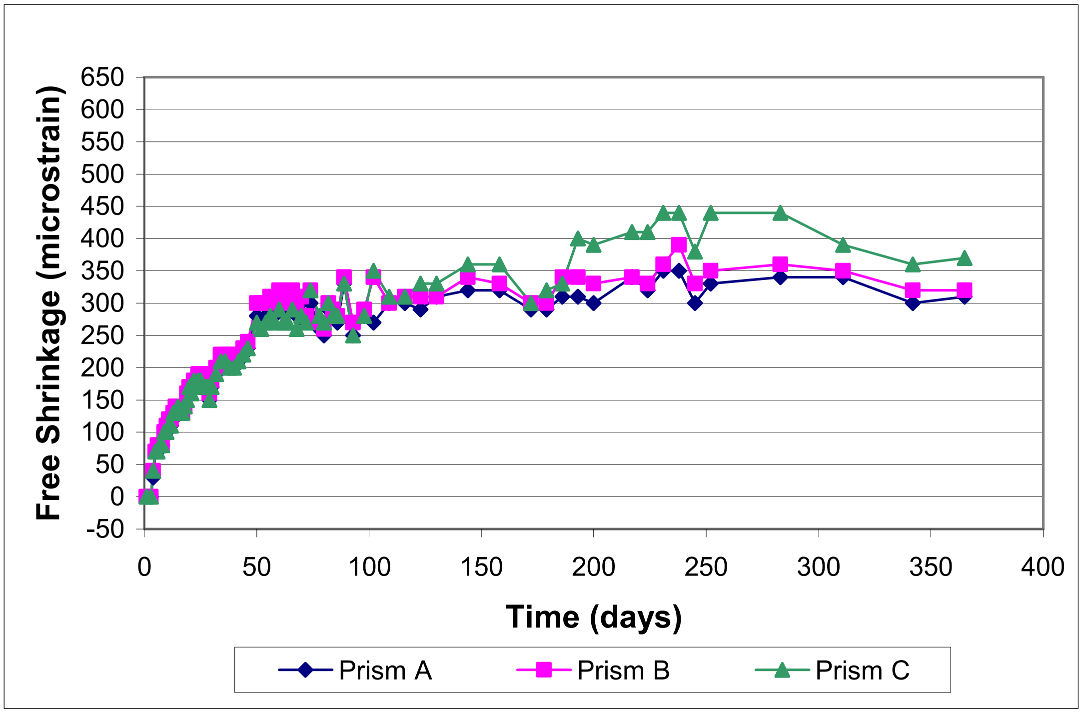

Figure A3.23 - Free Shrinkage, Batch 94. 70% Agg., 0.45 w/c., Type I/II cement. Drying begins at 3 days. Quartzite

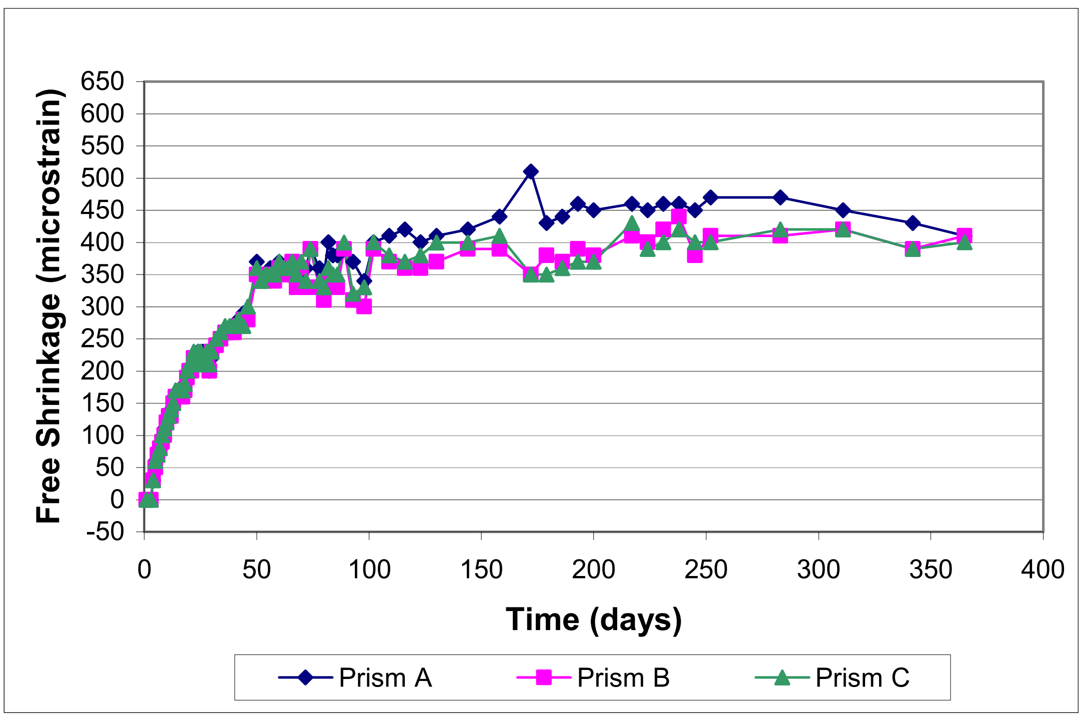

Figure A3.24 - Free Shrinkage, Batch 95. 70% Agg., 0.45 w/c., Type I/II cement. Drying begins at 3 days. Limestone

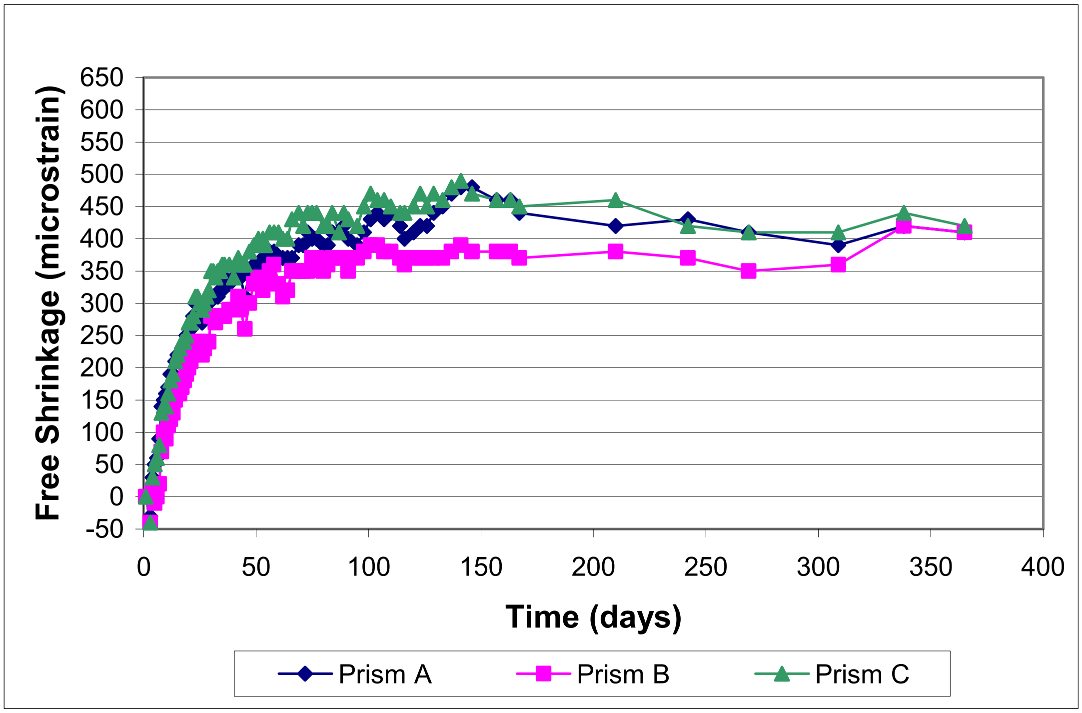

Figure A3.25 - Free Shrinkage, Batch 138. 69.5% Agg., 0.45 w/c., Type I/II cement. Drying begins at 3 days. Limestone

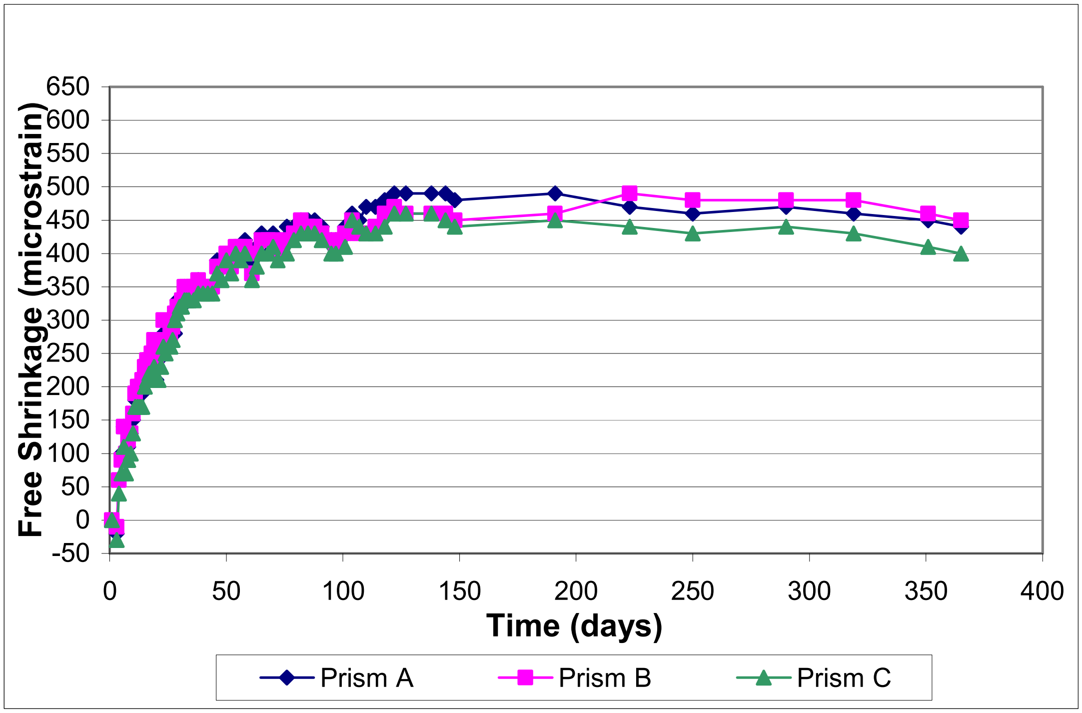

Figure A3.26 - Free Shrinkage, Batch 159. 67.5% Agg., 0.45 w/c., Type I/II cement. Drying begins at 3 days. Quartzite

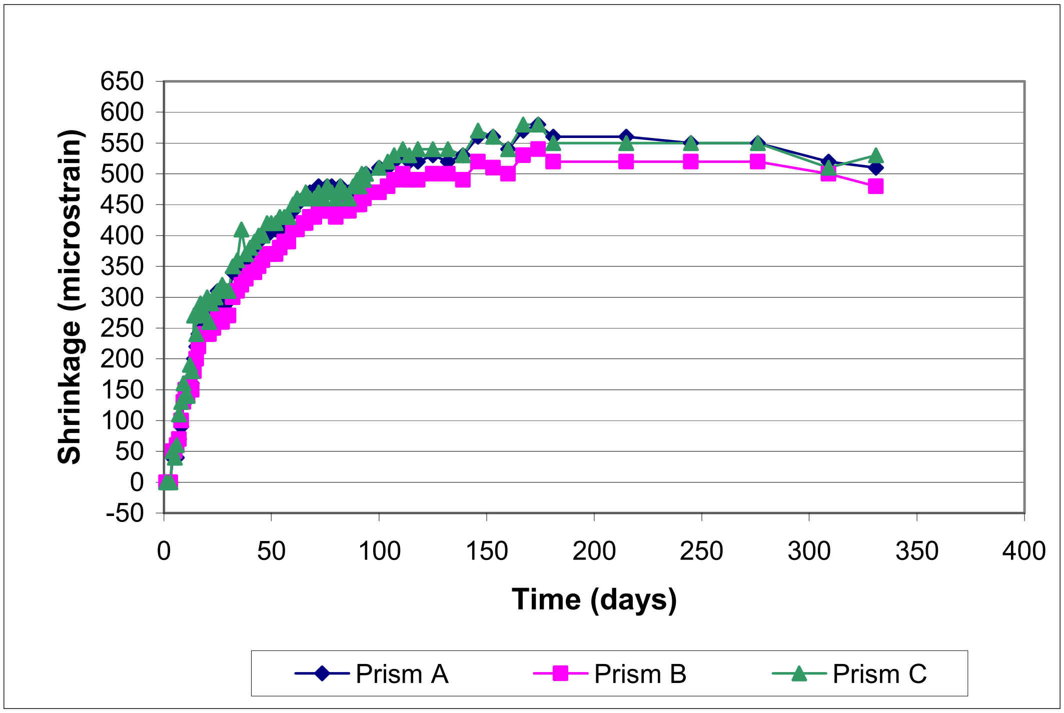

Figure A3.27a - Free Shrinkage, Batch 165, 3 day cure. 70% Agg., 0.45 w/c., Type I/II cement. Drying begins at 3 days.

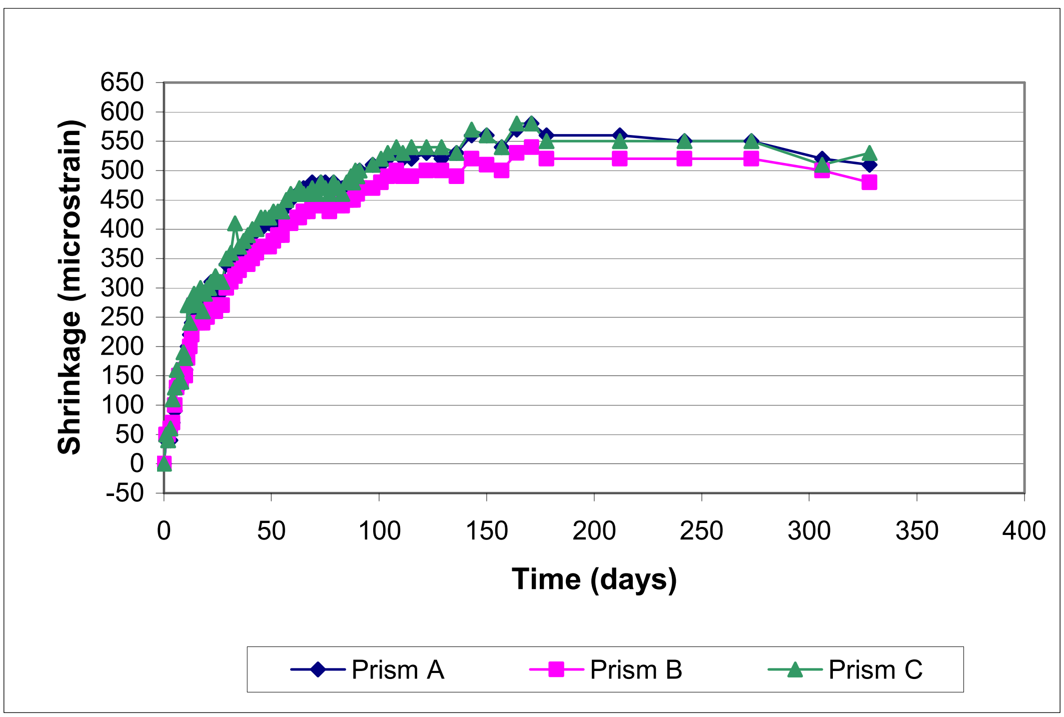

Figure A3.27b - Free Shrinkage, Batch 165, 3 day cure, drying only. 70% Agg., 0.45 w/c., Type I/II cement.

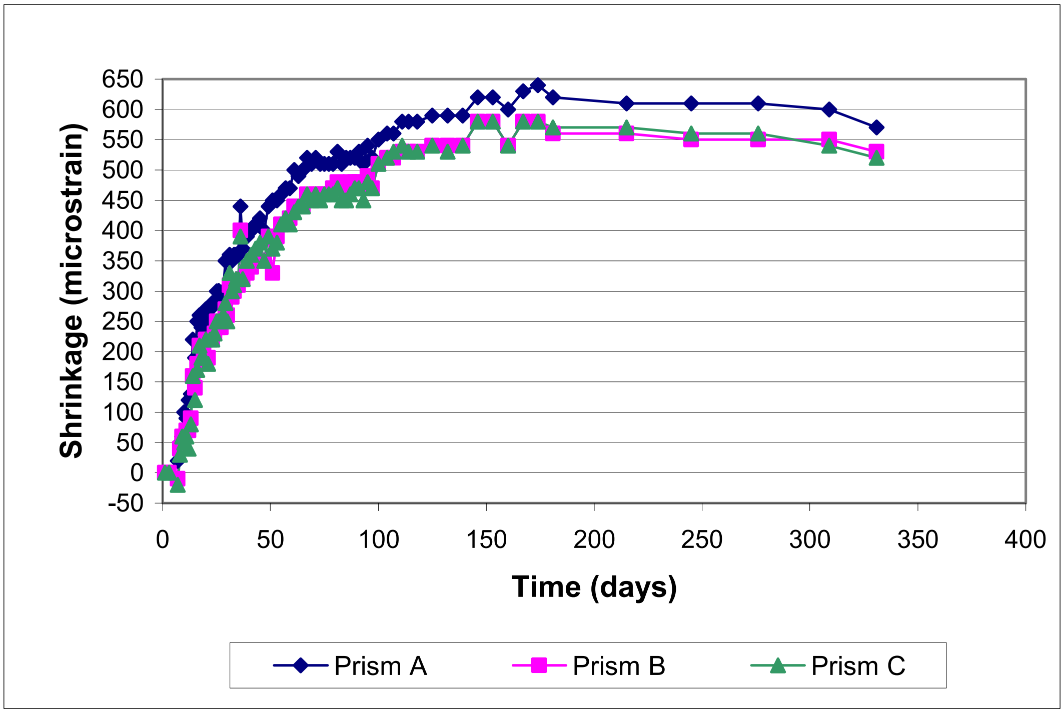

Figure A3.28a - Free Shrinkage, Batch 165, 7 day cure. 70% Agg., 0.45 w/c., Type I/II cement. Drying begins at 7 days.

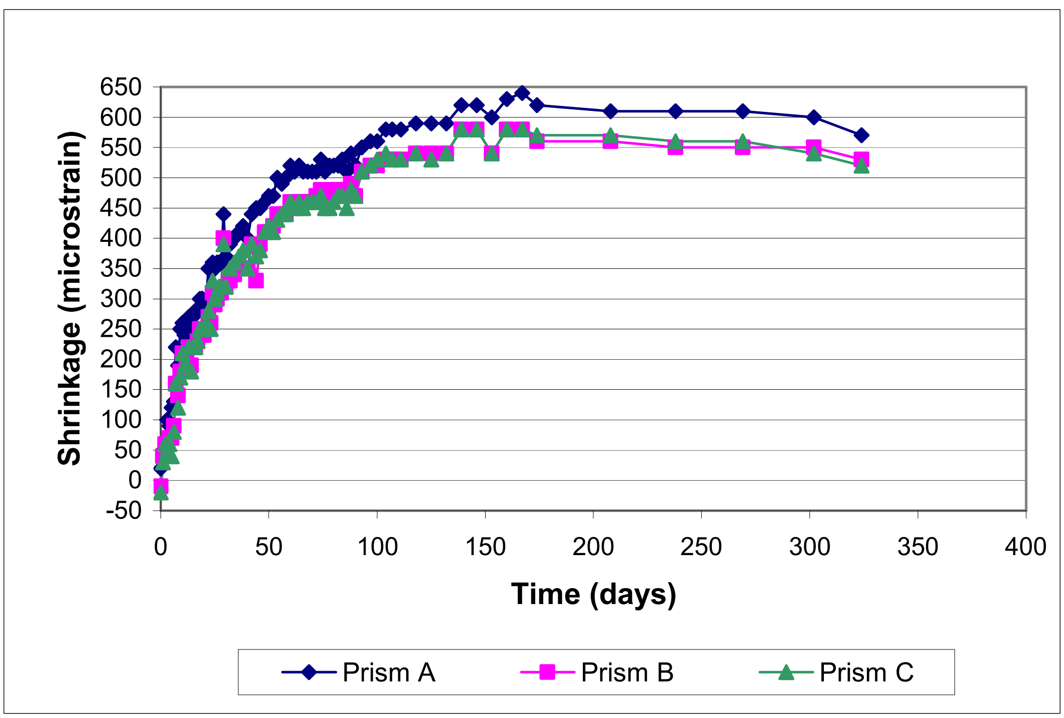

Figure A3.28b - Free Shrinkage, Batch 165, 7 day cure, drying only. 70% Agg., 0.45 w/c., Type I/II cement.

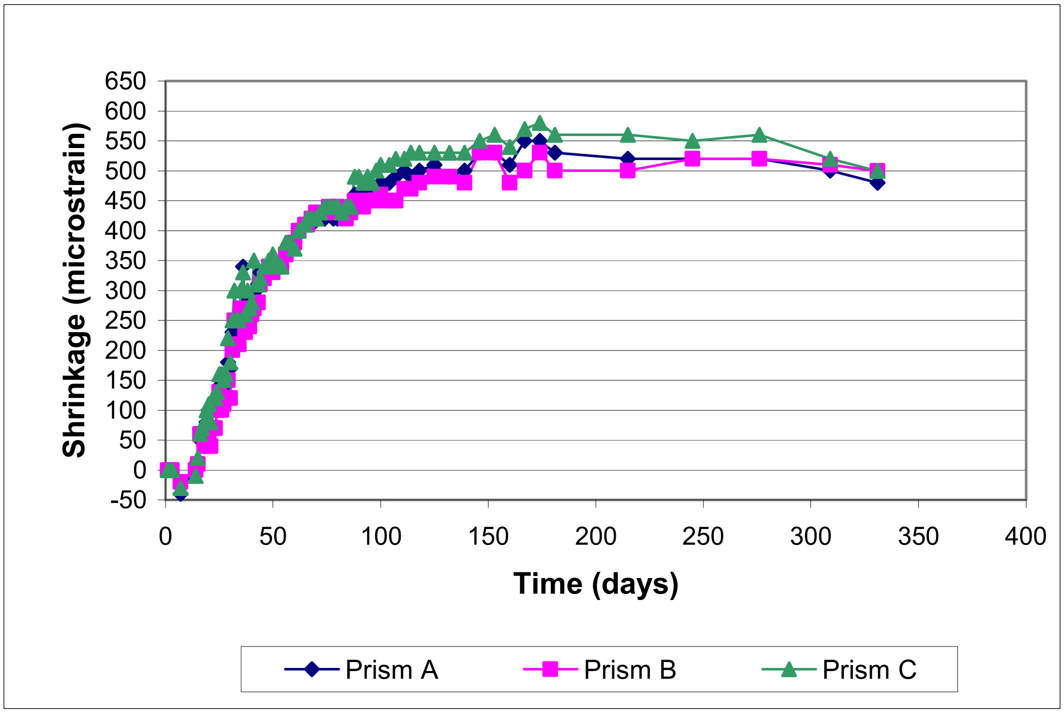

Figure A3.29a - Free Shrinkage, Batch 165, 14 day cure. 70% Agg., 0.45 w/c., Type I/II cement. Drying begins at 14 days.

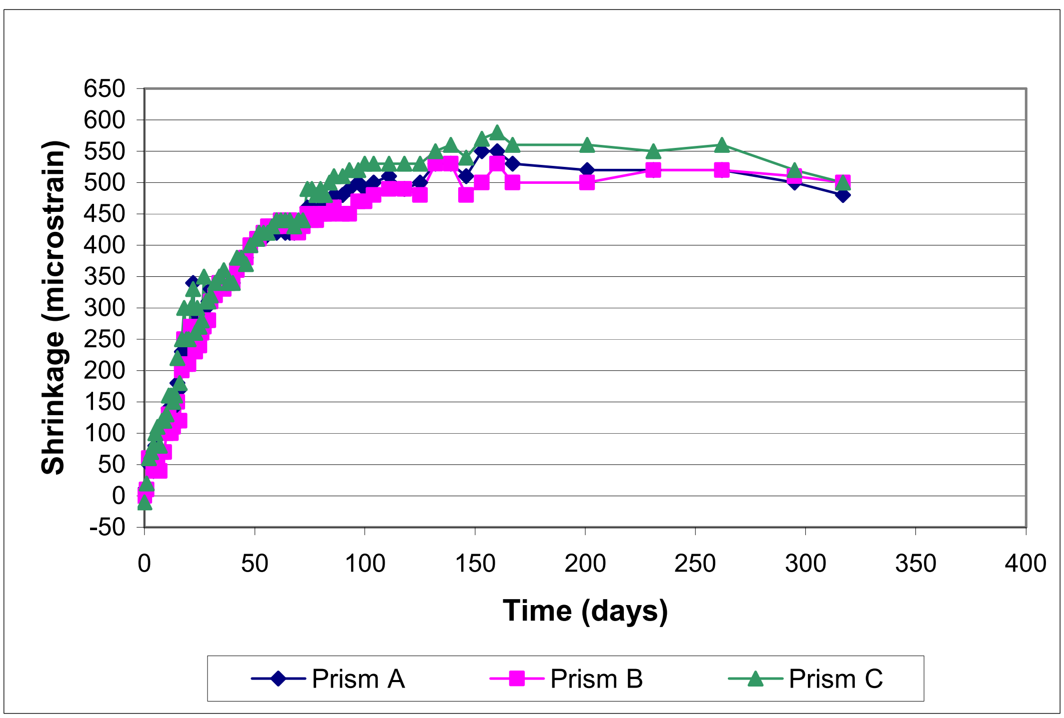

Figure A3.29b - Free Shrinkage, Batch 165, 14 day cure, drying only. 70% Agg., 0.45 w/c., Type I/II cement.

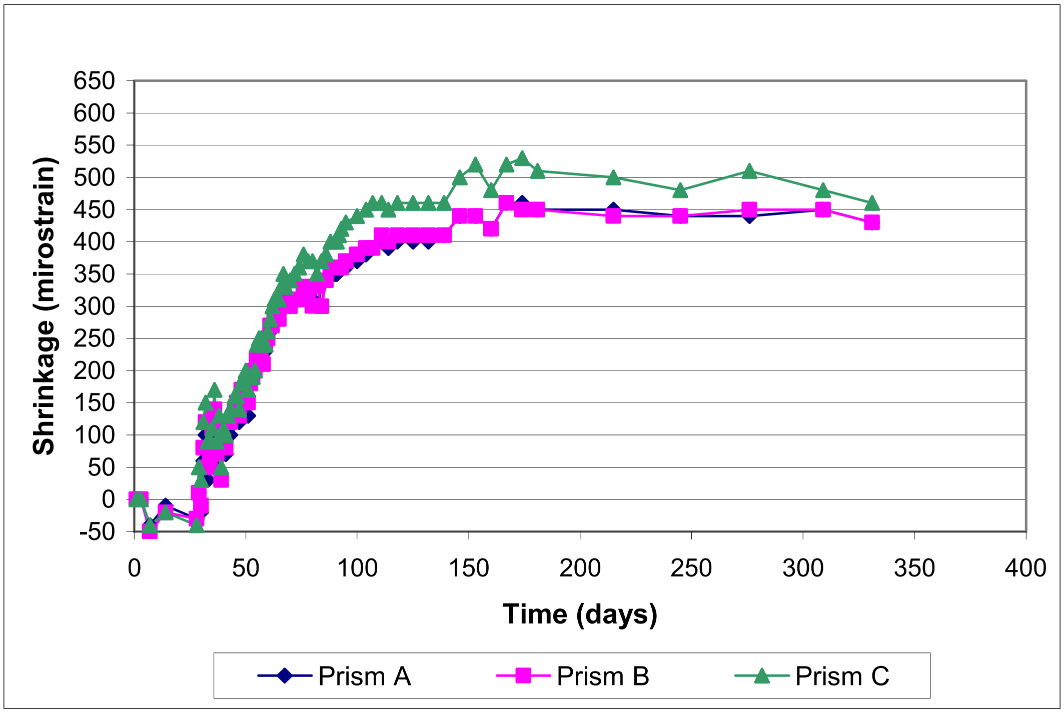

Figure A3.30a - Free Shrinkage, Batch 165, 28 day cure. 70% Agg., 0.45 w/c., Type I/II cement. Drying begins at 28 days.

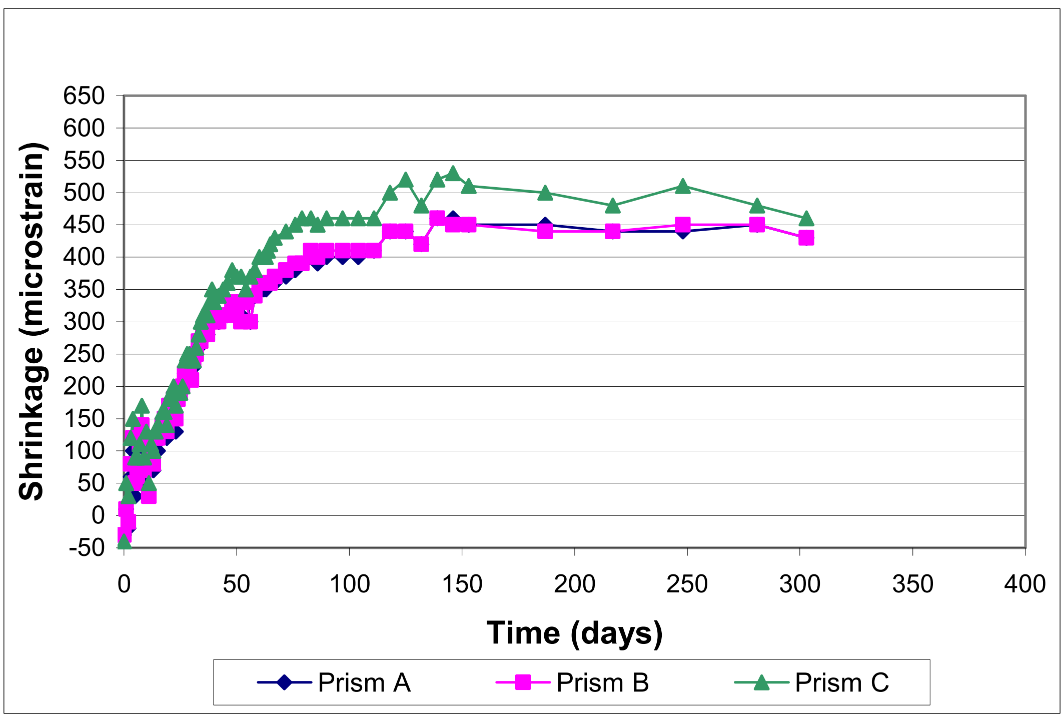

Figure A3.30b - Free Shrinkage, Batch 165, 28 day cure, drying only. 70% Agg., 0.45 w/c., Type I/II cement.

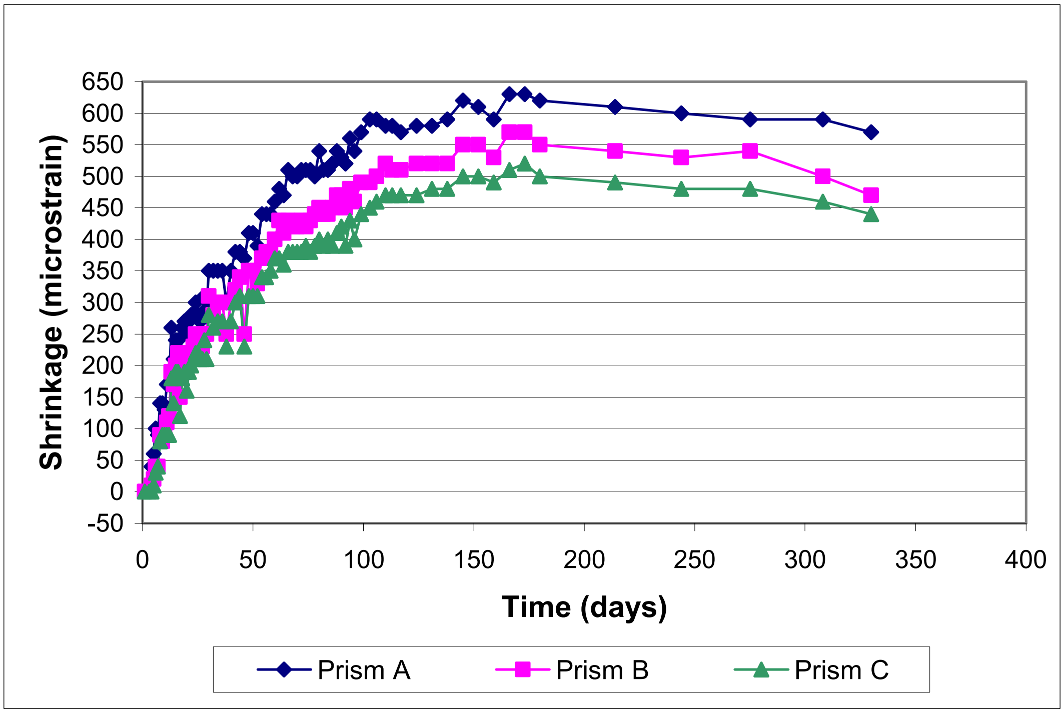

Figure A3.31a - Free Shrinkage, Batch 166, 3 day cure. 70% Agg., 0.45 w/c., Type II CG cement. Drying begins at 3 days.

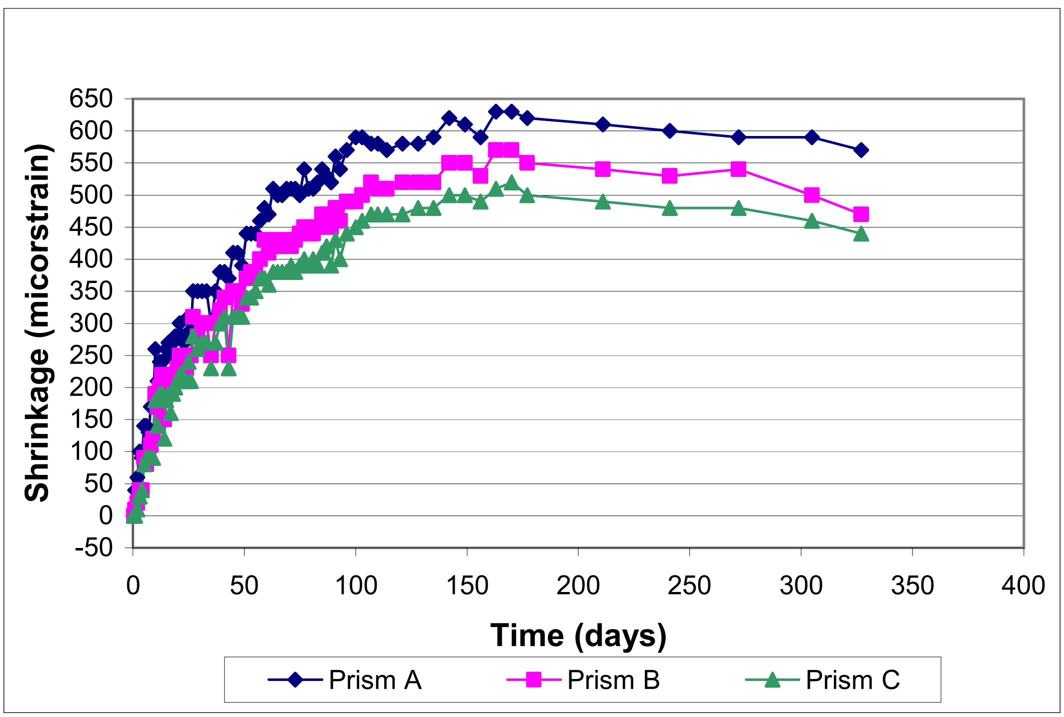

Figure A3.31b - Free Shrinkage, Batch 166, 3 day cure, drying only. 70% Agg., 0.45 w/c., Type II Coarse-Ground cement.

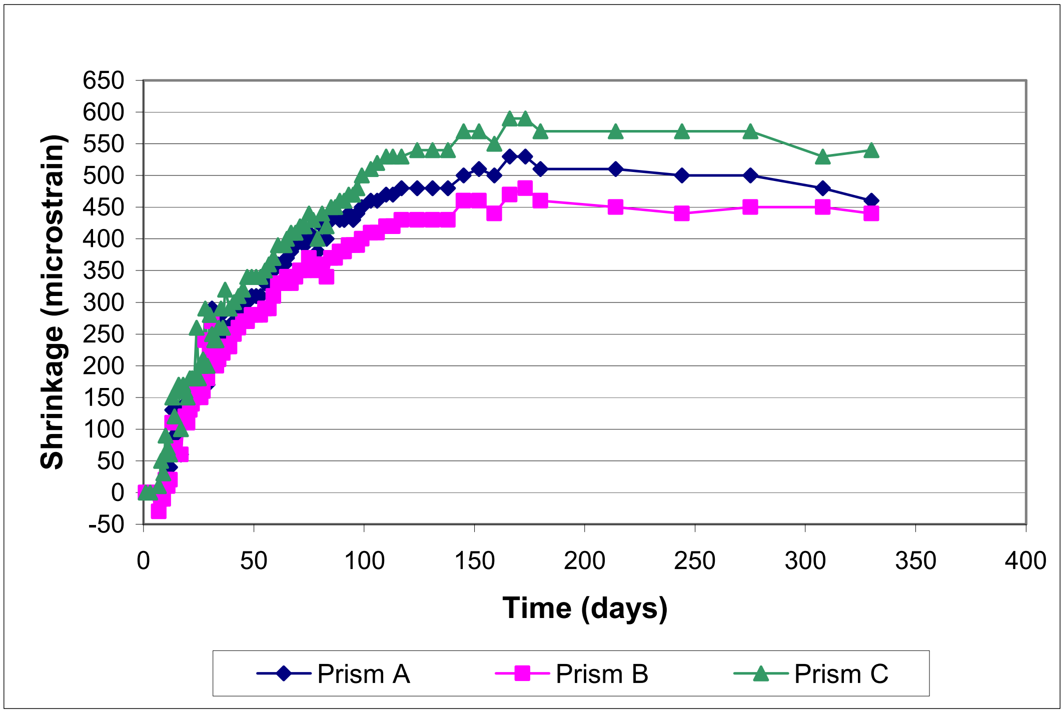

Figure A3.32a - Free Shrinkage, Batch 166, 7 day cure. 70% Agg., 0.45 w/c., Type II Coarse-Ground cement. Drying begins at 7 days.

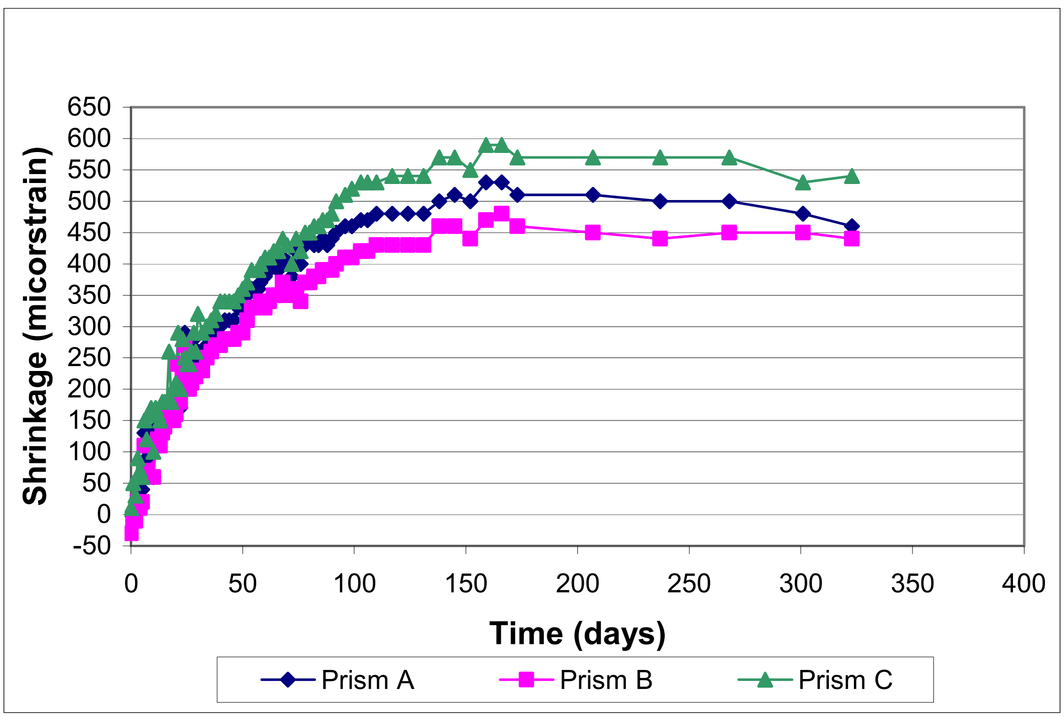

Figure A3.32b - Free Shrinkage, Batch 166, 7 day cure, drying only. 70% Agg., 0.45 w/c., Type II Coarse-Ground cement.

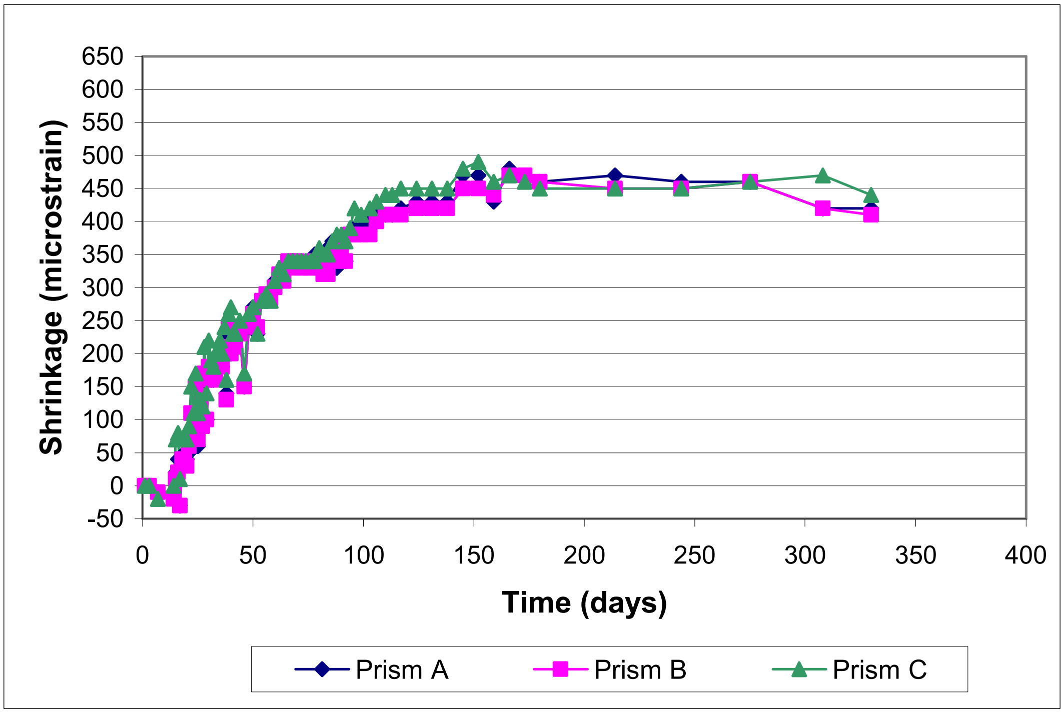

Figure A3.33a - Free Shrinkage, Batch 166, 14 day cure. 70% Agg., 0.45 w/c., Type II Coarse-Ground cement. Drying begins at 14 days.

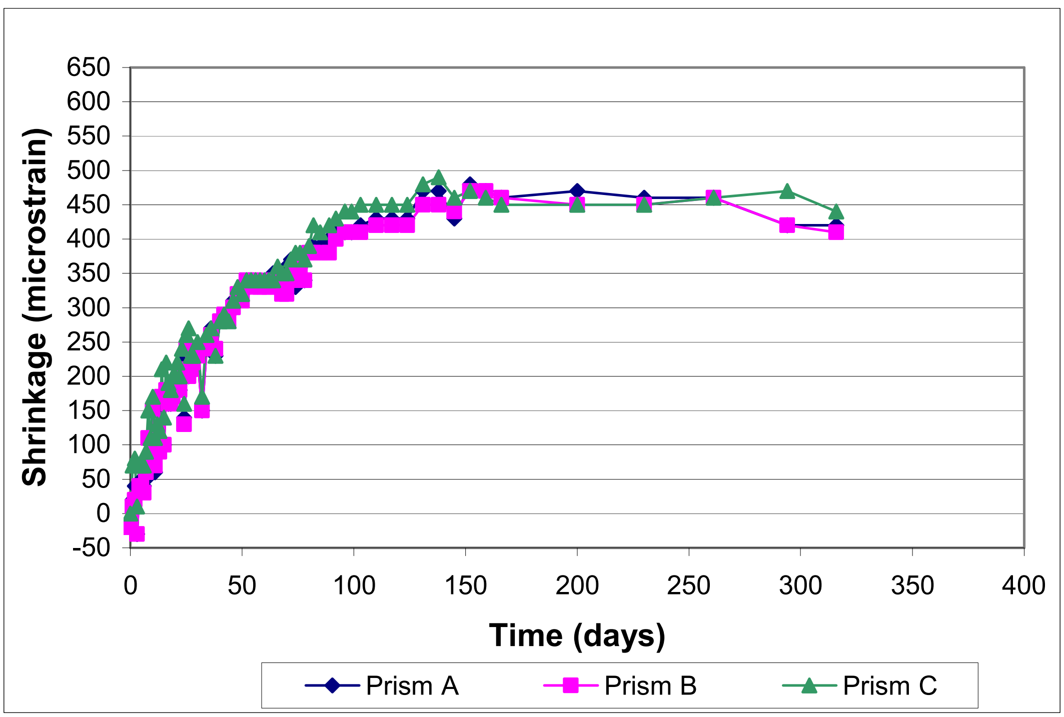

Figure A3.33b - Free Shrinkage, Batch 166, 14 day cure, drying only. 70% Agg., 0.45 w/c., Type II Coarse-Ground cement.

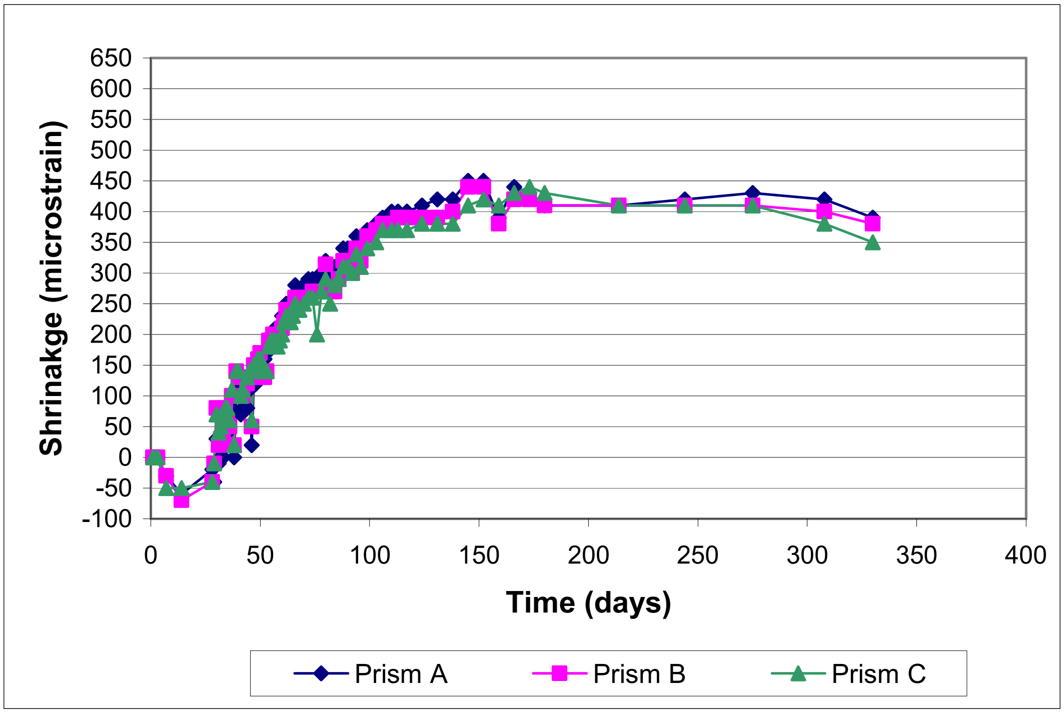

Figure A3.34a - Free Shrinkage, Batch 166, 28 day cure. 70% Agg., 0.45 w/c., Type II Coarse-Ground cement. Drying begins at 28 days.

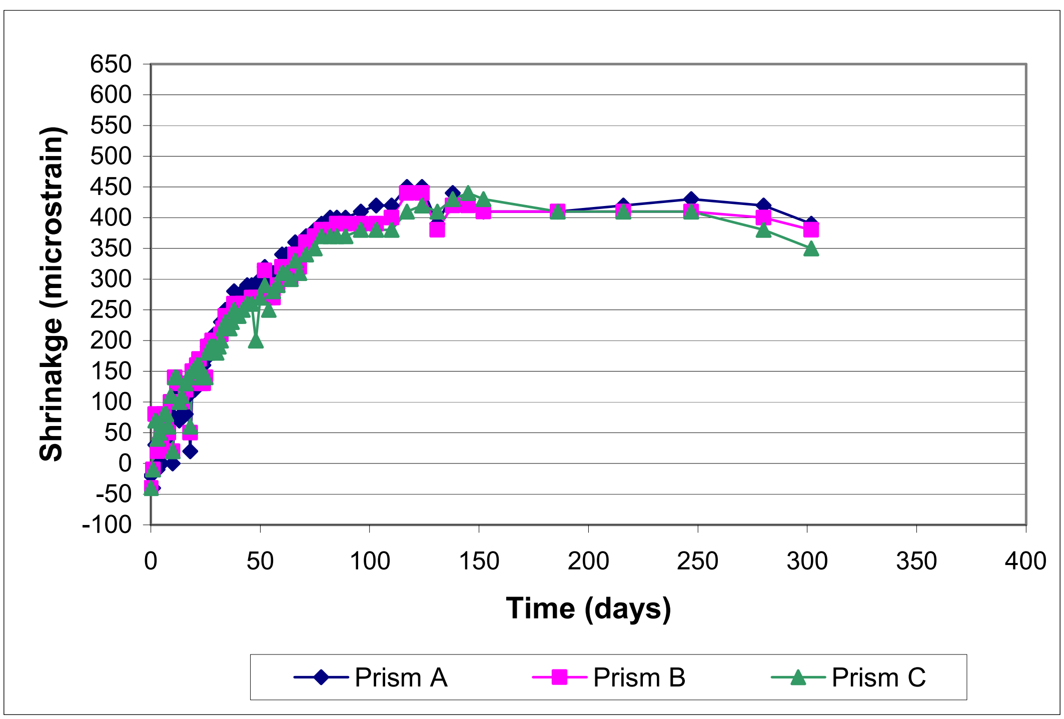

Figure A3.34b - Free Shrinkage, Batch 166, 28 day cure, drying only. 70% Agg., 0.45 w/c., Type II Coarse-Ground cement.

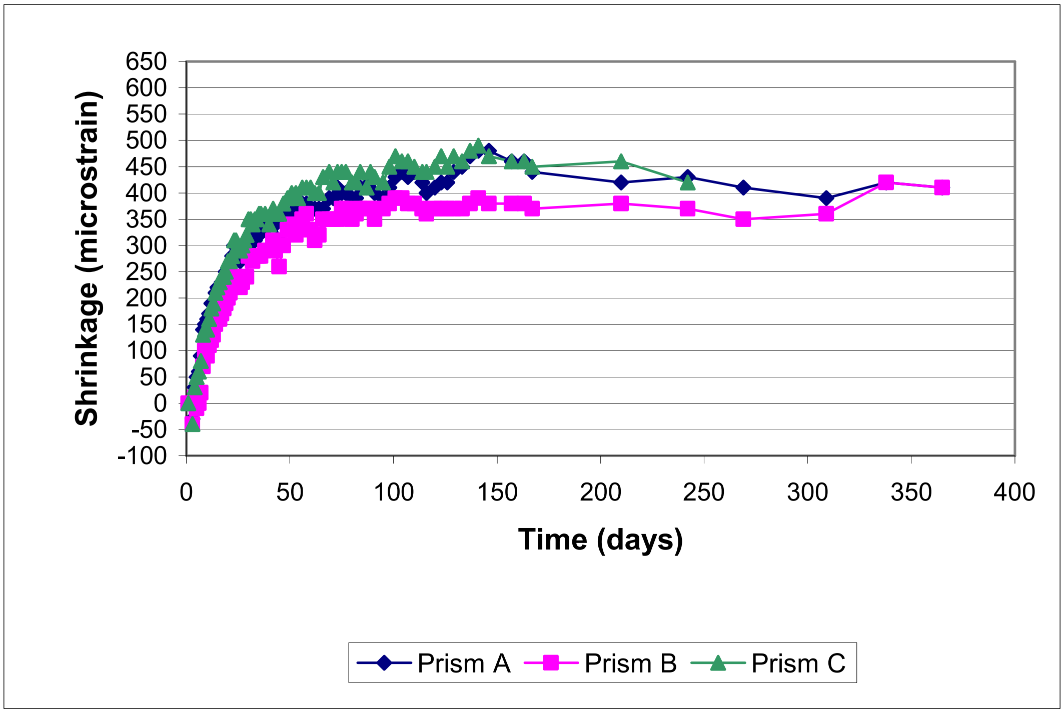

Figure A3.35a - Free Shrinkage, Batch 138, 3 day cure. 69.5% Agg., 0.45 w/c., Type I/II cement. Drying begins at 3 days.

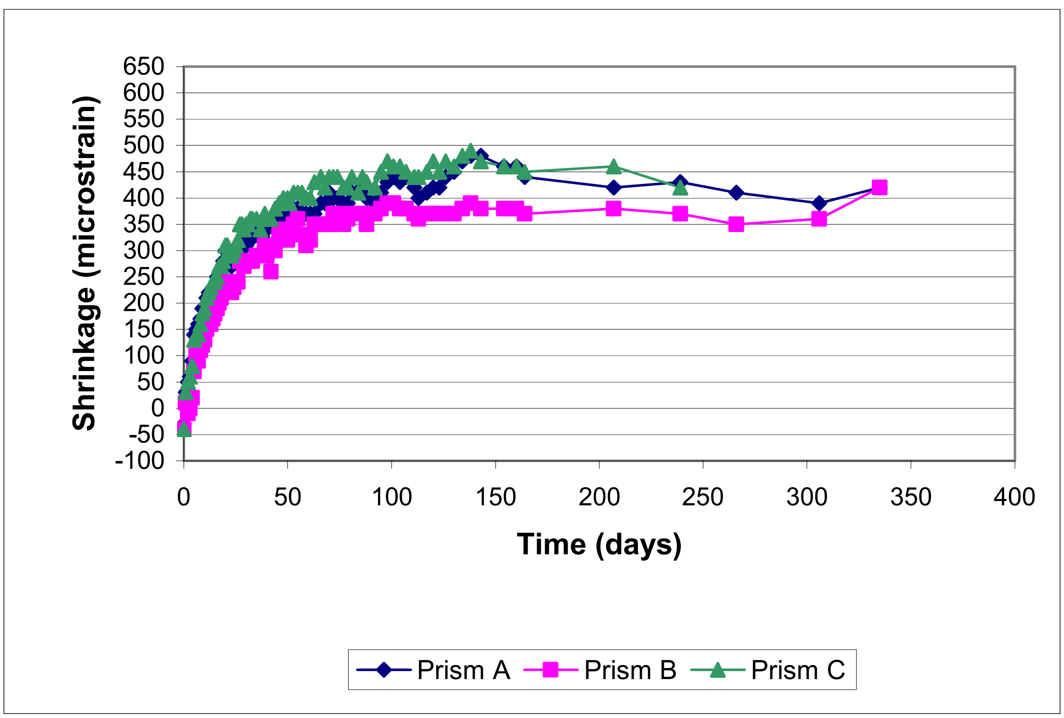

Figure A3.35b - Free Shrinkage, Batch 138, 3 day cure, drying only. 69.5% Agg., 0.45 w/c., Type I/II cement.

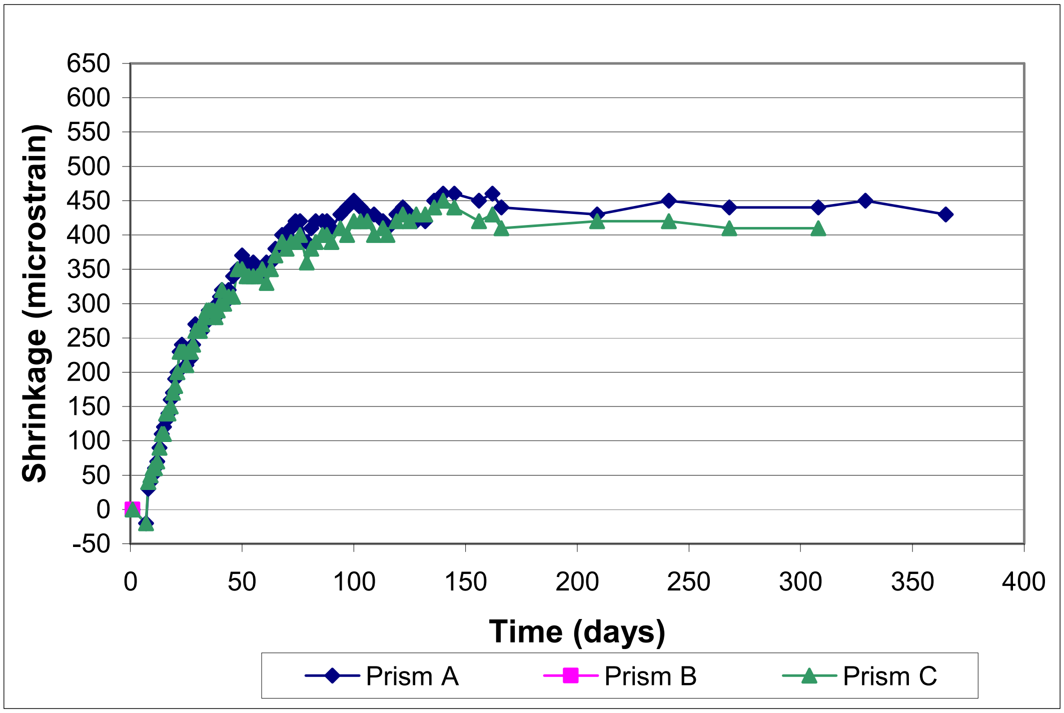

Figure A3.36a - Free Shrinkage, Batch 140, 7 day cure. 66.4% Agg., 0.45 w/c., Type I/II cement. Drying begins at 7 days.

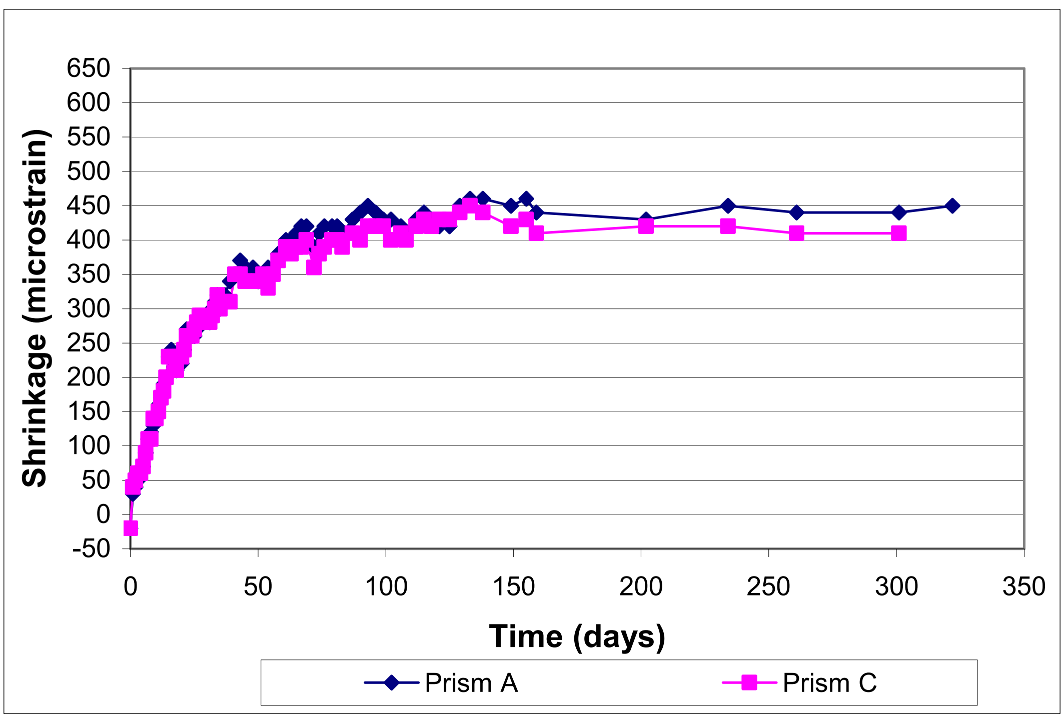

Figure A3.36b - Free Shrinkage, Batch 140, 7 day cure, drying only. 66.4% Agg., 0.45 w/c., Type I/II cement.

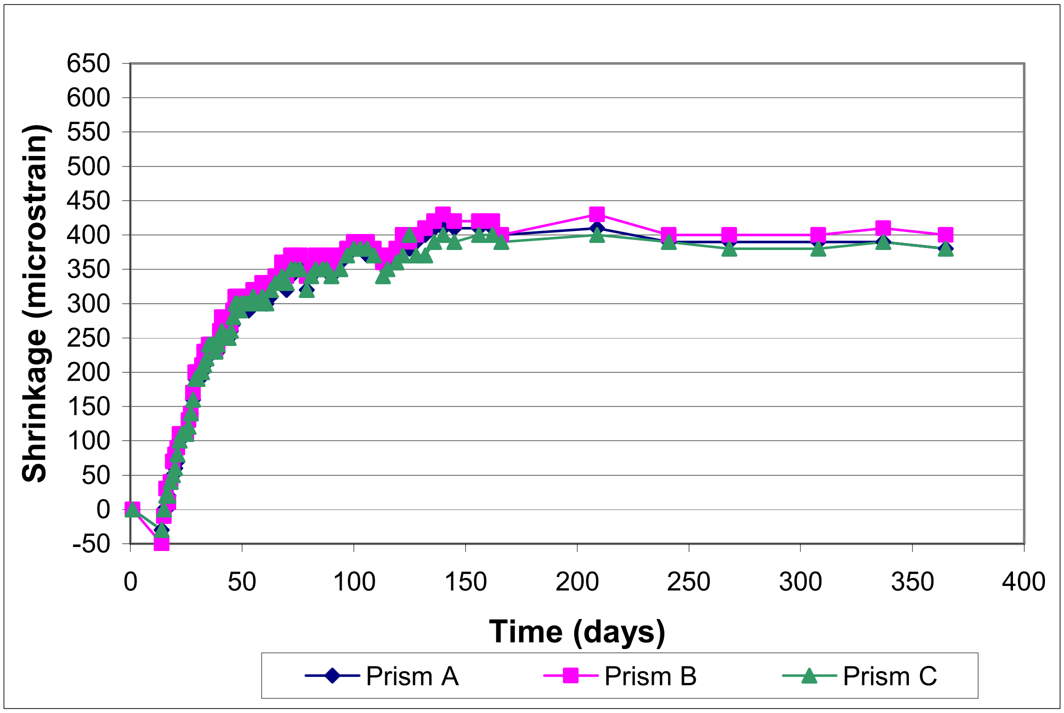

Figure A3.37a - Free Shrinkage, Batch 143, 14 day cure. 66.6% Agg., 0.45 w/c., Type I/II cement. Drying begins at 14 days.

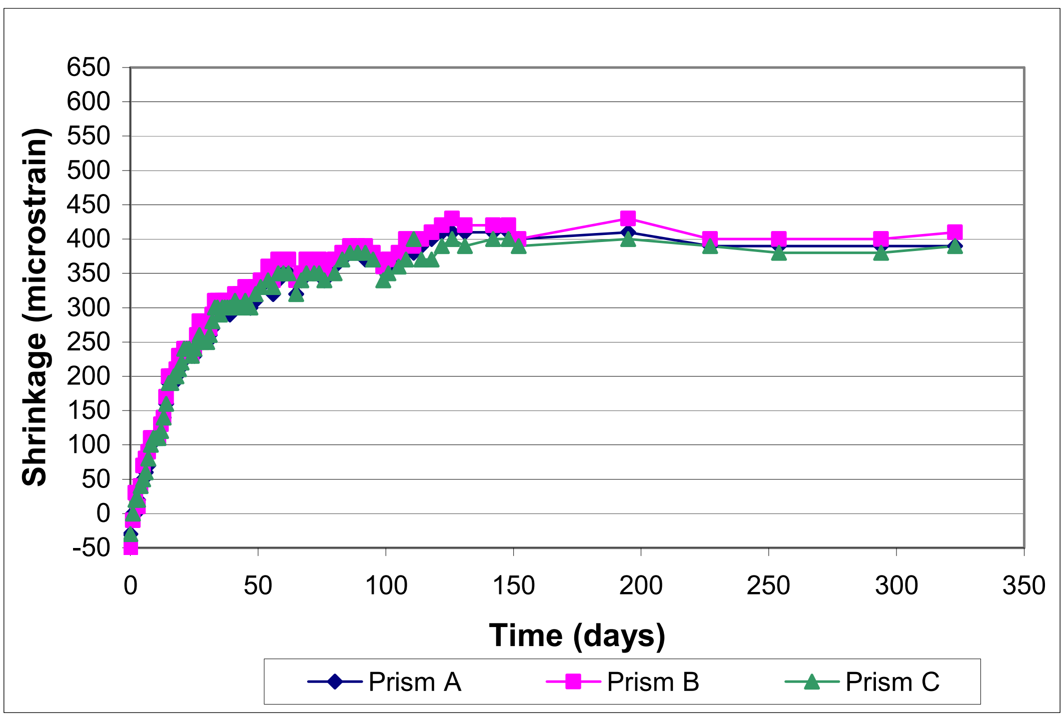

Figure A3.37b - Free Shrinkage, Batch 143, 14 day cure, drying only. 66.6% Agg., 0.45 w/c., Type I/II cement.

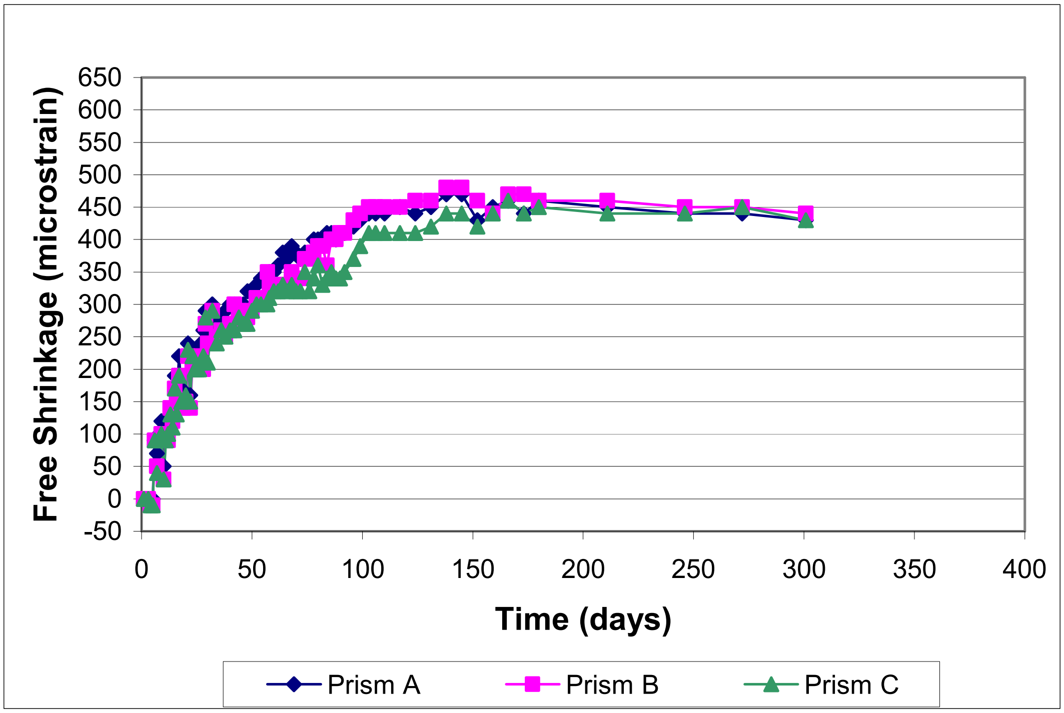

Figure A3.38 - Free Shrinkage, Batch 167. 75% Agg., 0.45 w/c., Type I/II cement. Drying begins at 3 days. Control, no chemical admixtures.

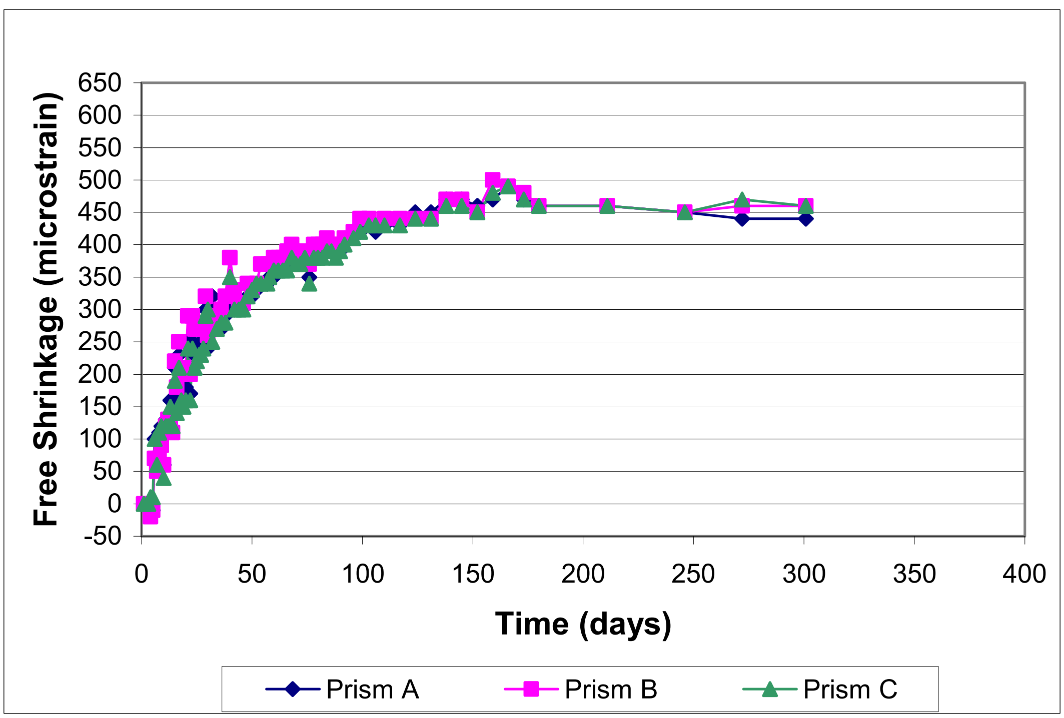

Figure A3.39 - Free Shrinkage, Batch 168. 75% Agg., 0.45 w/c., Type I/II cement. Drying begins at 3 days. Low dosage of Glenium 3000NS.

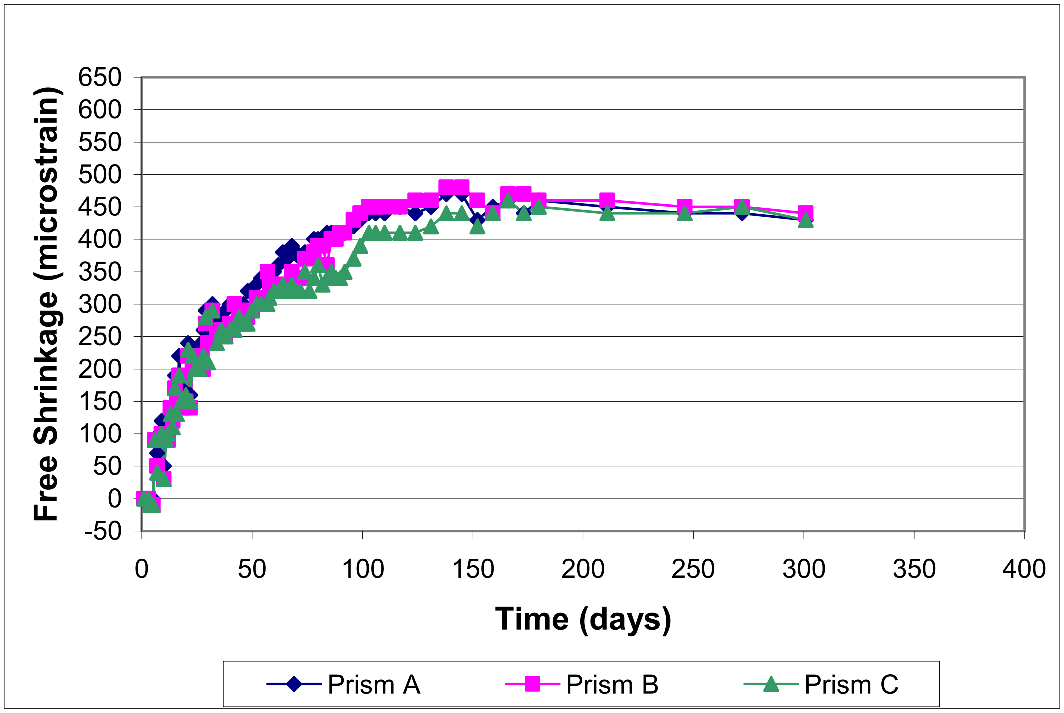

Figure A3.40 - Free Shrinkage, Batch 169. 75% Agg., 0.45 w/c., Type I/II cement. Drying begins at 3 days. Medium dosage of Glenium 3000NS

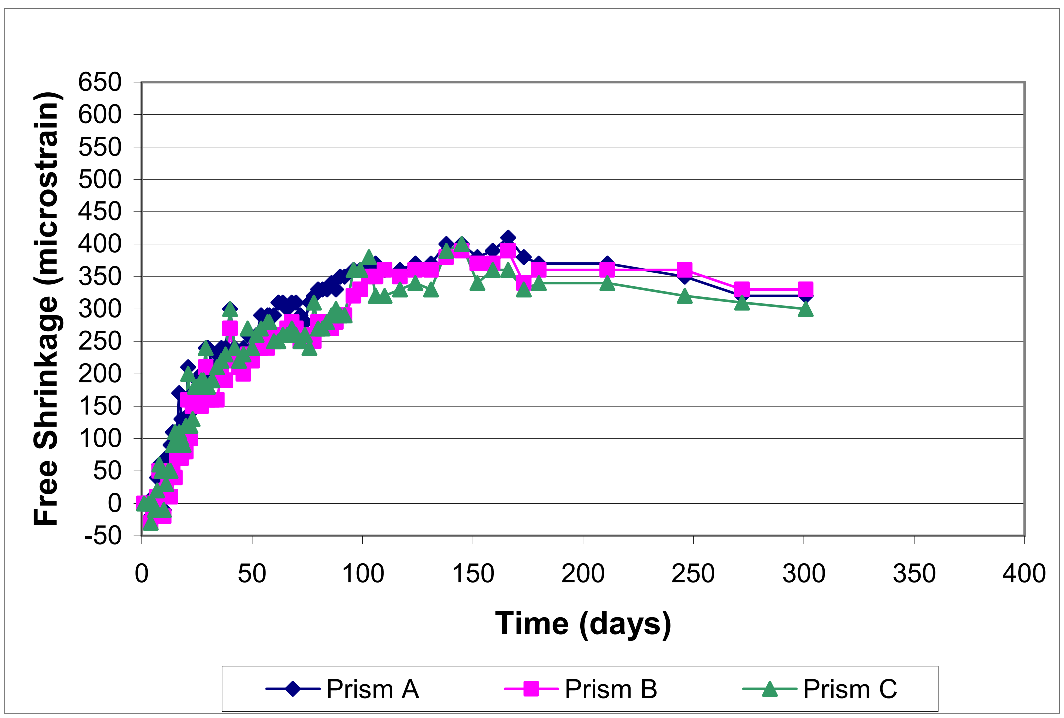

Figure A3.41 - Free Shrinkage, Batch 170. 75% Agg., 0.45 w/c., Type I/II cement. Drying begins at 3 days. High dosage of Glenium 3000NS. Cast Incorrectly.

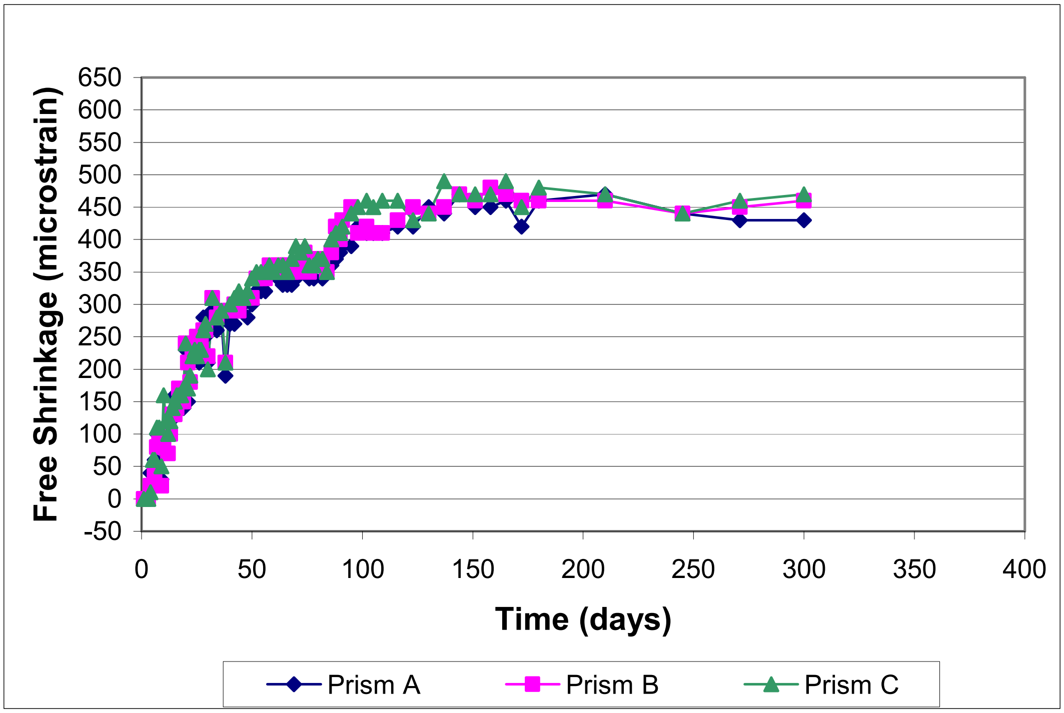

Figure A3.42 - Free Shrinkage, Batch 171. 75% Agg., 0.45 w/c., Type I/II cement. Drying begins at 3 days. Low dosage of Rheobuild 1000.

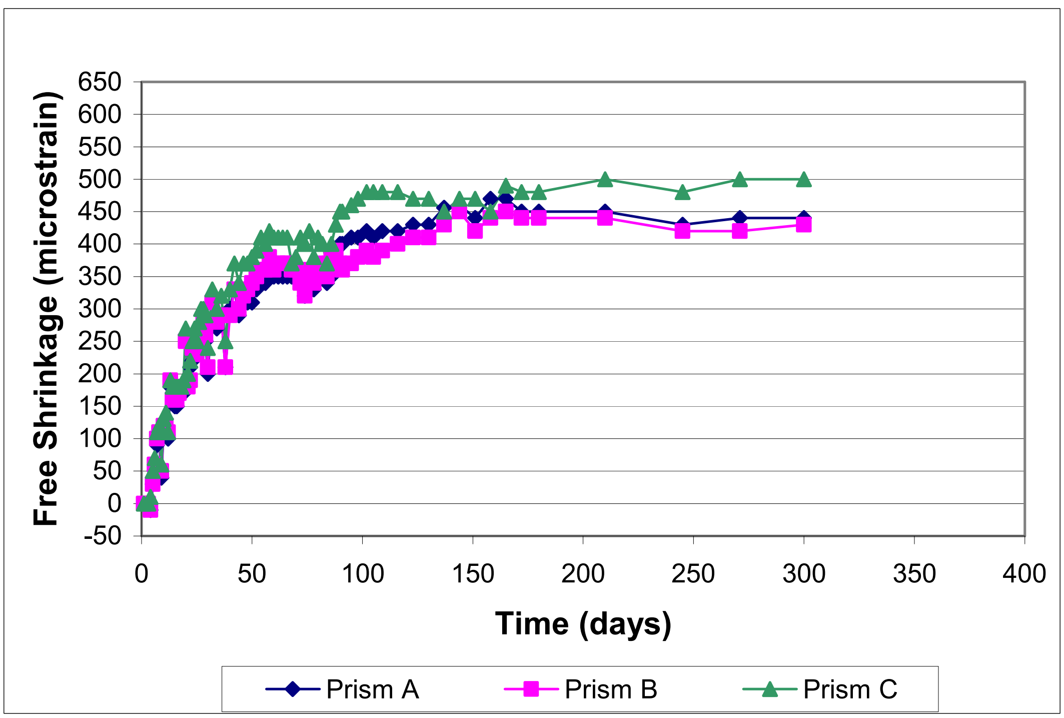

Figure A3.43 - Free Shrinkage, Batch 172. 75% Agg., 0.45 w/c., Type I/II cement. Drying begins at 3 days. Medium dosage of Rheobuild 1000.

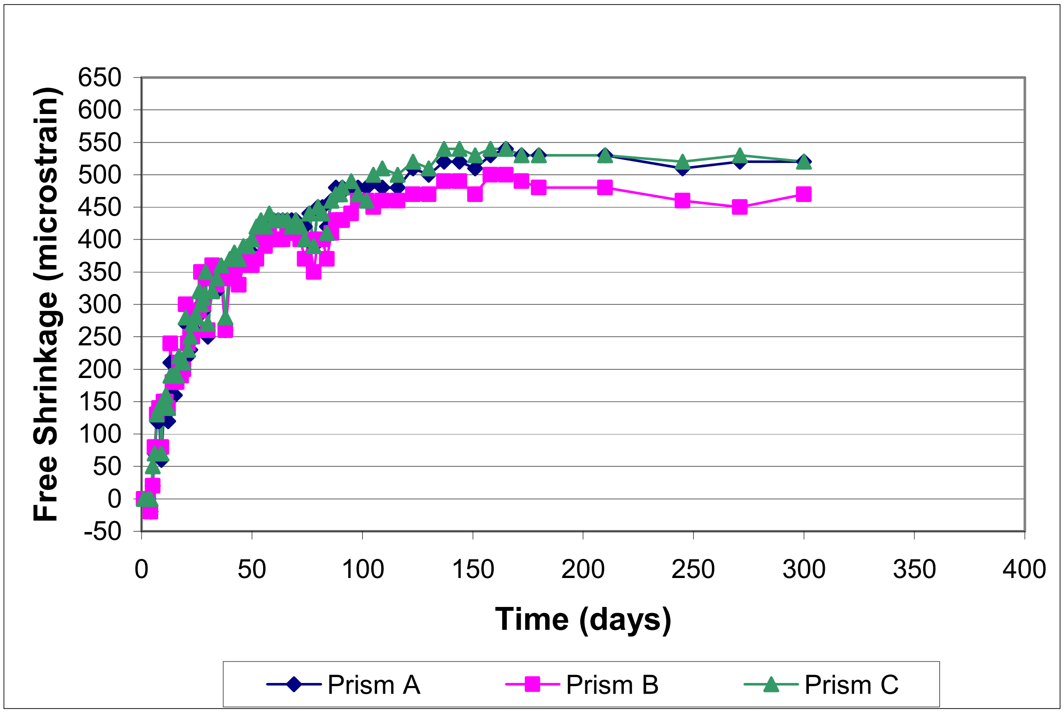

Figure A3.44 - Free Shrinkage, Batch 173. 75% Agg., 0.45 w/c., Type I/II cement. Drying begins at 3 days. High dosage of Rheobuild 1000.

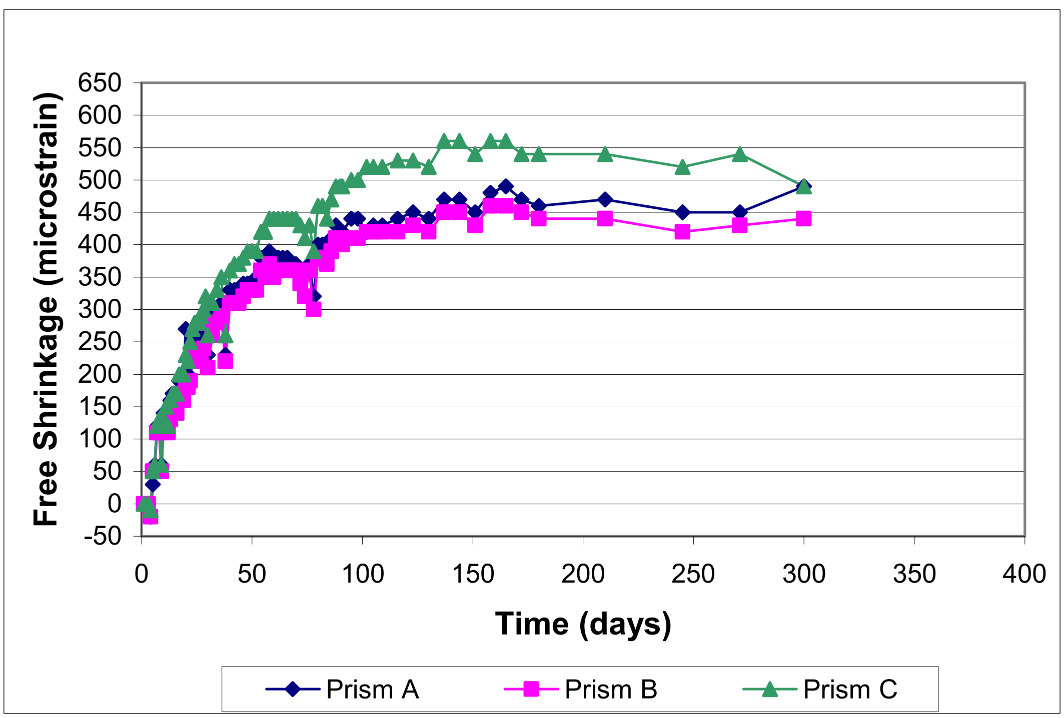

Figure A3.45 - Free Shrinkage, Batch 174. 75% Agg., 0.45 w/c., Type I/II cement. Drying begins at 3 days. High dosage of Glenium 3000NS. Cast correctly.

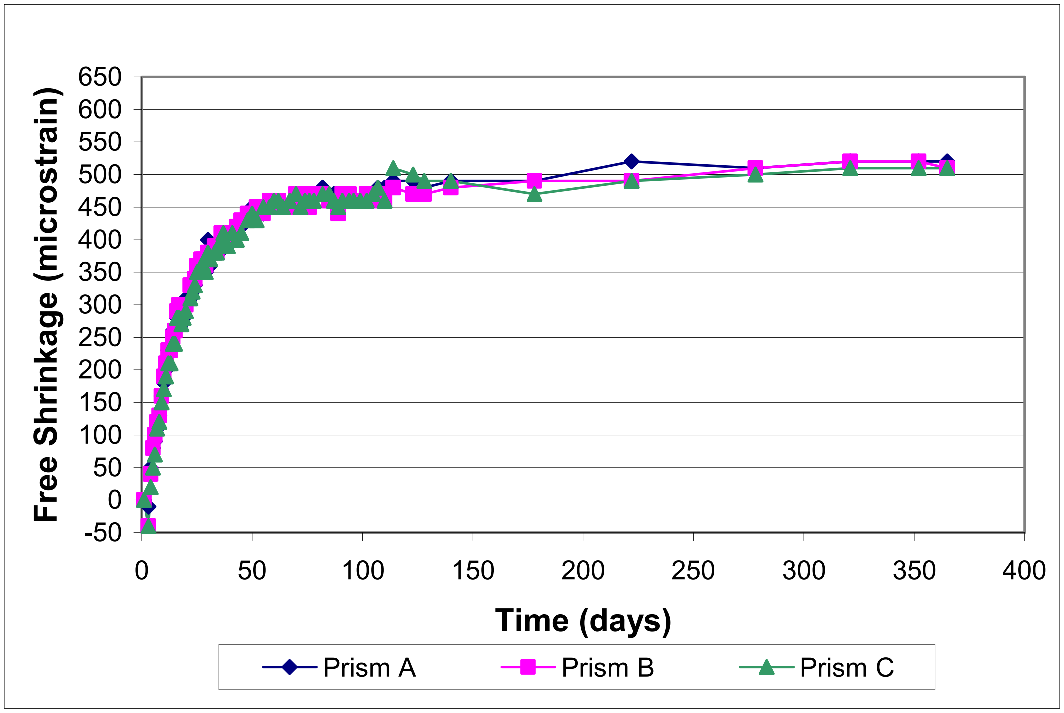

Figure A3.46 - Free Shrinkage, Batch 81, 317 kg/m^3 (535 lb/yd^3), Type I/II cement. Drying begins at 3 days. Control.

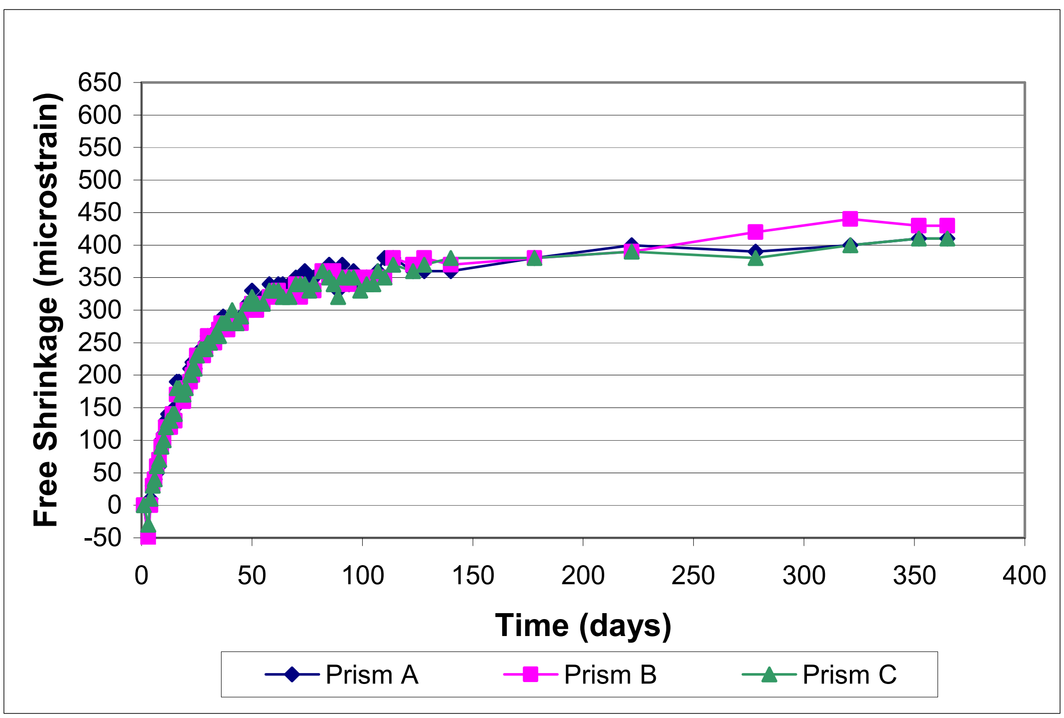

Figure A3.47 - Free Shrinkage, Batch 82, 317 kg/m^3 (535 lb/yd^3), Type II coarse-ground cement. Drying begins at 3 days.

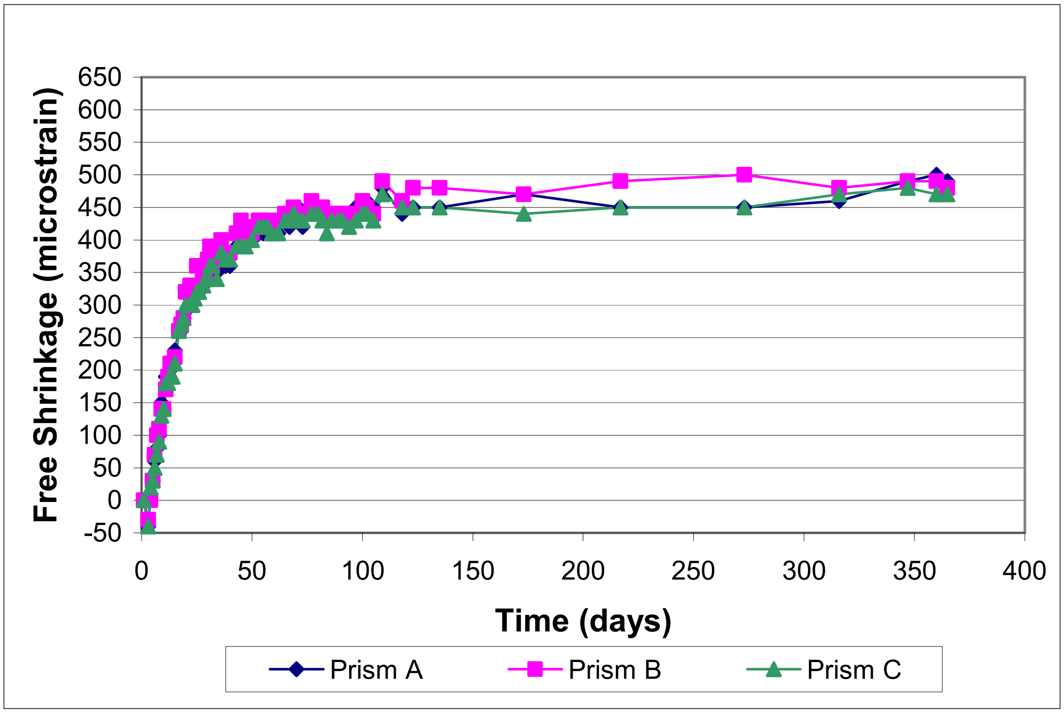

Figure A3.48 - Free Shrinkage, Batch 83, MoDOT mix. Drying begins at 3 days.

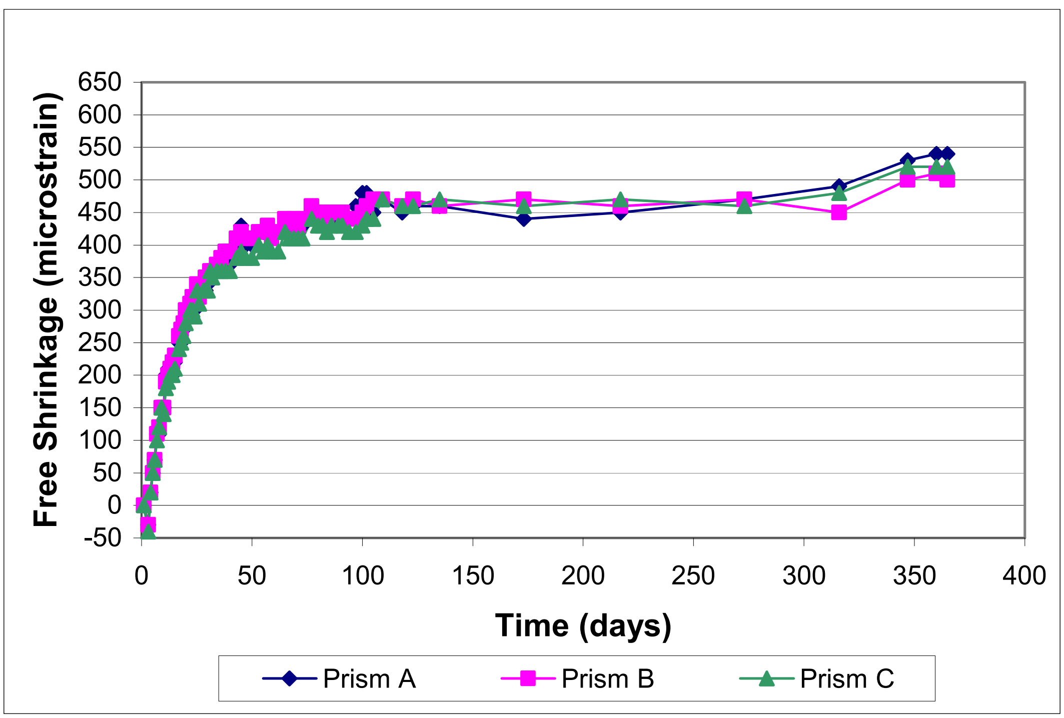

Figure A3.49 - Free Shrinkage, Batch 84, KDOT mix. Drying begins at 3 days.

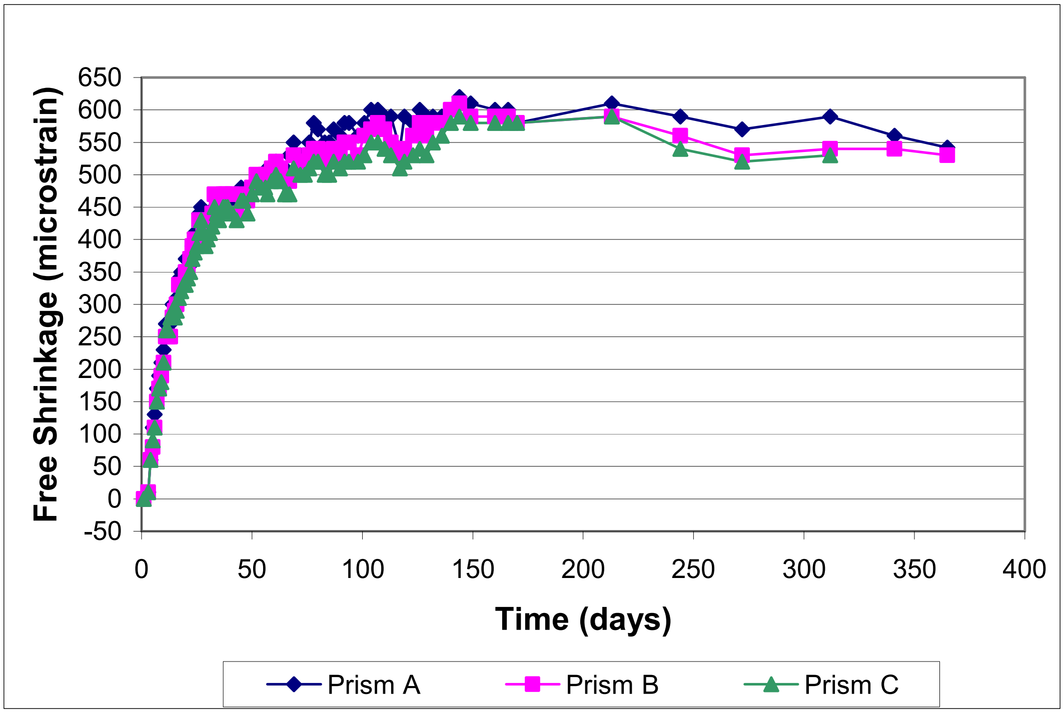

Figure A3.50 - Free Shrinkage, Batch 130, KDOT mix. Drying begins at 3 days.

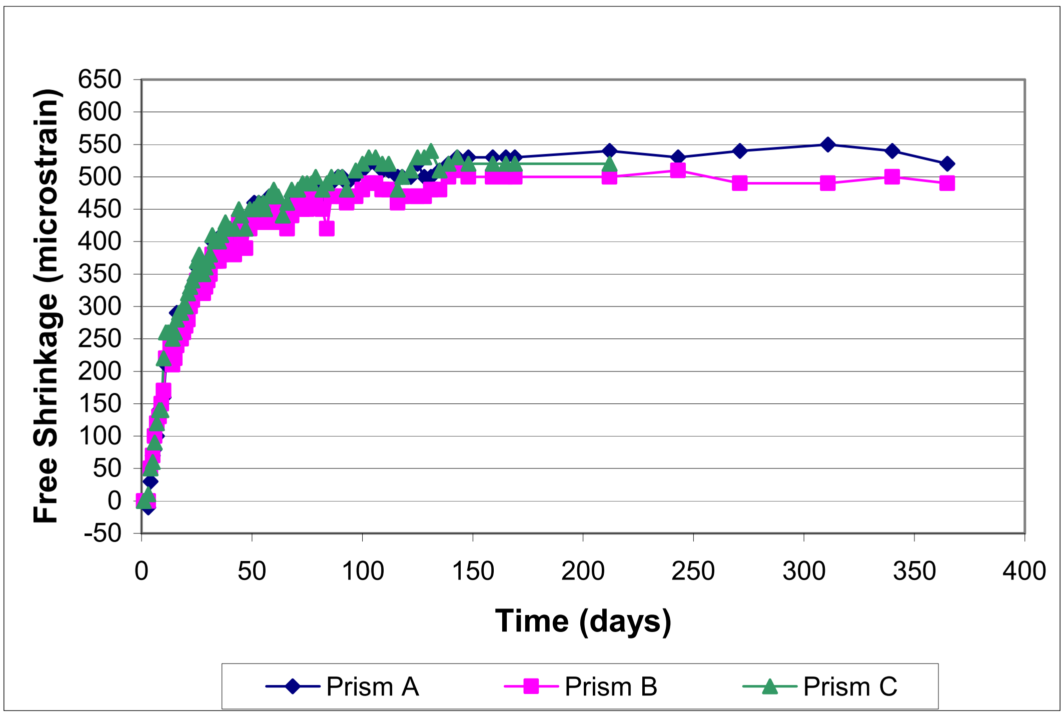

Figure A3.51 - Free Shrinkage, Batch 132, MoDOT mix. Drying begins at 3 days.

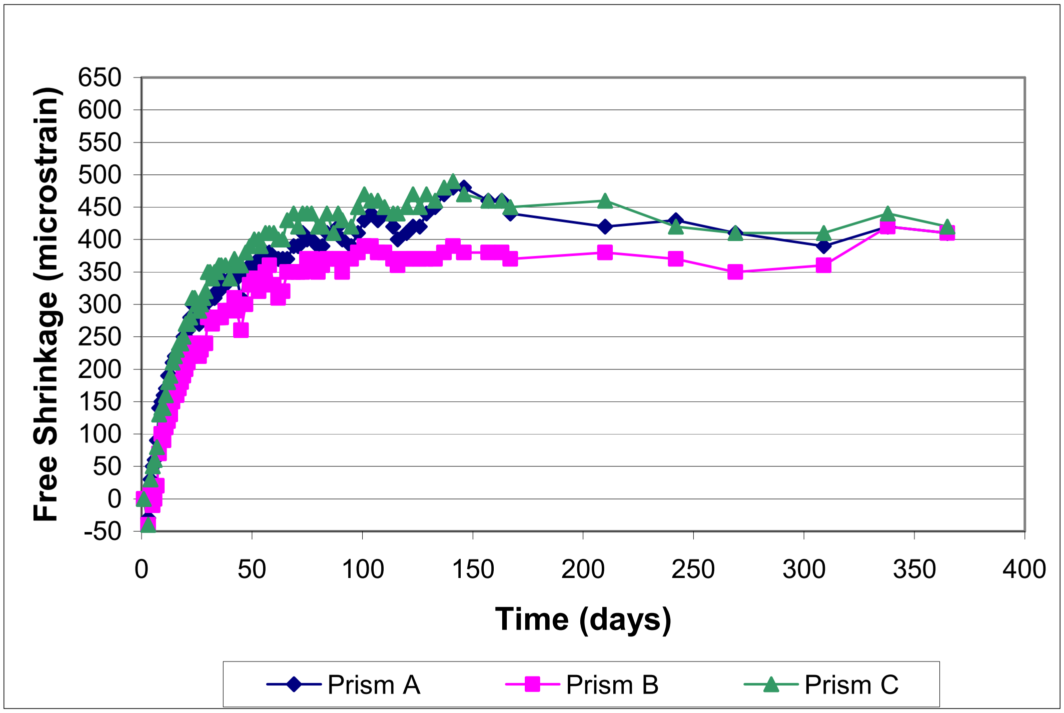

Figure A3.52 - Free Shrinkage, Batch 138, 317 kg/m^3 (535 lb/yd^3), Type I/II cement. Drying begins at 3 days. Control.

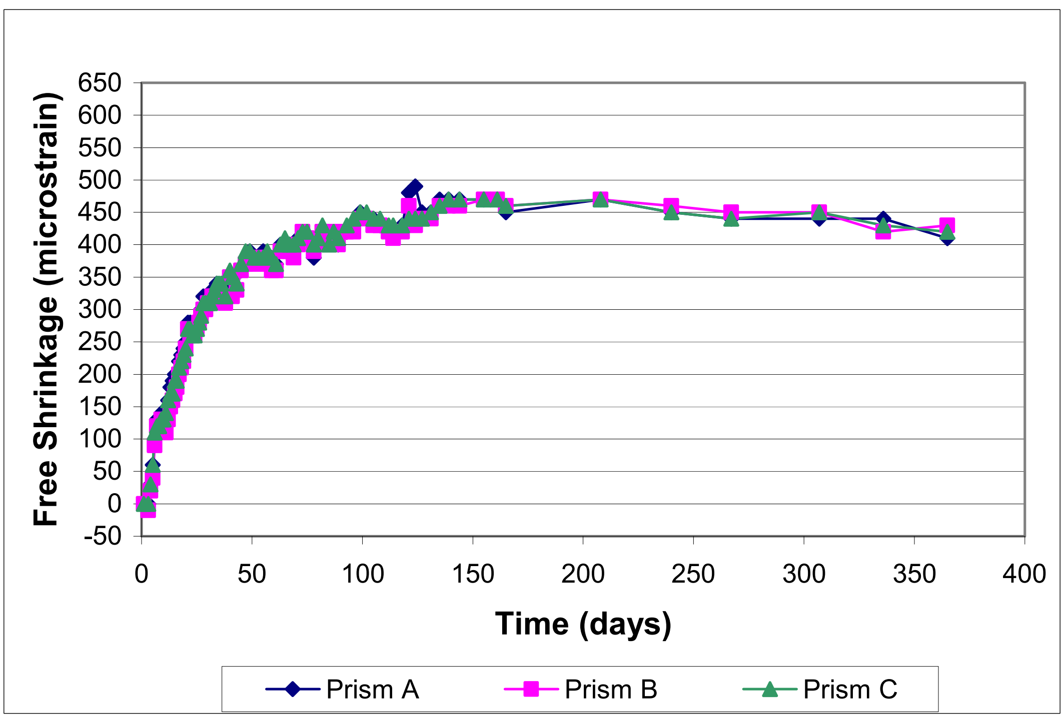

Figure A3.53 - Free Shrinkage, Batch 145, 317 kg/m^3 (535 lb/yd^3), Type II coarse-ground cement. Drying begins at 3 days.

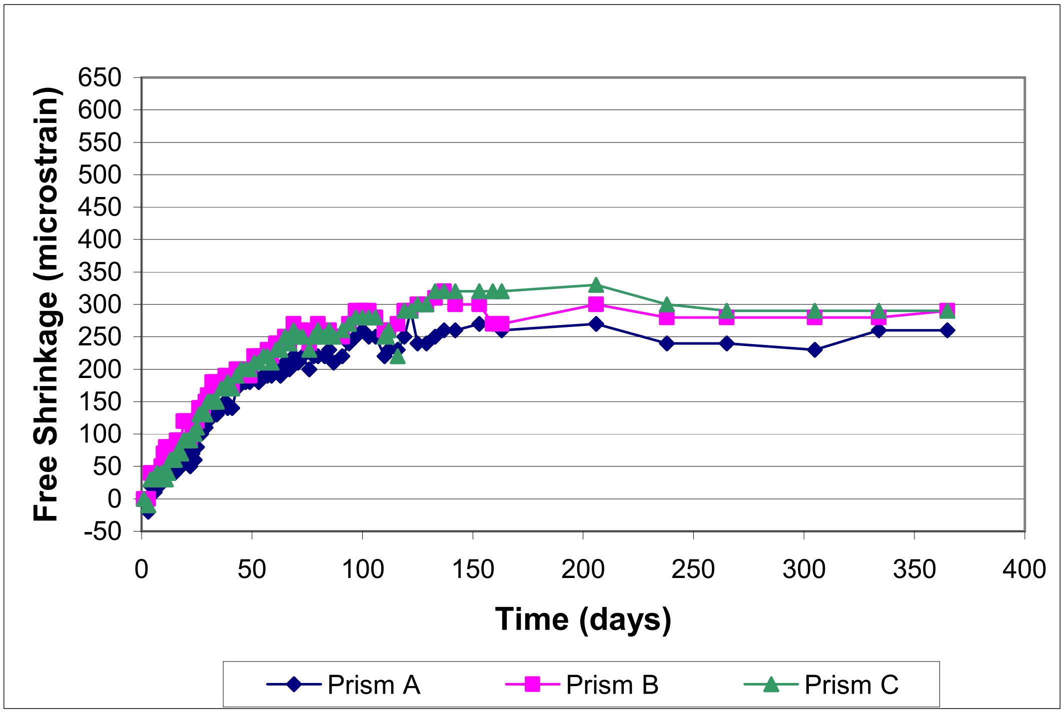

Figure A3.54 - Free Shrinkage, Batch 147, Shrinkage reducing admixture mix. Drying begins at 3 days.

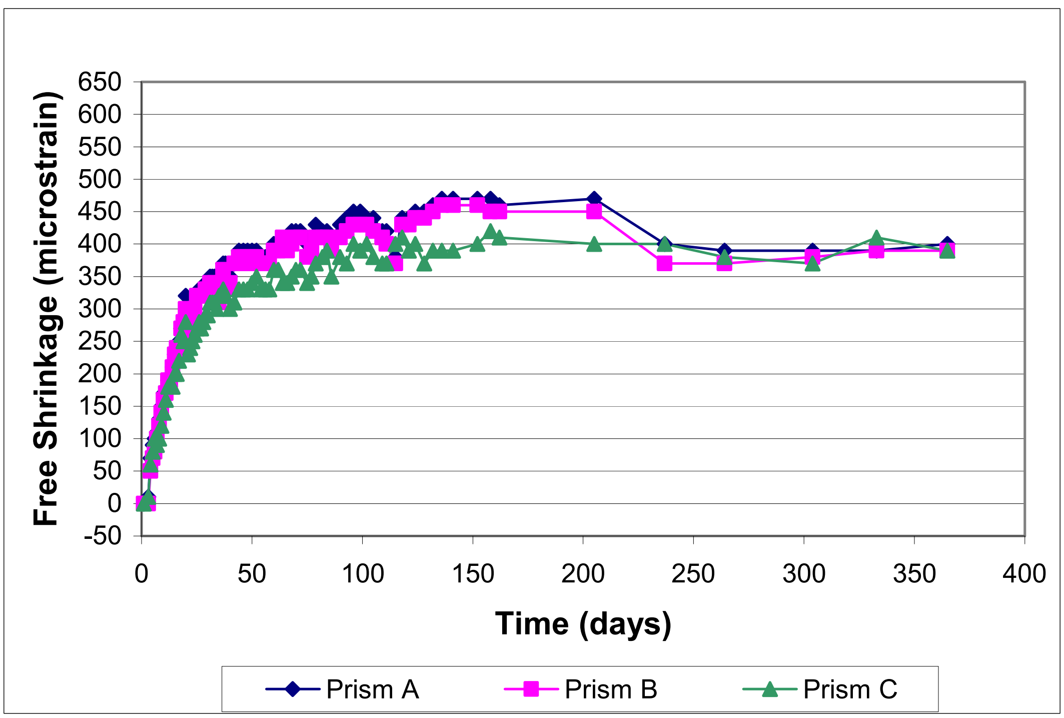

Figure A3.55 - Free Shrinkage, Batch 149, 295 kg/m^3 (497 lb/yd^3), Type I/II cement. Drying begins at 3 days. Reduced cement content mix.