Final Report

on

Highway Research Center Research Project

LABORATORY PERFORMANCE OF SHRINKAGE COMPENSATING CONCRETE MIXTURES DESIGNED TO REDUCE DRYING SHRINKAGE AND BRIDGE DECK CRACKING IN ALABAMA

Prepared by

G. Ed Ramey
B. Lee Cope

Department of Civil Engineering
Auburn University

September 1999

ABSTRACT

Cracking in bridge decks has plagued the infrastructure of roads and highways in Alabama for many years, and has often lead to premature deterioration of the deck and ultimately the entire bridge. The primary cause of premature deck cracking is believed to be caused by concrete shrinkage (primarily drying shrinkage). It is believed that using a concrete mixture that reduces drying shrinkage as well as having other appropriate fresh and hardened concrete properties would reduce premature deck cracking and thus extend the durability and service life of bridge decks in Alabama.

Three different concrete mixtures were examined in an attempt to reduce drying shrinkage along with the ALDOT standard bridge mixture for comparison. The three concrete mixtures included SCC-K, a concrete mixture containing Type-K cement, SCC-K/MS, a concrete mixture containing Type-K cement and micro silica, ALDOT-SRA, a concrete mixture including the standard ALDOT mixture with 1.5% shrinkage reducing admixture, Eclipse, by weight of cement. Several fresh and hardened concrete properties were observed for the four concrete mixtures. The fresh concrete properties were observed at three different ambient temperatures, (45° F, 75° F and 95° F) and the hardened concrete properties were observed at four different curing conditions.

Through extensive laboratory testing the SCC-K mixture exhibited superior results in reducing drying shrinkage as well as showing the best fresh and hardened concrete property results. It was observed that the SCC-K mixture relied heavily on achieving a good 7-day wet curing of the concrete. It is believed that the SCC-K mixture would result in less drying shrinkage, which in turn would result in bridge decks in Alabama having less drying shrinkage cracking and probably longer service lives.

ACKNOWLEDGEMENTS

This research was supported by the Highway Research Center (HRC), and the Civil Engineering Department at Auburn University. The PI is grateful to these sponsors for their support of this work. Also, the PI is grateful to Mr. Ed. Russell and Mr. John Jenkins of Blue Circle who provided technical and material support throughout the project, to Mr. Oscar Harper of Master Builders Technologies for supplying the concrete admixtures used in the project, and to Mr. Brit Simpson of Grace Construction Products for supplying the shrinkage reducing admixture.

Special thanks are due to Mr. Dan Morgan of Williams Brothers Construction in Atlanta, Georgia, for his assistance in helping to execute the laboratory testing program associated with the project. Last, the PI is grateful to Mr. John McInnis of the McInnis Corporation in Montgomery, Alabama, for his review and suggestions on the guidelines for constructing with shrinkage compensating concrete.

TABLE OF CONTENTS

1. INTRODUCTION

2. BACKGROUND AND LITERATURE REVIEW

3. LABORATORY TEST PROGRAM

4. LABORATORY EQUIPMENT, SPECIMENS AND PROCEDURES

5. PRESENTATION OF LABORATORY RESULTS

6. GUIDELINES FOR USE OF TYPE-K CEMENT/CONCRETE

7. CONCLUSIONS AND RECOMMENDATIONS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1 Statement of Problem

There appears to be a consensus of opinion of Alabama Department of Transportation (ALDOT) engineers that concrete shrinkage is the primary cause of bridge deck cracking, and in turn, deck cracking is the primary cause of premature deck deterioration and reduced durability. Thus, actions to mitigate deck concrete shrinkage and cracking should be identified and explored. Since shrinkage-compensating concrete (SCC) is known to substantially reduce net shrinkage and thus shrinkage cracking, this material should be closely examined as a candidate material for bridge decks to enhance their durability and service life. Additionally, a new shrinkage-reducing admixture (SRA) called "Eclipse" has been developed by the Grace Construction Products Company that looks promising as a concrete admixture to reduce early drying shrinkage cracking of bridge decks. Closely examining the fresh and hardened behavior and properties of SCC concrete and concrete employing SRA as an admixture was the impetus and purpose of this research.

1.2 Objectives

The ultimate objective of this research was to reduce instances of early bridge deck cracking, and thus improve the durability performance of bridge decks in Alabama. The specific sub-objectives of this project toward that end were as follows:

1. Develop effective, robust, and construction friendly shrinkage-compensating concrete (SCC) and shrinkage-reducing admixture (SRA) mixture designs which are appropriate for bridge deck applications in Alabama.
2. Determine the sensitivity of the mixture designs in (1) to curing conditions and construction time of year (temperature at construction).
3. Identify appropriate curing requirements, limitations on construction temperatures, and practical and effective concrete QC/QA monitoring/testing requirements to be employed when using SCC or SRA concrete.

1.3 Scope

The research work was limited to performing laboratory testing on fresh and hardened concrete for four mixture designs. One of the mixtures was ALDOT's standard structural concrete for control. The other three were a SCC mixture, a SCC with micro silica mixture, and an ALDOT standard mixture but with the SRA Eclipse added. Since the testing was limited to the laboratory, it was anticipated that a field verification testing program would be recommended for those mixtures exhibiting good behavior and performances in the laboratory.

2. BACKGROUND AND LITERATURE REVIEW

2.1 Background

Many bridge decks constructed in the U.S. in the 1950's and 1960's suffered from severe cracking and deterioration. These decks were typically in the 6"-6.5" thickness range. In the 1970's many state DOT's enacted deck design changes to address these premature deteriorations and poor durability performances. The primary changes were increased deck thickness (to approximately 8" – 8.5") and increased cover on the deck top reinforcing steel to 2" – 2.5" [38]. Texas, New York and New Jersey were three of the states marking such changes and they are most pleased with the improved deck performances. It is interesting to note that the ACI recommends a nominal minimum deck thickness of 8" [7].

The ALDOT employs thinner decks on their highway bridges than almost all other states and countries. Up until about two years ago, ALDOT deck depths ranged from 6.25" to 7.75", with the depth depending primarily on the girder spacing. About two years ago, the minimum depth was increased to 7" and thus ALDOT's deck depths now range from 7" to 7.75". Most parties view this increase in minimum deck thickness as a step to reduce deck cracking and enhance service life. However, even with the upgrade, ALDOT still employs thinner decks than most other highway agencies.

In addition to thin (and flexible) decks, which lead to greater structural deflections and cracking, the ALDOT (as has most other state DOT's) has, with time, changed to using higher cement content mixtures with smaller coarse aggregate and reduced requirements on wet curing for its deck concrete. All of these cause increased concrete drying shrinkage and cracking, and in turn, reduced service life.

The ALDOT, has many bridges which have good substructures and superstructures, but deteriorated decks which need rehabilitating or replacement. For example, there are numerous (approximately 80) bridges in the Birmingham area which are part of the I-65 and I-59 interstate highway system through the city which are approximately 28 years old and have badly cracked concrete decks (see Figures 2.1 and 2.2). It appears that these cracks are primarily the result of

- early drying and thermal shrinkage
- early concrete obstructed settlement
- thin and flexible deck (approximately 6.5 inches)
- light and flexible superstructure
- heavy traffic volume (≈77,000 ADT in 1995)
- heavy truck loading (8% in 1995 with many estimated as being overloaded)

The typical failure chronology for bridge decks in Alabama appears to be as follows:

- A significant level of early transverse shrinkage cracking
- Growth in width of transverse cracks due to crack movement and abrasion from traffic and environment loadings
- Development of longitudinal cracks at girder edges due to poor longitudinal distribution of truck tire loadings (due in part to extensive transverse cracking)
- Reduced bending stiffness in both the transverse and longitudinal directions due to crack growth which in turn leads to increased deck cracking

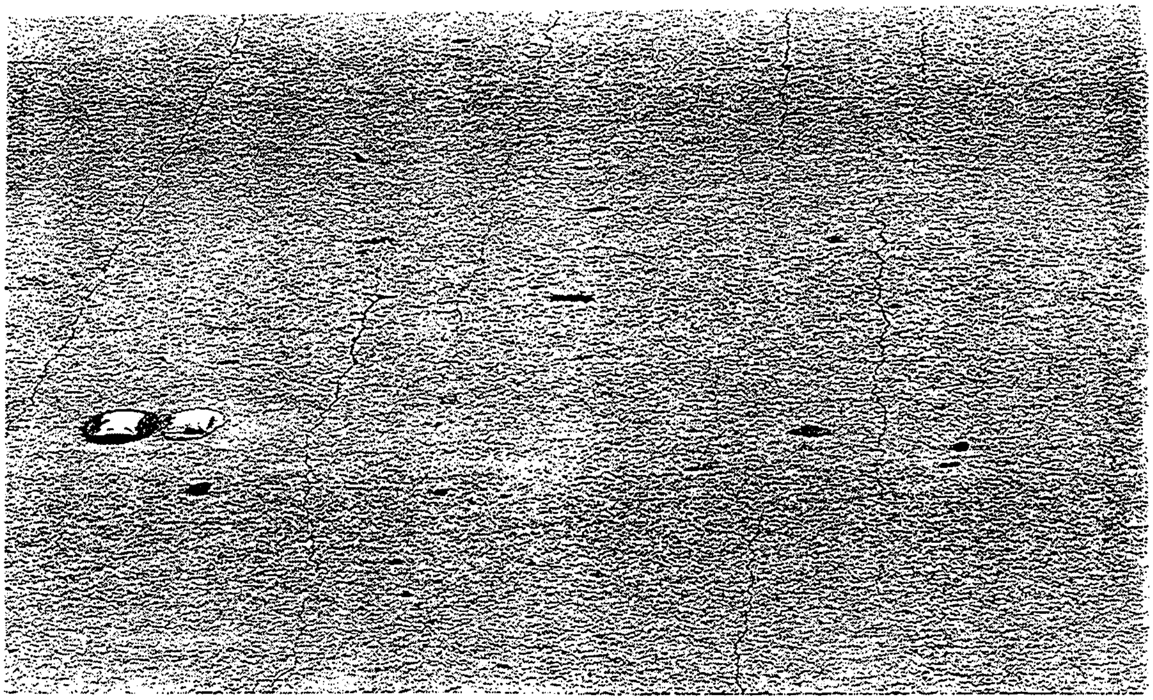


Figure 2.1. Close-up of Transverse Cracking on I-65 Bridge

Figure 2.2. I-65 Deck Surface Spall

- Local surface spalling requiring ever increasing maintenance attendance
- Eventual deck punching shear failures

2.2 Literature Review

2.2.1 Deck Cracking

Since deck cracking appears to be the initiating point for most bridge deck deterioration in Alabama, the causes of deck cracking were of particular interest. Bridge deck concrete shrinks as it dries out and cools down, and since it is constrained externally by the bridge longitudinal girders (whether intentionally by shear studs or unintentionally by adhesion and friction), and internally by the deck reinforcing steel, shrinkage stresses develop which may, and usually do, cause micro and macro shrinkage cracks in the deck. A cooperative study by PCA with ten states DOT's in the1970 [25] found that:

- transverse cracking was the predominate mode of deck cracking
- transverse cracking appeared to increase somewhat with age and increasing span length
- combinations of transverse and longitudinal cracking was the most detrimental as these often lead to surface spalls, potholes, or deck punching shear fractures
- on decks supported by steel girders, transverse cracking usually occurred at relatively short intervals throughout their length, regardless of being simple or continuous span structures
- transverse cracks typically occur directly over transverse rebars

Figure 2.3 shows an example of such transverse cracking which is believed to be primarily caused by drying shrinkage, and a combination of resistance to subsidence when the concrete is in the plastic state and later concrete tensile stress concentrations

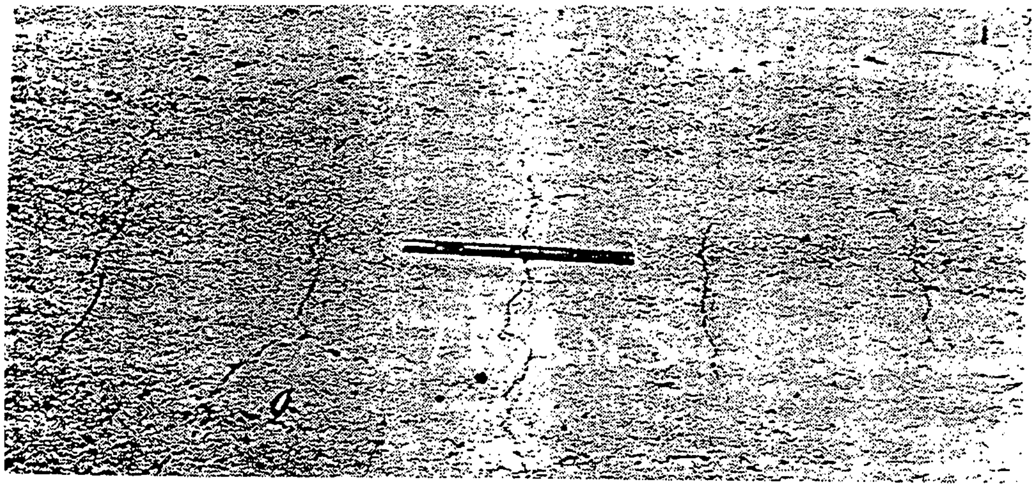


Figure 2.3 Deck with Truss Reinforcement-Transverse Cracks Developed Only Where Truss Bars are Near Top of Slab [24].

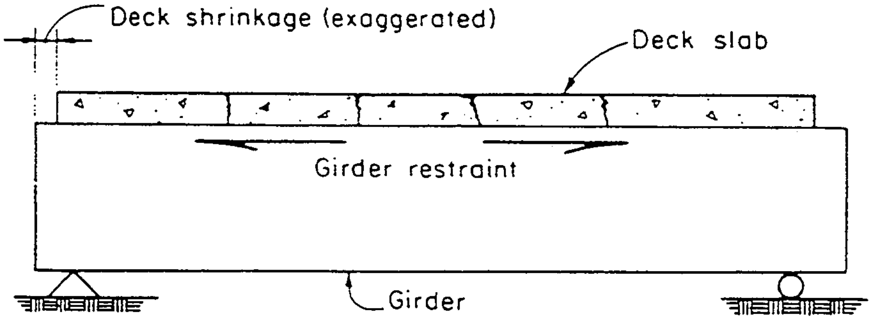


Figure 2.4 Girder Restrain to Volume Changes [24].

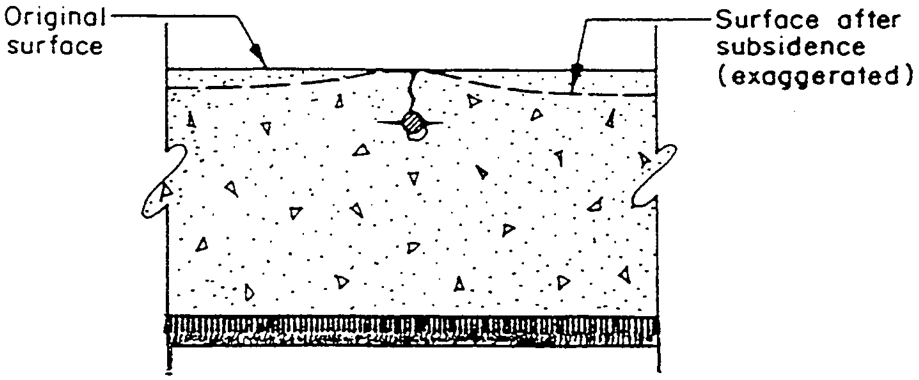


Figure 2.5 Resistance to Subsidence of Concrete by Top Reinforcement [24].

due to the presence of the top transverse rebars (see Figures 2.4 and 2.5). Results of recent surveys [1,2,3] indicate that restrained shrinkage of concrete is the leading cause of bridge deck cracking. The restraint may take the form of internal reinforcing steel, external deck/girder shear connectors, and girder/abutment connections. The drying shrinkage of concrete is caused by a loss of moisture either from evaporation or hydration, and is also affected by the relative paste volume, the aggregate type, and the relative humidity.

As indicated earlier, there appears to be a consensus of opinion of ALDOT engineers that concrete shrinkage is the primary cause of bridge deck cracking, and in turn deck cracking is the primary cause of premature deck deterioration and reduced durability. The primary causes of this are felt to be the concrete mixture design and poor quality concrete curing. Thus to effectively mitigate shrinkage cracking of bridge decks, improvements must be made in these two areas.

2.2.2 Concrete Shrinkage

Plastic, drying and thermal shrinkage of concrete are dependent on many parameters. However, the dominant ones appear to be:

1. The ingredients and mixture proportions of the concrete
2. The curing provided at time of placement
3. The weather exposure conditions

It is well known that plastic shrinkage cracking is dependent on the surface evaporation rate and the concrete bleed rate. The surface evaporation rate is a function of the weather exposure conditions, and the bleed rate is primarily a function of the concrete mixture design and the amount of water in the mixture and its bleed charactersitics. Also, drying and thermal shrinkage cracking are functions of the weather exposure conditions. Drying shrinkage is primarily a paste issue and it too is strongly dependent on the amount of water in the mixture. Thermal shrinkage is primarily a function of the mixture aggregates, cement type and content, and external temperature conditions.

Curing requirements are primarily a function of concrete mixture designs and weather exposure conditions. This is true during the plastic period (0-4 hours after placement) of the concrete (to prevent plastic shrinkage cracking), and during the following 4 hours-7 days period. The higher the evaporation rate (E_r) from the ACI 305 Evaporation Chart, the greater the curing water retention demands.

Results of a recent survey [10] indicated that restrained shrinkage of concrete is the leading cause of bridge deck cracking. The restraint may take the form of internal reinforcing steel, external deck/girder shear connectors, and girder/abutment connections. The drying shrinkage of concrete is caused by a loss of moisture either from evaporation or hydration, and it also affected by the relative paste volume, the aggregate type, and the relative humidity. There are two products that have been shown to substantially reduce drying shrinkage cracking, shrinking compensating cement, or Type-K cement and a new shrinkage reducing admixture, Eclipse. Shrinkage compensating cement reduces shrinkage cracking primarily by inducing an increase in the volume of the concrete shortly after the concrete sets. In turn this offsets the subsequent drying shrinkage of the concrete to reduce or eliminate the net drying shrinkage. The shrinkage reducing admixture, Eclipse, reduces the surface tension of water. With reduced surface tension, the force pulling in on the walls of the pores is reduced, reducing shrinkage strain and therefore drying shrinkage is reduced.

The dominant cause of bridge deck cracking in Alabama is probably drying shrinkage cracking, and the primary causes of this are probably the concrete mixture design and poor quality concrete curing. Thus, to effectively mitigate early shrinkage cracking of bridge decks, a comprehensive investigation to identify improved

- concrete mixture design
- concrete curing requirements

is needed. This is the impetus and purpose of this investigation.

Plastic Shrinkage: According to Lerch [19], plastic shrinkage is the shrinkage that occurs in the surface of fresh concrete within the first few hours after placement, while the concrete is still plastic and before it has attained any significant strength. He states that plastic shrinkage cracks do not appear to have a definite pattern but an occasional crow foot pattern has been observed. When cracking starts, it proceeds rapidly. The cracks are not usually progressive and do not immediately affect the structural performance of pavements or structures. Powers [25] states that the pattern of plastic shrinkage cracks is determined by the nature of restraint against contraction. If the concrete contains fixed objects such as a rectangular grid of reinforcement, the restraint of the movement by the steel bars may be reflected in the crack pattern. The pattern of cracking may also be influenced by the flaws developed during settlement. Raina [26] writes that plastic shrinkage cracking can occur in a variety of patterns: at 45° to the edges of the slab with the cracks 0.7 – 6.6 feet apart; normal to the wind direction since shrinkage would manifest in the direction of the wind, and following the pattern of reinforcement. These cracks usually pass through the full depth of the slab except in minor cases. Plastic shrinkage cracks which follow the pattern of reinforcing steel can be distinguished from plastic settlement cracks because the shrinkage cracks pass through the full depth of the slab and settlement cracks do not. However, it is important to note that other sources do not agree that plastic shrinkage cracks always pass through the entire depth of the slab, and indicate that they are usually superficial and limited to the top ½ - 1".

The consensus thought is that plastic shrinkage cracking is caused by excessive evaporation of water from the concrete surface. Shaeles and Hover [35] points out that the study of plastic shrinkage cracking is complicated because the material properties which determine whether such cracks will form are time dependent and change rapidly during the first few hours in the life of the concrete. Such properties include: rate at which water is lost from the concrete in response to evaporative conditions; the degree to which the loss of water results in volume reduction; the consistency or stiffness of the mixture; and the development of tensile stresses and strain capacity of the material.

In 1957, William Lerch [19] published findings from an extensive study of plastic shrinkage cracking of concrete. Field investigation presented in his study indicated that evaporation rate is the principle cause of plastic shrinkage cracking. With the same mixture and construction methods, plastic shrinkage cracks can occur at different times due to changes in weather conditions which increase the evaporation rate. At the time when evaporation rate exceeds the bleeding rate, cracks can propagate due to characteristics of the concrete. At this stage, the concrete has attained some rigidity and cannot accommodate the rapid volume change due to the plastic shrinkage by plastic flow. The concrete has not developed sufficient strength to withstand the tensile stresses which accompany the situation, therefore, plastic shrinkage cracks may develop.

Mindess and Young [21] conclude that the loss of water from the fresh concrete, if not prevented, can cause cracking. The most common situation is surface cracking due to evaporation of water form the concrete surface. When water is removed from the paste by exterior influences, such as evaporation at the surface, a complex series of menisci are formed. These, in turn, generate negative capillary pressures which will cause the volume of the paste to contract. Shrinkage occurs in the paste and is mitigated by aggregate as shown in Figure 2.6. Plastic shrinkage cracking is most common on horizontal surface pavements and slabs where rapid evaporation is possible and its occurrence will destroy the integrity of the surface and reduce its durability.

Lerch developed a nomograph, Figure 2.7, to predict evaporation rates on the exposed concrete surface. The nomograph requires to air temperature, relative humidity, concrete temperature, and wind velocity. Increase in temperature differential, concrete vs. ambient, decrease in relative humidity, and increase in wind velocity increase the evaporation rates. ACI 305 [6] specifies the nomograph developed by Lerch as the method to predict evaporation rate for placement of concrete. This nomograph will, hereafter, be referred to as the ACI 305 Surface Evaporation Chart. Kosmatka and Panarese [17] provide the following statements which summarize typical effects of weather conditions on concrete evaporation rate during and after finishing: a) If the air temperature and humidity remain the same and wind speed increases from 5 to 20 mph, evaporation rate will increase be 300 percent; b) If humidity and wind remain the same and the air temperature changes from 60 to 90° F, evaporation rate will increase by 300 percent; c) If air temperature and wind remain the same and humidity decreases from 90

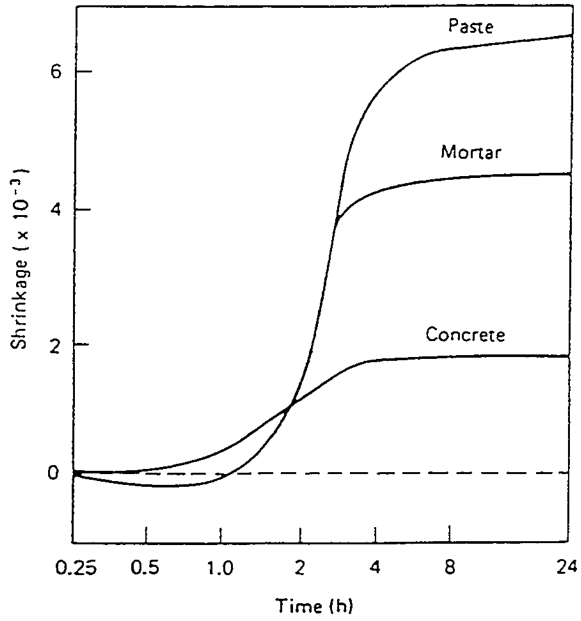
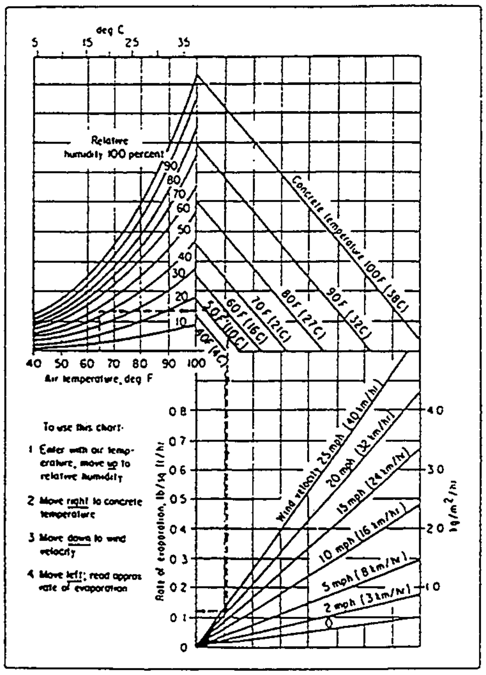


Figure 2.6 Effect of Aggregrate on Plastic Shrinkage [21].



To use this chart:

1 Enter with air temperature, move up to relative humidity

2 Move right to concrete temperature

3 Move down to wind velocity

4 Move left; read approx rate of evaporation

Figure 2.7 ACI 305 Surface Evaporation Chart [6,19].

to 70 percent, evaporation rate will increase by 300 percent; d) If all of the previous increases occur, the evaporation rate will increase by 900 percent.

The Federal Highway Administration (FHWA) [12] provides an equation in SI units to calculate the evaporation rate in accordance with the ACI 305 Surface Evaporation Chart:

$$E_r = \frac{1 + 0.2374W}{2906} * [(C^2 - 4.762C + 220.8 - RH(\frac{T^3 + 127.8^2 + 665.6T + 34283}{20415})]$$

Er = Evaporation Rate (kg/m^2/hr); C = Concrete Temperature (C°);

RH = Relative Humidity (%); T = Ambient Temperature (C°);

W = Wind Speed (km/hr).

What should be the limiting value for evaporation rate of concrete bridge deck placement is in dispute. ACI 305 [6] stipulates that when the evaporation rate exceeds 0.2 lbs/ft^2/hr, "precautions to inhibit plastic shrinkage cracking by reducing evaporation rate are necessary." FHWA [12] specifies "when placing concrete in bridge decks or other exposed slabs, limit expected evaporation rate to less than 0.5 kg/m^2/hr (0.1 lbs/ft^2/hr)." PCA sets the limit at 0.25 lbs/ft^2/hr. Mindess and Young [21] caution that if the evaporation rate exceeds 0.1 lbs/ft^2/hr, loss of moisture from the concrete may exceed the rate at which bleed water reaches the surface, creating the negative capillary pressures which cause plastic shrinkage. Precautionary measures should always be used if the evaporation rate exceeds 0.2 lbs/ft^2/hr.

Many studies have been conducted to determine at what time plastic shrinkage cracks will develop with respect to the time of placement and to the evaporation rate. Laboratory research cited by ACI 305 [26] shows the highest rate of water loss due to evaporation occurred in the first 4 hours for concretes with low water content, but more water was lost from concretes with high water content over a 24 hour period. Raina [26] says plastic shrinkage cracks develop within about one hour of placing concrete (longer with addition of retarders) but may not be noticed until much later. In field experiments conducted by Ravina and Shalon [32], plastic shrinkage cracks were observed a few hours after casting, following the disappearance of bleedwater. Plastic settlement cracks developed within one-half hour or so after casting while the concrete was still covered with bleedwater. These cracks tended to close unless exposed to rapid drying. In a lab study, cracks appeared 0.5-2 hours after evaporation of all visible water from the surface. No correlation between bleeding and cracking was found. Figure 2.8 plots shrinkage of the test mixtures vs. time. Each mixture is identified according to its environmental exposure conditions. The subscript of each mixture identifier represents the wind speed in km/hr. The superscript represents the air temperature in °C. Mixtures with the "rad" were exposed to infrared irradiation. Each mixture was exposed to relative humidity of 35% except for E^{20}_{20} which was exposed to 45% relative humidity. One can see that most of the shrinkage occurs in the first few hours after placement. A plot of water loss due to evaporation over time is given in Figure 2.9. It can be seen that following initial evaporation of the bleedwater, the rate remained constant for 2.5 to 4 hours and subsequently slowed down. Shaeles and Hover [35] found that plastic shrinkage cracking generally began 45 to 100 minutes after fans simulating wind were started. The fans were started 8 minutes after leveling the concrete and 30 minutes after mixing. The crack developed up to 2.5 hours.

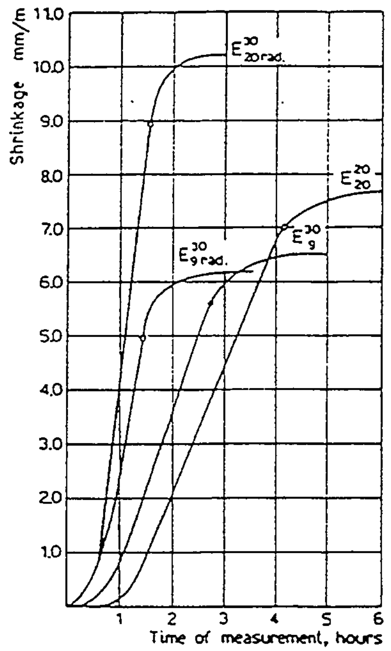


Figure 2.8 Shrinkage – Time Relationship [33].

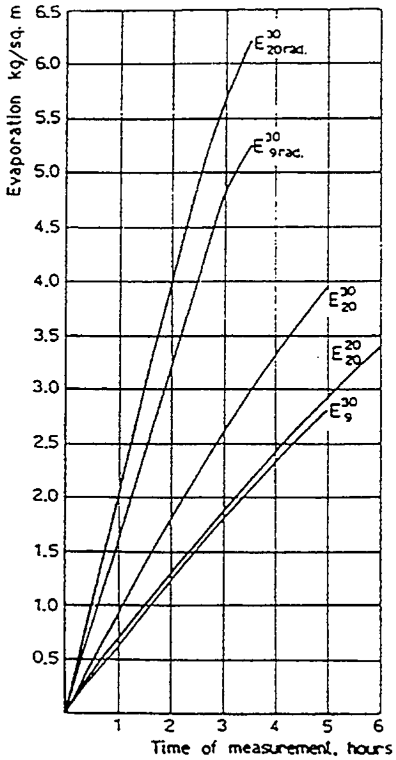


Figure 2.9 Evaporation – Time Relationship for Different Climatic Conditions [33]

Although plastic shrinkage is most common in hot weather, it can occur also in cold weather if the temperature of the concrete is significantly higher than the ambient temperature. Gebler [25] indicates that evaporation can occur from concrete even when there is 100% humidity. If the concrete temperature is greater than the ambient temperature, vapor pressure in the concrete is greater than vapor pressure of the air so water moves out of the concrete toward equilibrium. Senbetta and Bury [34] performed a study on the effectiveness of a freezing weather admixture (FWA) to mitigate plastic shrinkage cracking in cold weather. The results of the study revealed that an increase in the difference between ambient temperature and that of the concrete can result in a greater evaporation rate and increased plastic shrinkage cracking. Most of the cracks occurred within the first 4 to 5 hours after placing the mortar specimens into forms. The test panels were placed in an environment of 30° F. Panels with a mixture temperature of 65° F showed a larger cracking area than panels with a mixture temperature of 40° F. Plastic shrinkage cracking in the 65° F panels most likely occurred because the rate of evaporation facilitated by the large temperature difference between the warm mortar and cool environment exceeded the bleeding rate. A subsequent experiment proved that mortar specimens at 65° F lost more moisture than specimens at 40° F. The results are plotted in Figure 2.10. Data of the testing showed a strong correlation between total moisture loss and evaporation rates on the resulting test panels.

Early Thermal Shrinkage Cracking: Most commonly, the subject of concrete volume changes deals with the expansion and contraction due to temperature and moisture cycles. Thermal expansion and contraction of concrete varies with factors such as aggregate type, cement content, water cement ratio, temperature range, concrete age,

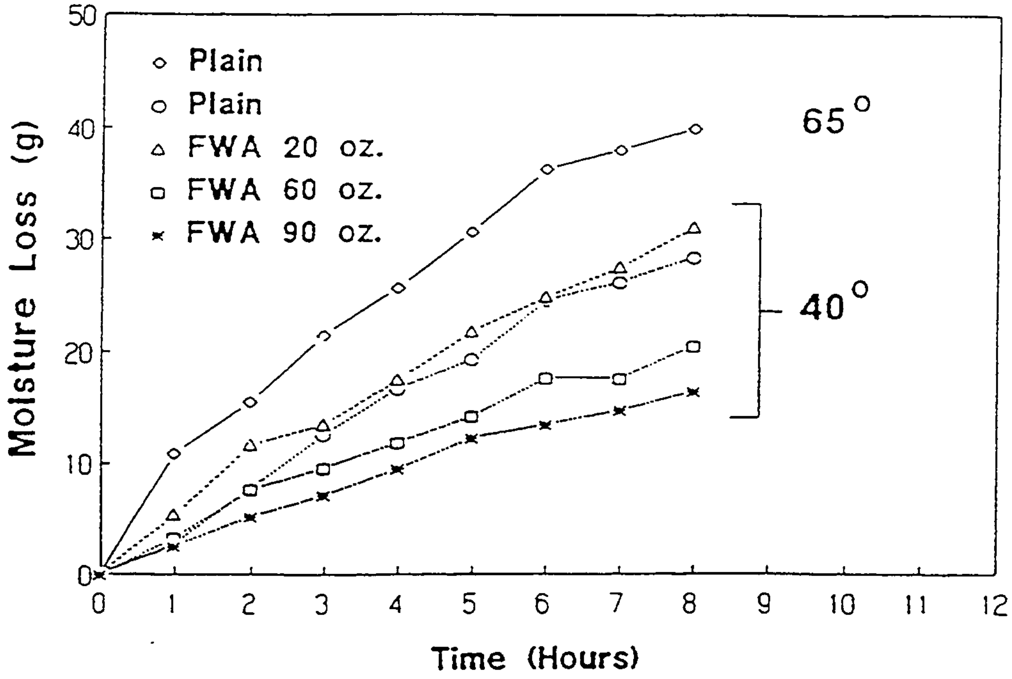


Figure 2.10 Effect of FWA on Loss of Water on Test Specimens [26].

Table 2.1 Effect of Aggregate on Thermal Coefficiant of Expansion of Concrete [16].

Aggregate type (from one source)	**Coefficiant of Expansion millionths in/in per °F**
Quartz	6.6
Sandstone	6.5
Gravel	6
Granite	5.3
Basalt	4.8
Limestone	3.8

and relative humidity. Of these, aggregate type probably has the greatest influence. Some aggregate types along with their effect on thermal coefficiant of expansion of concrete are listed in Table 2.1. An average value for the coefficient of thermal expansion of unreinforced and reinforced concrete is 5.5 and 6.0 millionths of an inch per inch per degree Fahrenheit, respectively.

According to Raina [26], early thermal contraction strains far exceed drying shrinkage strains and are primarily responsible for early cracking in retaining walls and reinforced concrete bridge deck structures. The reaction of cement with water, known as hydration, is a chemical reaction which produces heat. If insulated and large enough, the rate of heat gain in a concrete element is likely to exceed the rate of heat loss to the atmosphere, causing a rise in temperature. After the first day, the rate of heat gain falls below the rate of heat loss and the concrete member begins to cool, resulting in contraction. Cracking can result if the concrete is restrained internally or externally and adequate strength has not developed to resist tensile stresses caused by the contraction. Internal restraint occurs due to rebar mats and differential cooling of the member, e.g., the surface of the member cools faster than the core. External restraint refers to restraint provided by external supports. Raina indicates that the core of concrete cools to ambient in 7 to 14 days. Hence, thermal movement cracks are more likely to occur during this period. One of the most important factors which assists in differentiating between thermal movement cracks and long-term drying shrinkage cracks is knowledge of when the crack forms. A crack which develops in the first few weeks is unlikely to be a drying shrinkage crack unless the deck is subjected to extreme drying conditions.

Drying Shrinkage Cracking: Another type of shrinkage that can lead to early deck cracking is drying shrinkage. The effects of drying shrinkage are graphically illustrated in Figure 2.11. Raina [26] defines drying shrinkage as the reduction in volume of concrete caused by the chemical and physical loss of water from the concrete during the hardening process and exposure to unsatruated air. The drying shrinkage cracks result only in a restrained condition due to tensile stresses which develop from the drying shrinkage. Raina states that loss of water by evaporation is the primary cause of the drying shrinkage and, hence the relative humidity of the air surrounding the concrete greatly influences drying shrinkage. Decrease of relative humidity and windy conditions increase evaporation rate and, therefore, increase drying shrinkage. As relative humidity increases, the mechanism of drying shrinkage is reduced until relative humidity equals 95% and moisture movement ceases.

Concrete expands slightly with a gain in moisture and contracts with a loss in moisture. The effects of these moisture movements are illustrated schematically in Figure 2.12. Specimen A in that figure represents concrete stored continuously in water from time of casting; Specimen B represents the same concrete exposed first to drying in air and then to alternate cycles of wetting and drying [17]. It should be noted that the swelling that occurs during continuous wet storage over a period of several years is usually less than 150 μ strain or about one-fourth of the shrinkage of air-dried concrete for the same period.

Tests indicate that the drying shrinkage of small, plain concrete specimens (without reinforcement) ranges from about 400 to 800 μ strain when exposed to air at 50% humidity [17]. Drying shrinkage values decrease as relative humidities increase as

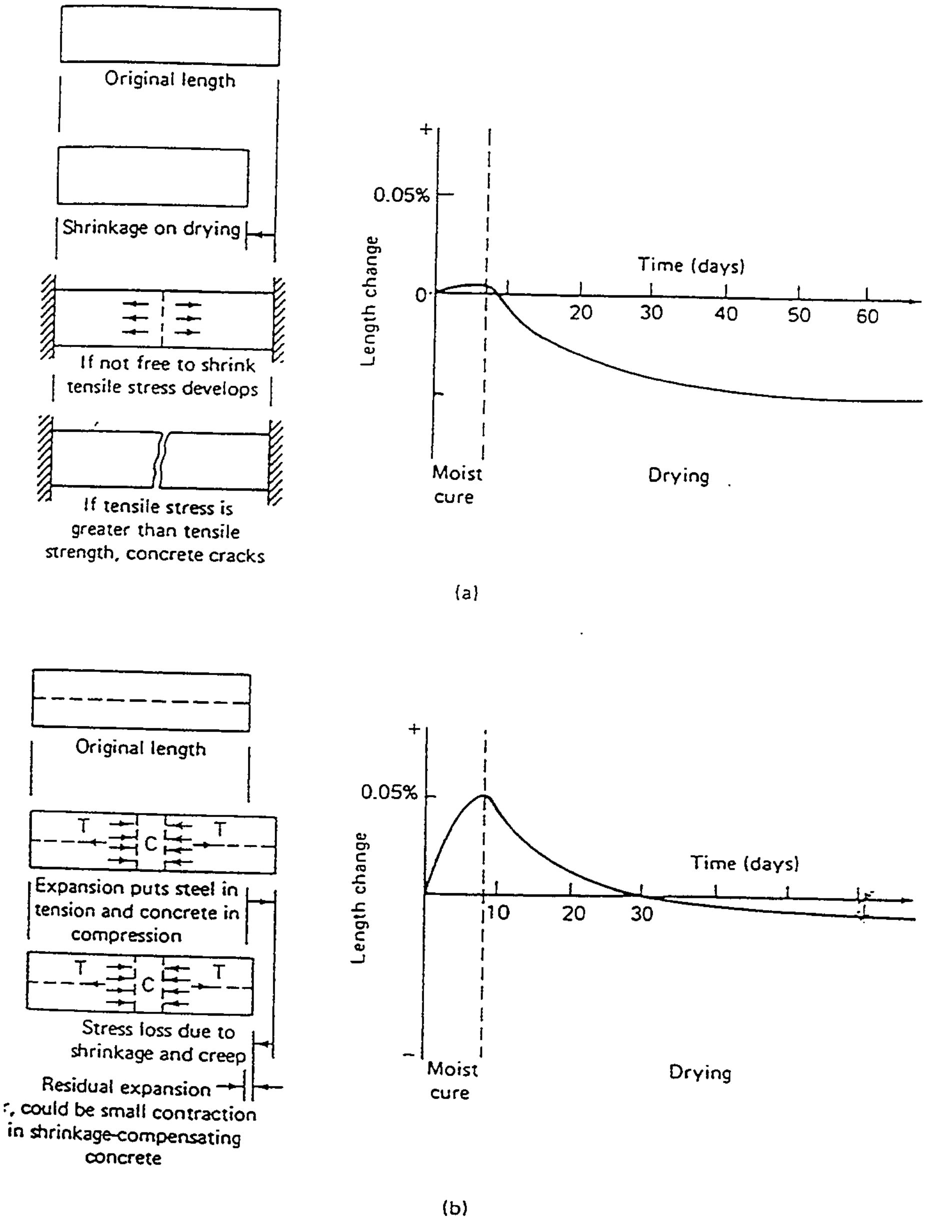


Figure 2.11 Drying Shrinkage of Concretes with: a) Type I Portland Cement; b) Expansive Cement [21].

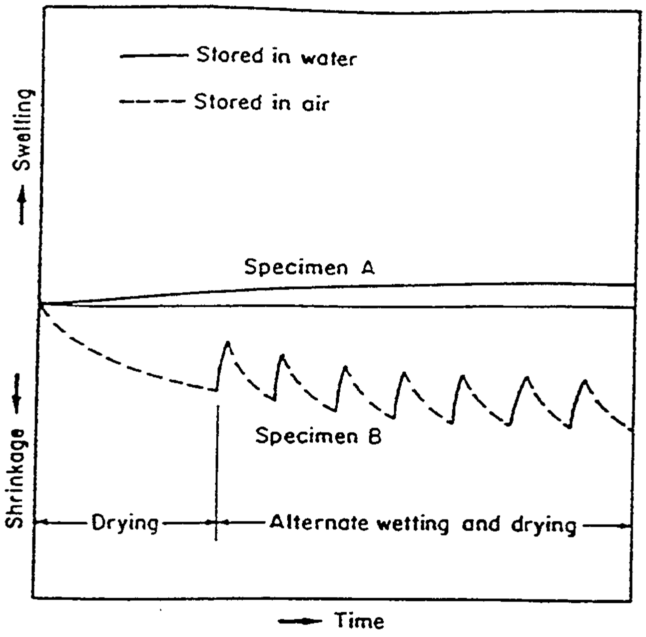


Figure 2.12 Illustration of Moisture Movements in Concrete [17].

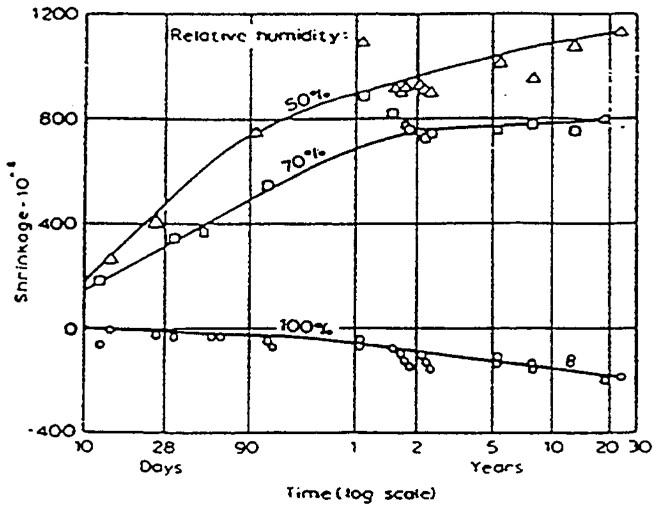


Figure 2.13 Shrinkage vs. Time for Concretes Stored at Different Relative Humidities [23].

can be seen in Fig.2.13. It can be noted that concrete with a unit shrinkage of 550 μ strain shortens about the same amount as the thermal contractions caused by a decrease in temperature of 100 degrees F.

The shrinkage of large concrete components is less than that of small test specimens because of movement restraints offered by other components of the structure, and by the concrete reinforcing steel. In reinforced concrete structures with normal amounts of reinforcement, drying shrinkage is commonly assumed to be 200 to 300 μ strain. This is approximately the same strain level as for 50 degrees F change in temperature.

The most important controllable factor affecting the drying shrinkage of normal portland cement concrete is the amount of water per unit volume of concrete. The results of tests illustrating the water content-shrinkage relationship are shown in Figure 2.14. This figure indicates that shrinkage is a direct function of the unit water content of fresh concrete. The close grouping of these curves shows that drying shrinkage is governed mainly by unit water content (note the narrowness of the band of water content on shrinkage regardless of cement content or water-cement ratio.).

The curves of Figure 2.14 along with results from other mixtures testing can be banded as shown in Figure 2.15, and illustrate the dramatic increases in drying shrinkage with increasing water content. Thus, shrinkage can be minimized by keeping the water content of concrete as low as possible (and still achieve the required workability). This is achieved by keeping the total coarse aggregate content of the concrete as high as possible. Use of low slumps and pacing methods that minimize water requirements are thus major factors in controlling concrete shrinkage [17]. Additionally, early, prolonged

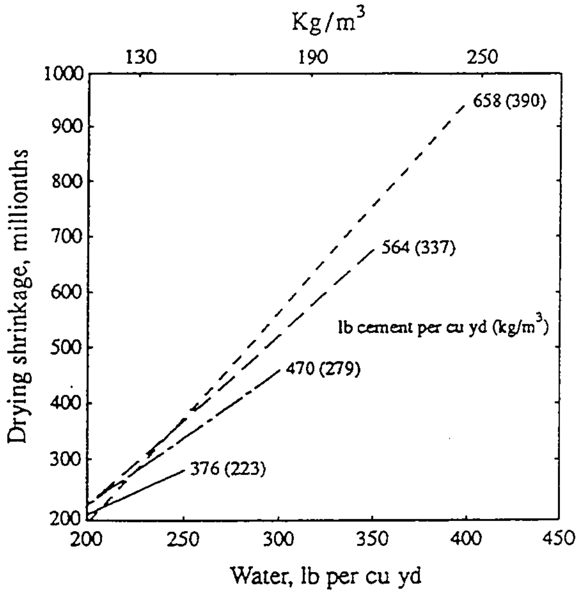


Figure 2.14 Interrelation of Shrinkage, Cement Content, and Water Content [Unknown Source].

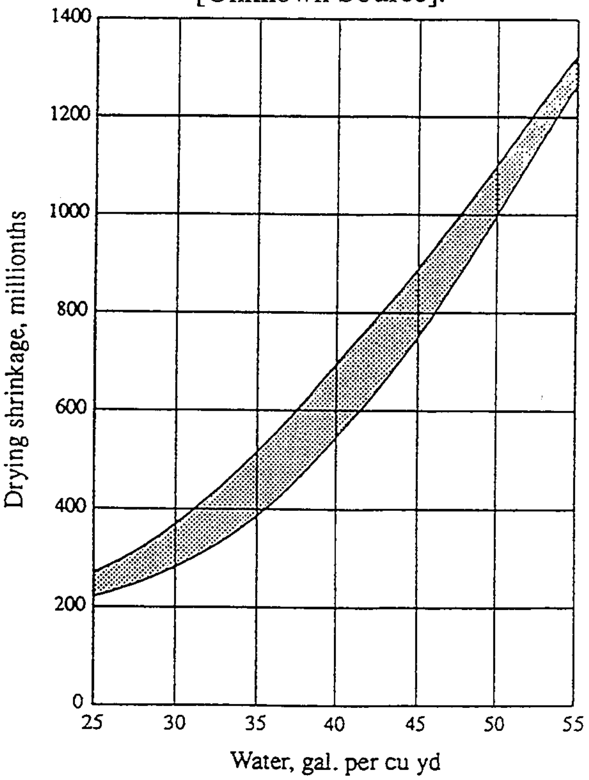
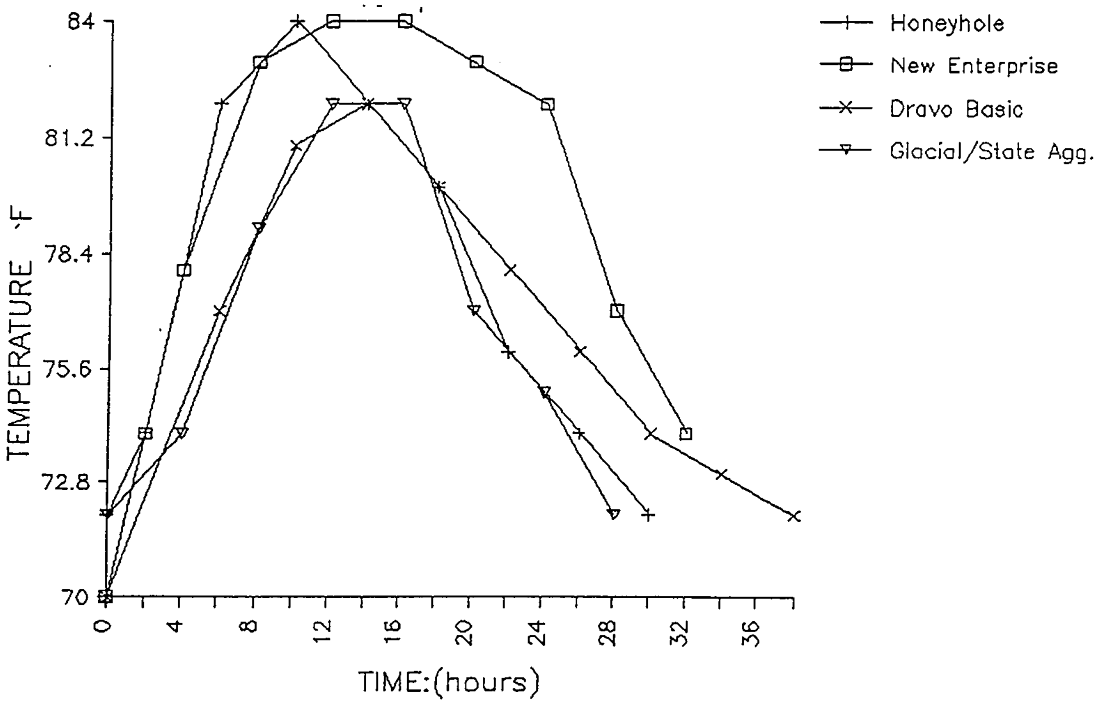


Figure 2.15 Water Content vs. Drying Shrinkage [17].

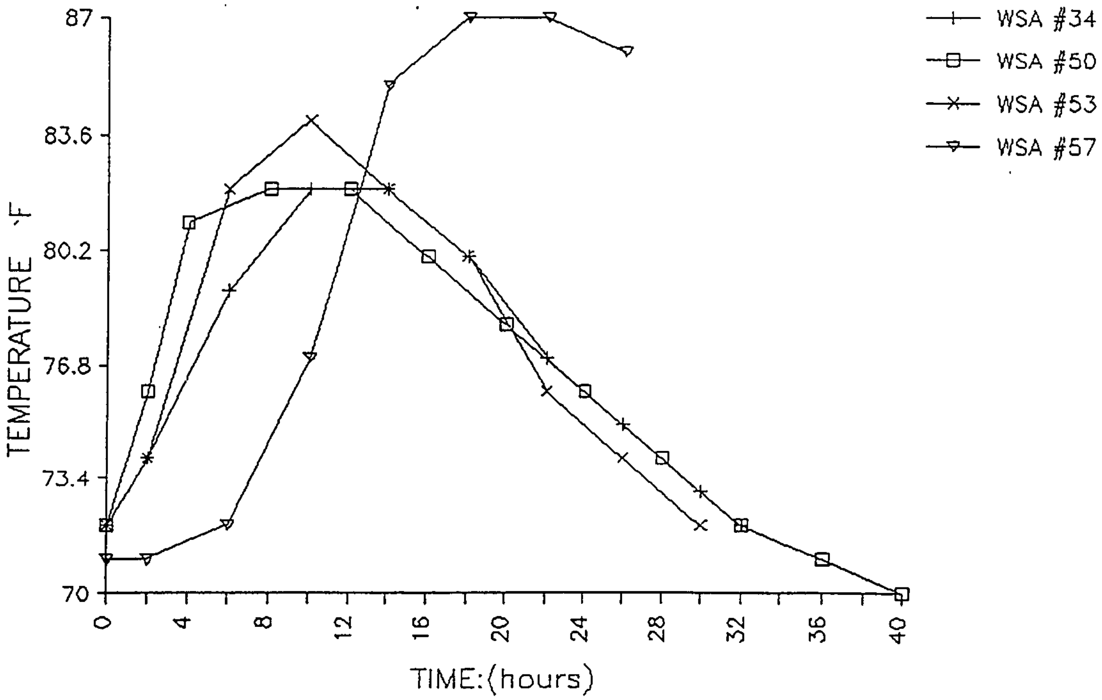
and careful curing is beneficial for shrinkage control. Any practice that increases the water requirement of the cement paste, such as the high slumps, excessively high freshly mixed concrete temperatures, high fine aggregate contents, or small-size coarse aggregate, will increase shrinkage.

Any workable concrete mixture contains more water than is needed for hydration. If the concrete is exposed to air, the larger part of this free water evaporates in time, with the rate and completeness of drying dependent on ambient temperature and humidity conditions. As the concrete dries, it shrinks in volume as indicated above. If this volume reduction is unrestrained then no shrinkage stresses or cracks are produced. However, if the concrete is restrained by other structure components or by embedded reinforcing steel, then the drying shrinkage results in shrinkage tensile stresses which in turn may result in concrete cracking. Also, as drying takes place, concrete near the surface dries and shrinks faster than the inner concrete, causing surface tensile stresses and possible cracking. Thus the effects of drying shrinkage are the same as those of thermal shrinkage, i.e., stresses are developed only when movement is restrained.

Unfortunately, the water content of the concrete is not the only mixture component which significantly affects drying shrinkage. Wilbur Smith & Associates [9] conducted limited laboratory testing to access the efforts of aggregate type/source, mixture proportions, cement type/source, and fly ash on drying shrinkage. The results of their testing are shown in Figure 2.16 and indicate a large variability in drying shrinkage for all of the mixture parameters shown. This points to the desirability of evaluating the characteristics of each concrete mixture/material source for concrete components, such as bridge decks, where drying shrinkage is important. Note in Figure 2.16 that most of the

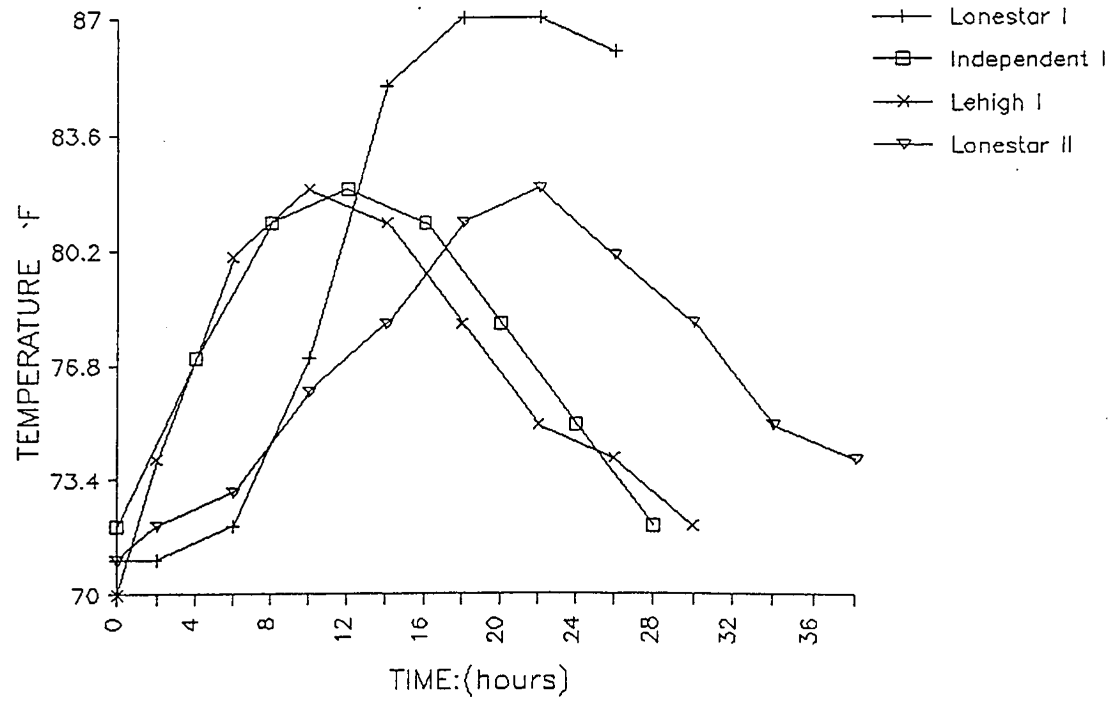


a) Effect of Aggregate Source

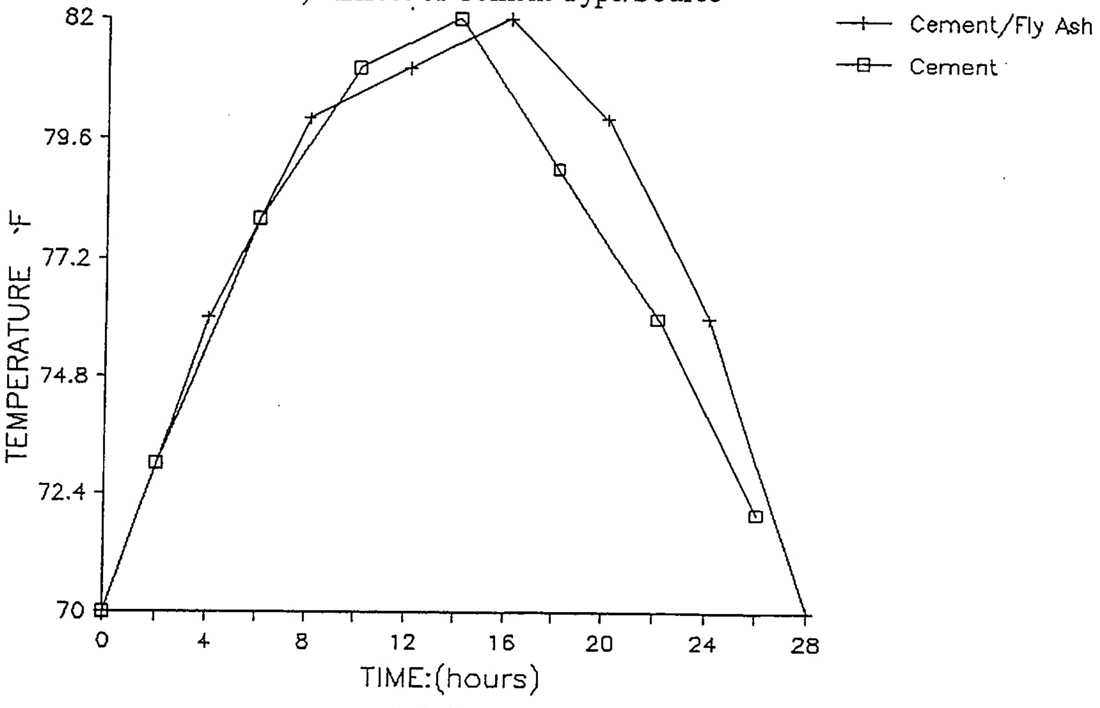


b) Effect of Mixture Design

Figure 2.16 Effect of Some Mixture Parameters on Concrete Drying Shrinkage [9].



c) Effect of Cement Type/Source



d) Effect of Flyash

Figure 2.16 (Continued) Effect of Some Mixture Parameters on Concrete Drying Shrinkage [9].

drying shrinkage took place during the first 56 days or 2 months. For larger concrete "specimens", such as bridge decks, the time period of significant shrinkage would probably be extended to approximately 1-year.

Typical concrete initial swelling and following drying shrinkage curves fall within the range of the curves shown in Figure 2.17. Typically early age behavior is that of swelling during wet curing of 7 days as indicated in Figure 2.17. This is followed by drying shrinkage to ultimate shrinkage strain levels of 600 to 800 μ strain. Weight loss and drying shrinkage time history curves for some concrete cylinders are shown in Figure 2.18. Concrete mixtures can be classified based on drying shrinkage as follows:

No shrinkage: < 0.004% shrinkage
Low shrinkage: 0.004% – 0.04% shrinkage
Moderate shrinkage: 0.04% - 0.08% shrinkage
High shrinkage: >0.08% shrinkage

2.2.3 Shrinkage Compensating Concrete

Blue Circle Cement Company [32] defines shrinkage compensating concrete (SCC) as concrete made with an expansive cement which when properly restrained by reinforcement or other means will expand an amount equal to or slightly greater than the anticipated drying shrinkage. Subsequent drying will reduce these expansive strains but, ideally, a residual expansion will remain in the concrete, thereby eliminating shrinkage cracking. Blue Circle Cement Company is one of the nations leading cement producers and manufacturers and distributes Type-K Expansive Cement which meets ASTM C845 Type E-1 (K), "Standard Specification for Expansive Hydraulic Cement." This is the type of cement used in the SCC investigated in this research.

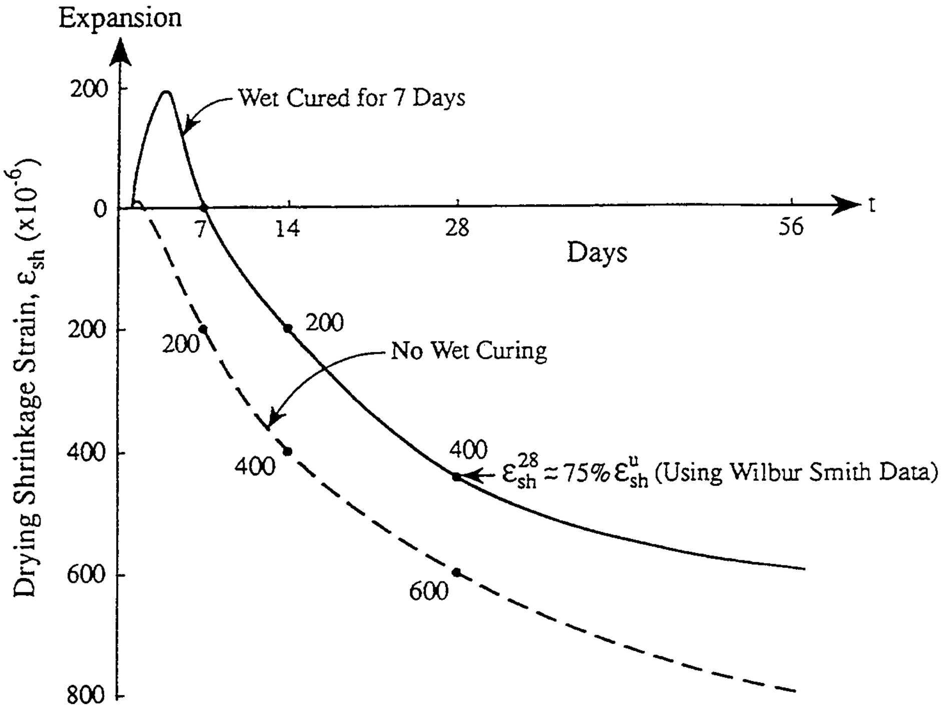


Figure 2.17 Approximate Drying Curves for Laboratory Test Prism Specimen [9].

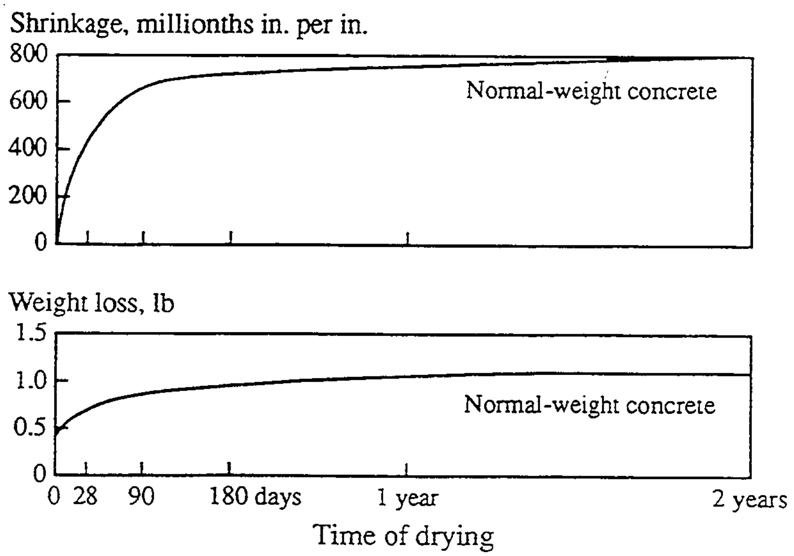


Figure 2.18 Weight Loss and Drying Shrinkage Curves for Concrete Cylinders [17].

Effects on Concrete Shrinkage: Type-K cement is manufactured by blending ordinary portland cement clinker with comentitious expansive components. The expansive component in Type-K cement is mostly anhydrous tetracalcium trialuminate sulfate (C_4A_3S) and calcium sulfate ($CASO_4$). This cement hydrates to form ettringite when it comes into contact with water forming a stable ettringite crystalline structure which causes the cement to expand. Ettringite is formed when the following chemical compounds are added together: $6CaO+Al_2O_3+3SO_3+32H_2O$ = Ettringite. ACI Committee 223 [31] states that ettringite starts to form during the mixing and continues to form during subsequent water curing until the SO_3 or Al_20_3 is exhausted. This formation of ettringite usually causes the cement to expand for the first seven days due to moist curing as can be seen in Figure 2.19. Research has shown [4], that the characteristics of expansion are influenced by many factors.

Effects of Chemical Composition and Particle Fineness: Expansion characteristics have been shown [19,21] to be a function of the chemical composition of the particular cement. ACI Committee 223 [4] has found that the expansive behavior is similar in the various expansive cement formulations and made the following observations: (a) the rate of expansion appears to depend on the amount of readily hydratable aluminates and is proportional to the amount present as long as $CaSO_4$ is still available, with the aluminate being C_4A_3S in Type-K cement and (b) for a given aluminate content the length of time that the expansion takes place appears dependent upon the amount of calcium sulfate present. This can be seen in Figure 2.20 for Type-S (another expansive cement) mortar, which reflects that at a fixed C_3A content the expansion increases with increasing sulfate content. Once the sulfate content is above the

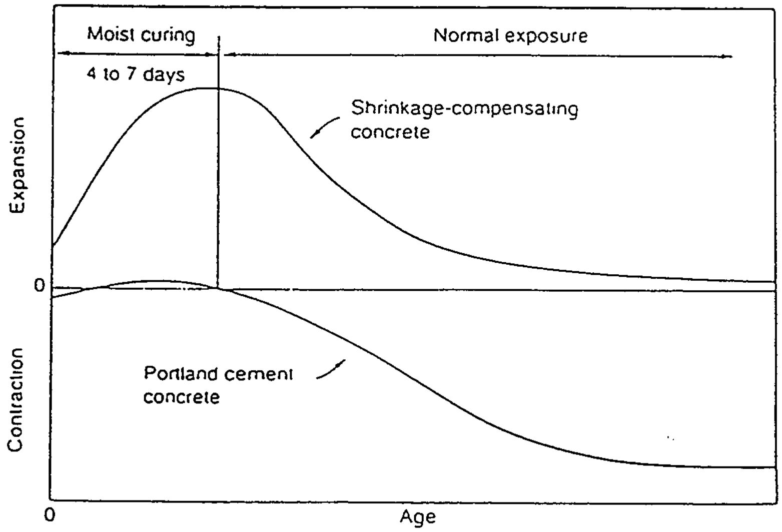


Figure 2.19 Time-Shrinkage Characteristics of Shrinkage Compensating and Portland Cement Concretes [32].

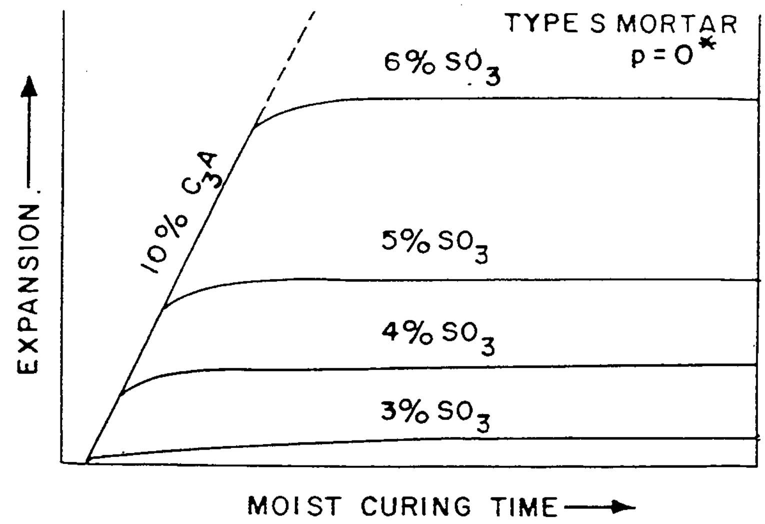


Figure 2.20 Effect of Sulfate Content on the Idealized Expansion-Time Characteristics of Type-S Mortar Made With a Constant Aluminate Content Cement [4].

minimum level required for expansion, expansion occurs and the sulfate to aluminate ratio will determine the length of time that the cement will expand.

The specific surface (fineness) of expansive cement particles has a major influence on the expansion characteristics. ACI Committee 223 [4] has shown as the specific surface increases with a given sulfate content, the amount of expansion decreases. The increase in specific surface accelerates very early formation of ettringite in the plastic mix. The typical effect of fineness on expansion of Type K cement is illustrated in Figure 2.21.

The amount of expansion is also closely related to the amount of expansive material in the cement. Commercially available Type K cement is proportioned to produce relatively low expansion in SCC. Type K cement contains approximately 10 to 15 percent expansive complexes having from 25 to 30 percent calculated C_4A_3S. Within the normal range of cement usage in concrete, an increase can be obtained by increasing the total cement content of the mixture as shown in Figure 2.22.

Effects of the Type and Size of the Aggregates: The type and size of aggregate can influence the rate and amount of expansion. ACI Committee 223 [4] has compared light weight versus normal weight concrete, as shown in Figure 2.23, and has compared the effects of three types of aggregates, expanded shale, crushed granite, and river gravel as shown in Figures 2.24 and 2.25. From Figure 2.23 it can be seen that lightweight concrete may expand more than normal weight concrete. Also from Figures 2.24 and 2.25 it is shown that expanded shale provides better shrinkage characteristics than crushed granite and river gravel, and river gravel and crushed granite have approximately the same effect.

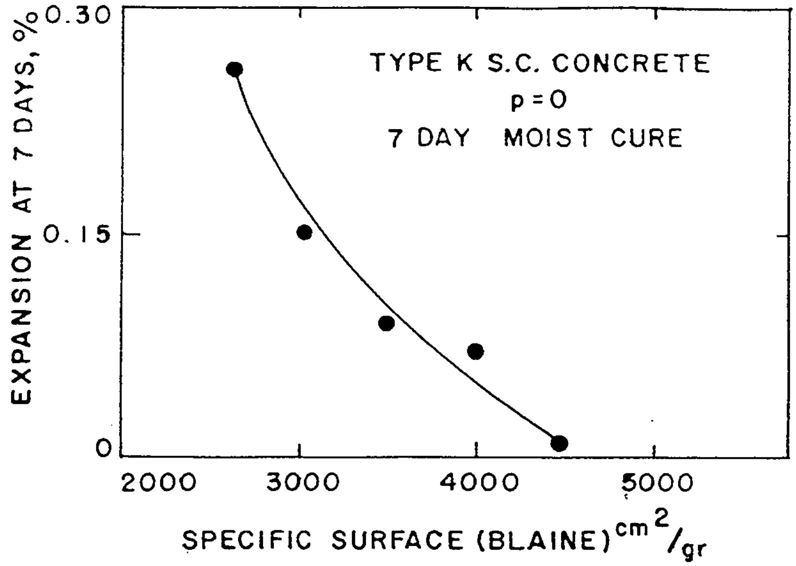


Figure 2.21 Effect of Specific Surface of Type K Cement on the 7-Day Unrestrained Expansion of Shrinkage Compensating Concrete [4].

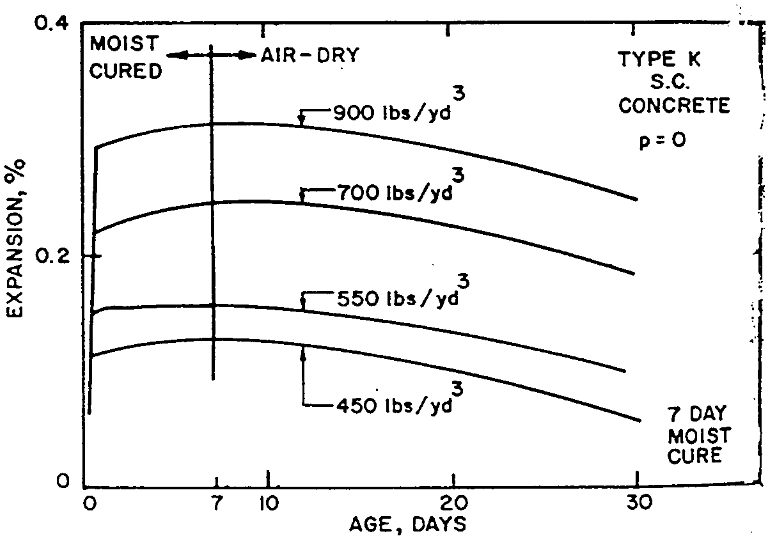


Figure 2.22 Effect of Cement Content on the Expansion Characteristics of Shrinkage Compensating Concrete Made With Type-K Cement [4].

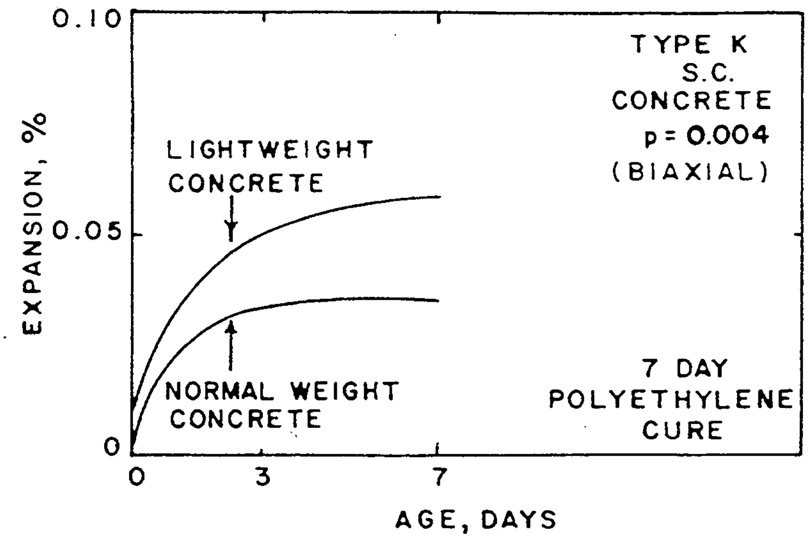


Figure 2.23 Effect of Lightweight Aggregate Versus Normal Weight Aggregate on the Expansion of Type-K Cement Shrinkage Compensating Concrete [4].

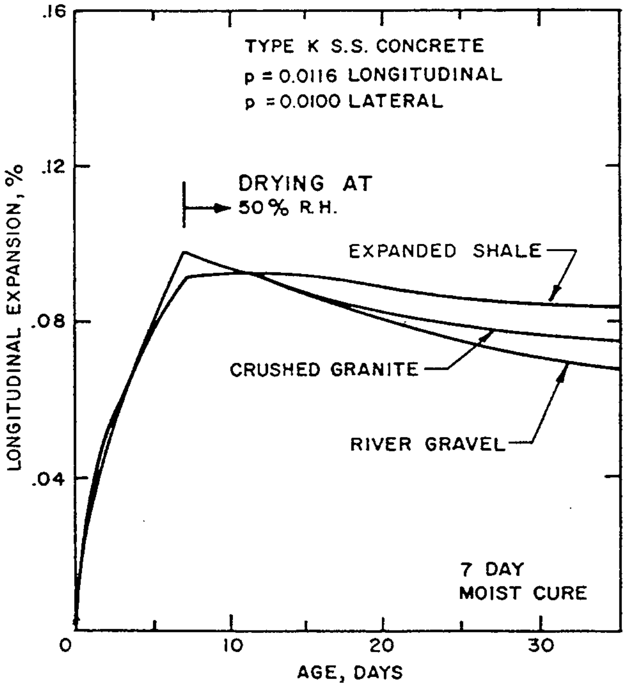


Figure 2.24 Effect of Aggregate Type on Longitudinal Expansion of Triaxially Restrained Concretes Moist Cured 7 days [4].

Effects of Curing: The requirements for proper curing of expansive cement concrete are more stringent than those of regular portland cement concrete. Since the formation of ettringite is dependent on the presence of water, it has been well established [4] that all expansive cement concrete expands significantly more when cured in water or in a moist room than when cured in an environment which can not supply water to the concrete. Slate and Matheus [36] have demonstrated that the presence of free water is required for development of expansion.

Effects of Curing Temperature: ACI Committee 223 [4] also investigated the effects of curing temperatures on expansion. Unrestrained Type K cement self-stressing concretes show increased expansion with increased temperature of the curing environment. However, Type K cement restrained self-stressing concretes exhibited almost no expansion as the temperature was raised as can be seen in Figure 2.26.

Effects on Concrete Properties: ACI Committee 223 [4] has examined the effects of SCC on many different concrete properties. ACI Committee 223 states that the following properties were comparable to portland cement when tests were ran according to the appropriate ASTM Test Method: Time of Setting, Unit Weight and Yield, Compressive Strength, Modulus of Elasticity, Bond Strength, Coefficient of Thermal Expansion, Resistance to deicer scaling, Resistance to Sulfate Attack, Abrasion Resistance, Effect of Alternate Wetting and Drying, Permeability, Creep, and Effect of Temperature Cycling.

Construction Procedures: The following construction procedure observations were made by the Ohio Turnpike Commision (OTC) [29], the nation's leading user of Type K cement bridge decks. No special equipment is required for placing and finishing concrete

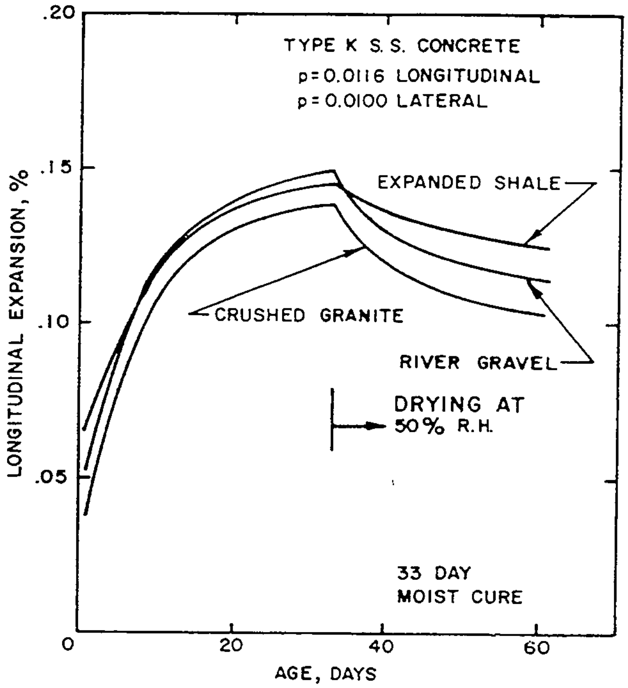


Figure 2.25 Effect of Aggregate Type on Longitudinal Expansion of Triaxially Restrained Concretes Moist Cured for 33-Days [4].

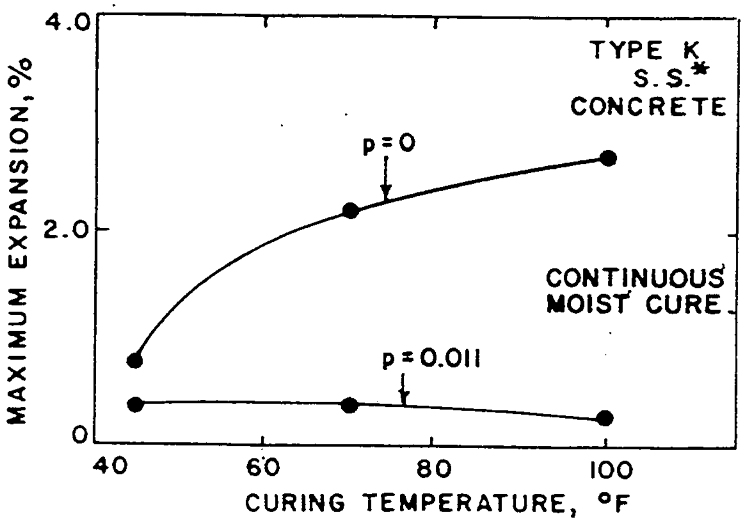


Figure 2.26 Effect of Curing Temperature on the Maximum Unrestrained and Restrained Expansion of Type-K Cement Self Stressing Concretes [4].

made with Type K cement. Generally speaking, normal, sound practices of concreting can be followed for mixing, placing, finishing, and curing the SCC. Even though Type K cement is more expensive that portland cement, Type K cement has several advantages that can mitigate the increased material costs. For example, it is easier to place and finish Type-K cement, and therefore the contractor can save labor costs in placing decks, especially those of 300 cubic yards or more.

Type K concrete require a greater water content (to provide for ettringite growth) and produces higher slump (about 2" more slump than regular concrete is necessary to provide and equivalent slump when a 30 minute haul is required) and provides a concrete with good cohesiveness characteristics. These characteristics provide good finishing qualities. However, because these characteristics make Type K cement different from other cements, owners and contractors must consider the following factors when using Type K cement:

1. Fog-spraying should be available, especially for placement during hot weather
2. Delaying placing activities at the job site should be avoided since SCC concrete loses slump faster than normal concrete.
3. Concrete made with SCC will exhibit little or no bleed water; therefore, care must be taken to begin finishing operations at the proper time.
4. Pouring should be scheduled early in the day before temperatures rise; the deck should not be placed if the ambient temperature is above 80° F. Evening placement also has advantages in that the greatest exothermic heat will occur during the cool nighttime ambient temperatures.
5. Water curing should always be used with Type K concrete decks.

6. Pre-construction and/or pre-placement conferences should be held involving the inspectors, contractor, test lab, and ready-mix producer to discuss in detail before construction begins. This meeting is especially important if any of the "players" mentioned above is inexperienced in using SCC.

The Ohio Turnpike Commision has been using Type-K Cement for the past 15 years to decrease drying shrinkage. Table 2.2 shows a major mitigation of drying shrinkage cracking with the use of Type-K cement and proper placement and curing conditions.

Since Blue Circle Type-K Cement expands to compensate for shrinkage, Type-K Shrinkage-Compensating Concrete can be placed over larger areas with fewer joints. This feature means lower maintenance costs, longer life, less water stops, and reduced permeability. Studies of Type-K Shrinkage Compensating Concrete bridge decks have shown drying shrinkage cracking is greatly reduced, mitigating steel reinforcing corrosion, and extending service life.

2.2.4 Shrinkage Reducing Admixtures

The use of shrinkage compensating concrete is a viable approach to attempt to minimize shrinkage cracking and has been used successfully in many applications. Nevertheless, this technology has not been widely embraced by the concrete construction industry. This lack of widespread acceptance is due in part to the difficulty in understanding and harnessing the benefits of shrinkage compensating cement. For instance Folliard and Berke (13) have shown that due to the abundance of ettringite formed during the early hydration stages, rapid slump loss is often observed and can be problematic. In addition, since moisture is needed to trigger the expansive reaction,

Table 2.2 Ohio Turnpike Bridge Deck Replacement Program and Summary of Deck Cracking Due to Drying Shrinkage [30].

Year	Degree of Cracking				Total Decks Replaced
	None	Minor	Moderate	Severe	
1983	3 50%	2 33%	1 17%	- 0%	6
1984	17[1] 25%	15 22%	16 24%	19 29%	67
1985[2]	33 87%	4 10%	1 3%	- 0%	38
1986	43 96%	2 4%	- 0%	- 0%	45
1987	72 97%	1 1/5%	1 1.5%	- 0%	74
1988	57 96%	1 2%	1 2%	- 0%	59
1989	53 100%	- 0%	- 0%	- 0%	53

[1] Includes 2 bridge decks using Type-K cement (this was a trial project using Type-K cement)

[2] All bridge decks replaced after 1984 contained Type-K cement only.

proper moist curing is essential. Lastly, the amount of restraint provided within the concrete element (formwork, reinforcing steel, etc.) must be accurately designed and incorporated into the structure to achieve the desired restrained expansion. For these reasons SCC has not been widely accepted.

Folliard and Berke (13) believe that a novel approach to minimizing drying shrinkage is the advent of a shrinkage-reducing admixtures (SRA), Eclipse. Berke, Dallaire, Hicks, and Kerkar (11) found that this admixture confronts the shrinkage problem by reducing short and long term drying shrinkage, but without the reliance on expansive reactions. SRA provides a method to reduce the associated strains caused by drying and the resulting stresses. Advantages to this method are that with the exception of the added SRA, concrete mixture proportions and many requirements remain relatively unchanged. The shrinkage reducing admixture Eclipse, is manufactured by Grace Constructon Products Company and Grace (15) has shown that concrete containing Eclipse at a dosage of two percent by weight of cement has been shown to reduces shrinkage, as measured by ASTM C157, by as much as 80% at 28 days, and up to 50% at one year or beyond as indicated in Figure 2.27. This level of shrinkage reduction in well proportioned concrete mixtures utilizing quality materials, has been shown to eliminate drying shrinkage cracking in fully restrained concrete.

Eclipse will provide the most value in structures and environments where cracks due to drying shrinkage are prevalent and recursions are most severe. Some examples of applications when this is true are high performance industrial floors, bridge decks, parking garages, marine structures, hydraulic structures, waste water treatment facilities and primary and secondary containment [15].

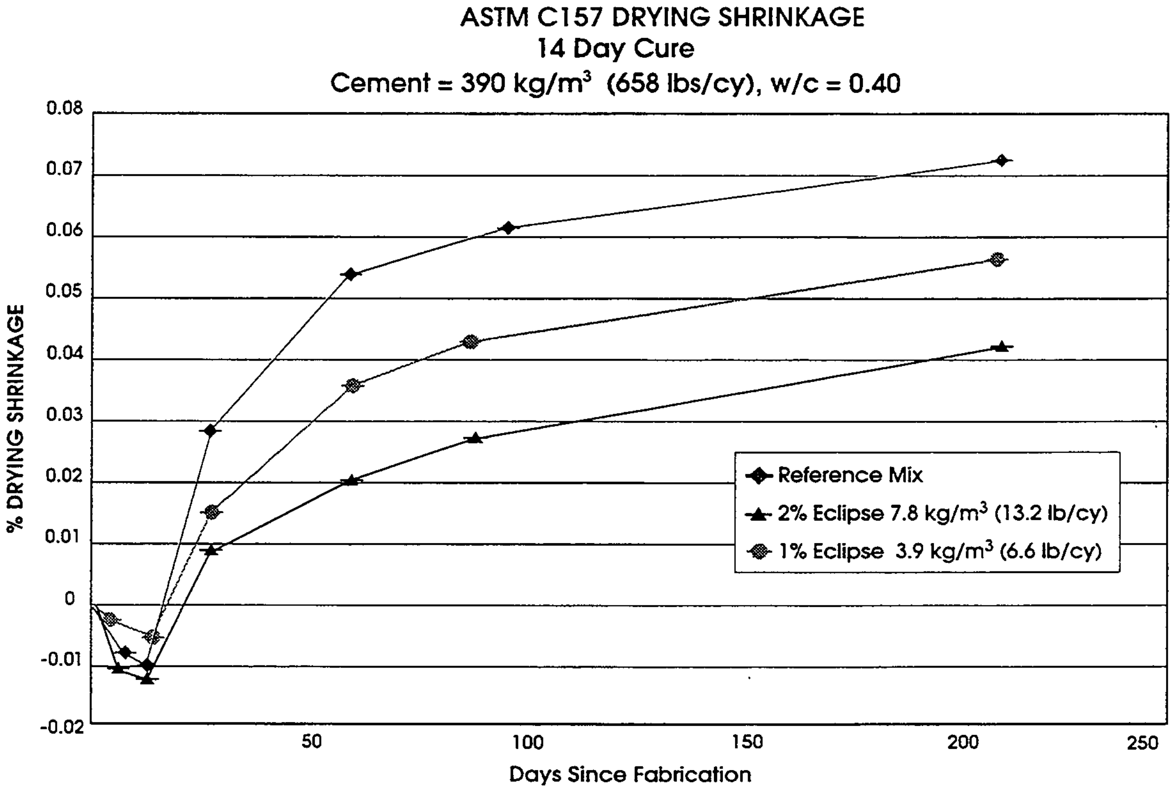


Figure 2.27 Time Shrinkage Characteristics of Eclipse and Regular Portland Cement [15].

Like shrinkage compensating cement, Eclipse also has it advantages as well as its disadvantages, and these are listed below:

<u>Advantages</u> [15,39, 41]

1. Eclipse works to reduce shrinkage by reducing the surface tension of the water in all the filled pores in the concrete therefore reducing drying shrinkage.
2. Eclipse is user friendly with all cements and admixtures.
3. Eclipse can be added to any concrete mixture without readjusting its mixture proportions, other than Grace Construction Products recommends that when incorporating Eclipse into an established mixture design that it should replace an equal amount of water.
4. Eclipse has little or no effect on slump.
5. Eclipse has been described by concrete finishers to be equal or superior in terms of its finishing characteristics to reference concrete mixtures.
6. Eclipse acts to flatten out the heat generation due to hydration and reduces the concrete peak temperature.

<u>Disadvantages</u> [15,39, 41]

1. Eclipse has a slight retarding effect on concrete.
2. Mixtures with Eclipse will require increased amounts of air entrainer to achieve a specified level of air.
3. Eclipse reduces the concrete's compressive strength.
4. Eclipse is a potentially combustible material with a flash point of 96 degrees Celsius (205 degrees Fahrenheit).

Since SRA is relatively new to the construction industry information regarding the effects of Eclipse on different concrete properties has not yet been determined in full. Therefore, this research can add to the knowledge based on how Eclipse effects concrete properties compared to the effects from SCC and regular portland cement.

2.2.5 Silica Fume

Silica fume, also referred to as "micro-silica", is a by mineral material from the production of silica metal or ferrosilicon alloys in electric arc furnaces. Silica fume contains 85% amorphous silica (SiO2) and consists of very fine particles that are of two orders of magnitude finer than regular portland cement, whose average particle diameter is around 0.1 micro meter.

When added to concrete silica fume quickly forms calcium silicate hydrate, filling in the normally weak interstitial spaces between the cement paste matrix and aggregate particles, which results in a dense, strong and relatively impermeable material. Silica furme has been reported[40] to reduce creep while increasing drying shrinkage. Another disadvantage of this fine mixture is that it usually calls for a unusually high water demand and a fairly high amount of high range water reducer is needed to obtain a workable concrete at a reasonable water-cement ratio.

It has been reported that silica fume in quantities above approximately 8% of the total mixture does little good and that any extra is considered to be wasteful. This research uses 5.15%.

The purpose for adding silica fume is to decrease the permeability of the concrete. This is particularly important in bridge deck and bridge overlay applications in northern regions where deicing salts are used.

3. LABORATORY TEST PROGRAM

3.1 General

A primary objective of this research was to identify concrete mixtures for bridge decks which have enhanced drying shrinkage cracking properties (relative to the current standard ALDOT mixture), and are construction friendly. Three candidate mixtures were selected for testing along with ALDOT's standard mixture for reference/control. These were:

1. SCC Mixture with Type-K Cement (SCC-K)
2. SCC Mixture with Type-K Cement and Micro Silica (SCC-K/MS)
3. ALDOT Standard Mixture with 1.5% Shrinkage-Reducing Admixture (ALDOT-SRA)
4. ALDOT Standard Bridge Deck Mixture (for reference/control) (ALDOT)

Mixture proportions used in the testing are given in Table 3.1.

It should be noted that the two SCC mixtures were designed by concrete materials personnel of Blue Circle Cement Company in Atlanta. Georgia under the specific charge of designing a mixture for bridge deck applications in Alabama. Their mixture designs employ Alabama materials, and were aimed at minimizing plastic and drying shrinkage cracking while maintaining good constructionability. The ALDOT standard mixture has developed with time by their materials engineers. The ALDOT standard mixture with

SRA was simply the ALDOT mixture with 1.5% water replacement by the SRA, Eclipse (manufacturer recommends 1.5 – 2.0% replacement).

ALDOT is particularly interested in the long-term strength, shrinkage/cracking, and durability properties of any bridge deck concrete mixture. They are also very interested in properties of the fresh concrete and particularly those related to workability and plastic shrinkage cracking and early curing requirements.

Thus, a laboratory-testing program was developed to focus on these two primary areas of concern, i.e.,

- fresh (plastic) concrete properties
- hardened concrete properties

Brief outlines of the testing program in each of these areas are presented below.

3.2 Fresh Concrete Test Program

This program was conducted to assess the workability/construction friendliness of the candidate mixtures. It basically consisted of determining slump, rate of slump loss, set-time, air content, unit weight, early heat of hydration temperature increases, and sensitivity to time of year (temperature) of construction of each of the mixtures. The testing/property evaluations conducted were as shown in Table 3.2.

3.3 Hardened Concrete Test Program

This program was conducted to evaluate important mechanical properties and characteristics of the hardened concrete for those mixtures performing satisfactorily in the fresh concrete property evaluation testing. Standard ASTM type of testing conducted and properties evaluated are shown in Table 3.3.

In addition to the standard ASTM testing indicated in Table 3.3, two nonstandard tests were performed on each of the mixtures to more fully evaluate their drying and thermal shrinkage cracking performances. These were,

1. Monitoring concrete temperature (T_c) vs. time (t) during the period 1 hr – 24 hrs after mixing to assess the relative heat of hydration build-up for the four mixtures. This data will allow the plotting of T_c vs. t curves for the mixtures which will show the relative "hotness" of the mixtures which, in-turn has an impact on early thermal strains and stresses for bridge decks of the mixtures. The T_c vs. t data will be determined via thermocouples embedded in 6" x 12" cylinders.
2. Concrete shrinkage ring tests (see Figure 3.1) integrate the drying and thermal shrinkage characteristics of a concrete mixture with its tensile strength characteristics to assess the cracking potential of the mixture. These tests require the presence of an inner ring of steel or other material to resist shrinkage strains and thus develop shrinkage stresses in the concrete ring. If the concrete mixture exhibits significant shrinkage strains/stresses and has low tensile strength, then cracking of the ring will occur. In addition to monitoring the cracking or noncracking of the concrete ring specimen, strain gages mounted on the inner steel ring will allow monitoring of the strain development with time. This will allow later correlation with shrinkage bar and tensile strength results for the test mixtures. It should be noted that for SCC mixtures to mitigate cracking, they must be restrained to develop compressive stresses during the early expansion phase of their life. Hence either external or internal restraint must be provided for the SCC mixtures. To allow a fair comparison, this same restraint must be

provided for the ALDOT mixtures. In this study an outer restraining steel ring was employed (and removed after 4-days) as indicated in Figure 3.1.

Table 3.1 Concrete Test Mixture Proportions

Mixture Component	Concrete Mixture			
	SCC-K	**SCC-K/MS**	**ALDOT-SRA**	**ALDOT (Control)**
Cement (lb/yd^3) (Type I or K)	715	680	620	620
Silica Fume (lb/yd^3)	0	35	0	0
Coarse Aggregate (No.67) (lb/yd^3)	1825	1825	1879	1879
Fine Aggregate (No. 100) (lb/yd^3)	856	842	1091	1091
AEA[1] (ml/yd^3)	171	159	125	46
WR[2] (ml/yd^3)	708	672[3]	547	547
SRA (lb/yd^3)	0	0	9.3[4]	0
Water (lb/yd^3)	357	357	265	275
W/C Ratio[5]	.5	.5	.44	.44

[1] MB AE90 from Master Builders
[2] POZZOLITH 220-N from Master Builders
[3] After the 20 minute rest period required by ACI 223 a high range water reducer (Rheobuild 1000 from Master Builders) was added (approximately 700ml/yd^3) to bring the slump to 8" which was required by the mix design. Value in Table does not include the high range water reducer used to increase the concrete's slump.
[4] Shrinkage reducing admixture (Eclipse) SRA dosage = 1.5% by weight of cement
[5] W/C = (water + SRA)/(cement + silica fume)

Table 3.2 Fresh Concrete Property Testing

Ambient Temperature[1] (°F)	Concrete Property/Parameter		Concrete Mixture			
			SCC-K	SCC-K/MS	ALDOT-SRA	ALDOT (Control)
45° 75° 95°	Slump ASTMC231	1 – min.	X	X	X	X
		15 – min.	X	X	X	X
		30 – min.	X	X	X	X
		45 – min.	X	X	X	X
	Air Content ASTM C231		X	X	X	X
	Unit Weight ASTM C138		X	X	X	X
	Set Time ASTM C403	Initial	X	X	X	X
		Final	X	X	X	X
	Concrete Temperature [2,3] ASTM C1064		X	X	X	X

[1] Each of the fresh concrete properties shown was evaluated at ambient (and mixture ingrediant) temperatures of 45° F, 75° F and 95° F.

[2] At time of conducting air content and unit weight tests.

[3] Special temperature vs. time testing over the period of 0 – 48 hours will also be conducted to access heat of hydration and potential thermal strain differences between the mixtures.

Table 3.3 Hardened Concrete Property Testing

Curing Condition[1]	Concrete Property		Concrete Mixture			
			SCC-K	**SCC-K/MS**	**ALDOT-SRA**	**ALDOT (Control)**
LS, E, F, P	Compressive Strength ASTM C39	3 – day	X	X	X	X
		7 – day	X	X	X	X
		28 – day	X	X	X	X
		56 – day	X	X	X	X
	Splitting Tensile Strength ASTM C496	7 – day	X	X	X	X
		28 - day	X	X	X	X
	Drying Shrinkage	Restrained Bar 1 – 61 days ASTM C878	X	X	X	X
		Unrestrained Bar 1 – 61 days ASTM C157	X	X	X	X
LS	Elastic Modulus ASTM C 469	7 – day	X	X	X	X
		28 – day	X	X	X	X
		56 – day	X	X	X	X
	Freeze – Thaw Durabiltiy ASTM C666		X	X	X	X
	Rapid Chloride Permeability ASTM C1202	28 – day	X	X	X	X
		56 – day	X	X	X	X

[1] Curing Conditions (See Section 4.6 in Chapter 4 for a detailed listing of the curing conditions).

[2] Freeze-Thaw testing starts at 14 days and runs for 300 cycles. Reading are taken every 30 cycles.

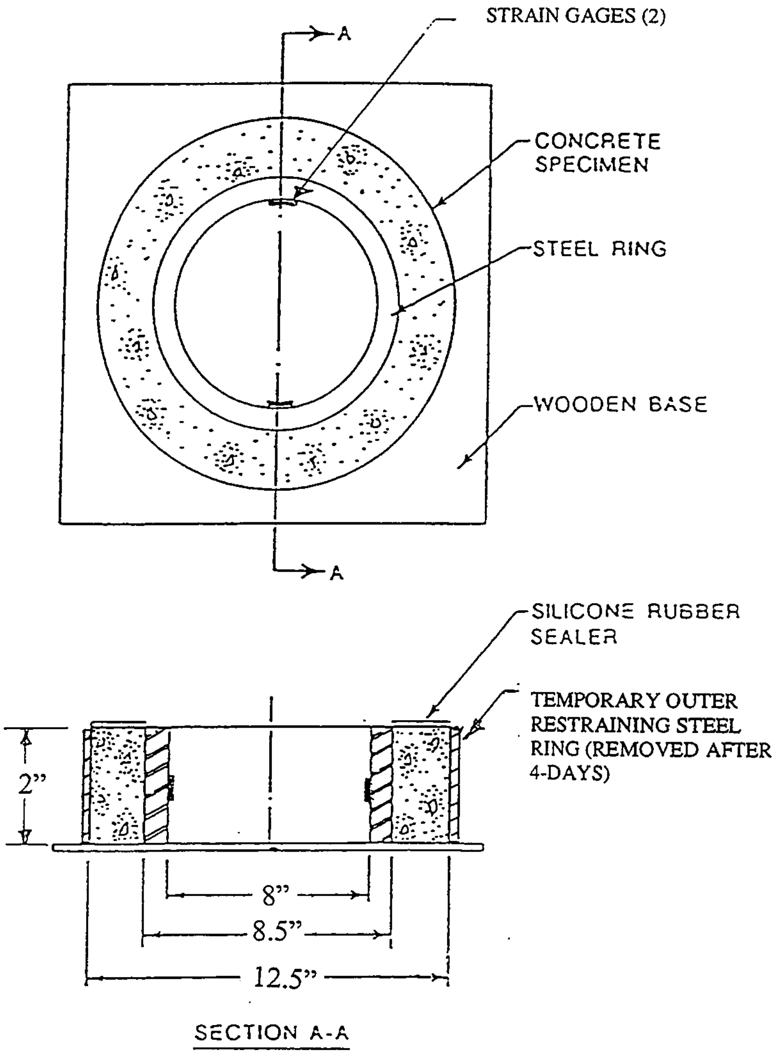


Fig. 3.1. Shrinkage Ring Test Specimens

4. LABORATORY EQUIPMENT, SPECIMENS AND PROCEDURES

4.1 General

As indicated in the Laboratory Test Program outlined in Chapter 3, the purpose of this research was to investigate the following properties of four different concrete mixtures:

- The long-term strength, shrinkage/cracking, and durability properties.
- The properties of fresh concrete that are most related to workability and plastic shrinkage cracking and early curing requirements.

To determine these properties, testing was done at three different temperatures (45°, 75°, and 95°F) while using four different curing conditions (Lab Standard, Excellent, Fair, and Poor). This process allowed simulation of curing conditions that would occur in the "field" at different times of the year.

4.2 Concrete Mixture Designs

The concrete mixture designs used in this research was developed to reduce instances of early bridge deck cracking, and thus improve the durability performance of bridge decks in Alabama. The mixtures used were as follows:

1. SCC Mixture with Type K Cement (SCC-K), This concrete mixture was designed by the Blue Circle Cement Company in Atlanta, Georgia especially for for bridge deck applications in Alabama.

2. SCC Mixture with Type K Cement and Micro Silica (SCC-K/MS). This concrete mixture was also designed by the Blue Circle Cement Company in Atlanta, Georgia. Micro-silica was added to the original Type-K mixture hoping that it would further reduce drying shrinkage and reduce permeability and thus enhance durability.
3. ALDOT Standard Mixture with 1.5% Shrinkage Reducing Admixture (ALDOT-SRA). Eclipse was added to the ALDOT (Control) mixture to compare its performance with the shrinkage compensating concrete mixtures, and with ALDOT's standard mixture.
4. ALDOT Standard Bridge Deck Mixture. This concrete mixture is used as the reference or control mixture. It is the standard mixture design that the ALDOT currently uses in bridge decks.

4.3 Raw Materials Used

The concrete mixtures were formulated using Type-I portland cement, Type-K expansive cement, micro-silica, a shrinkage reducing admixture – Eclipse, a air entraining agent, a water reducing agent, and a high range water reducer. A brief discussion of each ingredient follows:

- Type-I Portland Cement – . The Type-1 Cement was Roberta Brand portland cement manufactured by Blue Circle Cement Company to meet the requirements of ASTM C150. This cement was obtained from the Blue Circle Cement Company based in Marietta, Georgia.
- Type-K Expansive Cement - The Type-K expansive cement was manufactured by the Blue Circle Cement Company in Atlanta, Georgia to meet the requirements of ASTM

C845 Type E-1 (K), “Standard Specification for Expansive Hydraulic Cement”. This cement was obtained from the Blue Circle Cement Company based in Marietta, Georgia.

- Micro Silica - The micro-silica used for this research was manufactured by Master Builders Technologies.
- Shrinkage Reducing Admixture - The shrinkage reducing admixture used in this research was Eclipse, a product manufactured by Grace Construction Products. Eclipse was added to the ALDOT (Control) mixture to investigate its effect on shrinkage and shrinkage cracking and to compare its results with the shrinkage compensating concrete mixtures and ALDOT's standard mixture. The amount of Eclipse used was 1.5% of the weight of cement. This amount of Eclipse was subtracted from the original water content.
- Air Entraining Agent – The air entraining agent used in this research was MB AE-90 which is manufactured by Master Builders Technologies and is in accordance with ASTM C260. MB AE-90 was applied to each mixture in order to provide entrained air in each concrete mixture in an attempt to reach the mixture design's specification for air content.
- Water Reducing Agent – The water reducing agent used in this research was Pozzolith 220N manufactured by Master Builders Technologies and meets the requirements of ASTM C494, Type A, B, and D. Pozzolith 220N was applied to the mixtures in an attempt to achieve the mixture design specifications of slump with the designated water-cement ratio and also to provide improved workability to the mixtures.

- High Range Water Reducer – The high range water reducer used in this research was Rheobuild 1000 which is also manufactured by Master Builders and meets the requirements of ASTM C494, Type A and F. Rheobuild 1000 was added to the Type-K mixture with micro-silica after the 20 minute rest period required by the mix design.
- Aggregates - The coarse and fine aggregates used in this research where #67 and #100 river gravel and river sand respectively. The aggregate was from Shorter, Alabama at the Pinkston Pit and was obtained from the Blue Circle Cement plant in Auburn, Alabama.

4.4 Concrete Mixing Procedure

The concrete mixing procedure used in this research was performed as per ACI 223, Method B. There are two different methods associated with ACI 223, Method A and Method B. The difference between the two is that in Method B one is allowed to add more water to the concrete after its rest period. This procedure was chosen because it was felt to be more representative of field applications. Contractors often add water to the concrete in field situations if allowed. The procedure is as follows:

1. Add the batch ingredients to the mixer
2. Start the mixer and mix for 3 minutes
3. Stop the mixer and let the mixture rest for 3 minutes
4. Start the mixer and mix for 2 minutes
5. Stop the mixer and run tests to determine the fresh concrete properties

The above procedure was implemented when mixing the ALDOT mixtures with and without Eclipse. For the Type-K mixtures a slightly different procedure was implemented (ACI 223, Method B requires additional time for the concrete to rest due to the swelling effects of shrinkage compensating concrete). The procedure is as follows:

1. Add the batch ingredients to the mixer
2. Start the mixer and mix for 3 minutes
3. Stop the mixer and let the mixture rest for 3 minutes
4. Run initial tests to determine if the fresh concrete properties are as desired
5. Let the mixture rest for an additional 20 minutes
6. Start the mixer and mix for 2 minutes
7. Adjust the water content if needed
8. Mix for an additional 1 minute
9. Stop the mixer and run tests again to determine the fresh concrete properties.

It is to be noted that when Type-K cement is mixed for construction purposes, the 20 minute rest period is usually observed as the truck is in route to the jobsite.

4.5 Testing

After the concrete was mixed, tests were conducted to assess the fresh concrete properties and the hardened concrete properties of the test mixtures. Since tests for fresh concrete properties are common tests used in testing concrete, detailed discussions of these will not be given. However, some of the tests for hardened concrete properties are not as common and familiar, and therefore detailed discussions of these are included in a later section in this chapter, as well as discussions of special tests that were conducted.

The fresh concrete properties were observed at three different temperature (45 °, 75 °, and 95 ° F). When testing the concretes fresh concrete properties, the concrete was mixed in a environmental chamber where the temperature was held constant. The ingredients of the concrete mixtures was placed in the environmental room the day before the concrete was mixed. This simulated the concrete being mixed at different times of the year.

Fresh Concrete Properties. Testing conducted on all of the test mixtures to assess their fresh concrete properties was as follows:

- Air Content (ASTM C231) – Conducted on every mixture to ensure that the same quality of mixture was used for each test. Values were measured at three different mixing temperatures (45 °, 75 °, and 95 ° F).
- Slump (ASTM C143) – Conducted on every mixture to ensure that the same quality of mixture was used for each test. Values were measured at three different mixing temperatures (45 °, 75 °, and 95 ° F).
- Unit Weight (ASTM C138) – Conducted for each mixture at three different mixing temperatures (45 °, 75 °, and 95 ° F).
- Set - Time (ASTM C403) – Conducted for each mixture to determine its initial set time (500 psi) and its final set-time (4000psi) at three different mixing temperatures (45°, 75°, and 95° F).
- Concrete Temperature (ASTM C1064) – Conducted for each mixture by placing a thermometer in the fresh concrete and recording the concrete's temperature after mixing at three different ambient temperature (45 °, 75 °, and 95 ° F).

As mentioned above each one of the fresh concrete properties were observed at 45°, 75° and 95° F. All of the ingredients, except for the water, experienced the ambient temperature for approximately 12 hours before mixing the concrete to simulate "real" mixing conditions. The water did not experience the same exposure as the other ingredients because it was felt that using regular tap water simulated actual mixing conditions that would take place at a batch plant (i.e., batch plants do not use 95° F water when the ambient temperature is 95° F, they use regular tap water that is approximately 70° F).

Hardened Concrete Properties. Testing conducted on all of the test mixtures to assess their hardened concrete properties was as follows.

- Compressive Strength (ASTM C39) – Conducted on three specimens of each mixture at the different curing conditions
- Split Tensile (ASTM C496) – Conducted on two specimens of each mixture at the different curing conditions.
- Drying Shrinkage (Restrained (ASTM C878) & Unrestrained (ASTM C157)) - Conducted on two specimens of each mixture at the different curing conditions.
- Elastic Modulus (ASTM C469) - Conducted on two specimens of each mixture at the different curing conditions.
- Freeze Thaw (ASTM C666) - Conducted on two specimens of each mixture at the different curing conditions.
- Rapid Chloride Ion Penetration/Permeability (ASTM C1202) - Conducted on two specimens of each mixture at the different curing conditions.

Special Tests. Nonstandard or special tests conducted on all of the test mixtures were as follows:

- Ring Tests – One ring test (discussed later) was conducted on a specimen with no curing and one on a specimen that was wet cured for seven days for each of the mixtures.
- Heat of Hydration Test – This test was conducted on each mixture by placing a thermocouple in a 12" x 6" cylinder and monitoring the temperature change with time over a 24 hour period.

4.6 Curing Conditions

The hardened concrete properties for each test mixture were observed for four different curing conditions. The four curing conditions were as follows:

- Lab Standard – Specimens were stripped from the molds and submerged in water for 7 days and then placed on a shelf where they experienced lab condition temperature and humidity throughout the rest of the test cycle.
- Excellent – Specimens were stripped from the molds and submerged in water for the first 7 days and then removed and coated with a curing compound. The specimens were then placed on a shelf where they experience lab condition temperature and humidity throughout the rest of the test cycle.
- Fair – Specimens were stripped from the molds and coated with a curing compound and then placed on a shelf where they experience lab condition temperature and humidity throughout the rest of the test cycle.
- Poor – Specimens were stripped from the molds and placed on a shelf where they experience lab condition temperature and humidity throughout the rest of the test cycle.

4.7 Drying Shrinkage

Restrained Bars. The restrained bar test procedure was used to determine the expansion of concrete made with shrinkage compensating cement (as described in ASTMC878), but it can be readily adopted to other cements as well. In preparation for this procedure the concrete was mixed in accordance with ASTM C192. After the concrete was mixed it was placed in molds (Figure 4.1) with dimensions shown in Figure 4.2. The concrete was placed in two equal layers and was rodded 30 times with a 3/8" rod (the first layer, just covering the threaded restraining rod). Once the mold was filled and rodded, the specimens was covered with saran wrap. After 6 hours the specimens were removed from their molds and their initial length readings were taken using the length comparator instrument shown in Figure 4.3. This instrument is in accordance to ASTM C490 and reads to the nearest thousandths of an inch. If a specimen did not reach its final set-time (as determined in ASTM C403) within 6 hours, then the specimen was left in its mold until 30 minutes after its final set-time. Once the molds where stripped and the specimens initial reading were made, the specimen were subjected to the four curing conditions described in the previous section. This test, which consisted of daily mounting the specimen in the length comparator instrument and measuring its length (see figure 4.3), was conducted on each specimen for 61 days.

Unrestrained Bars. The unrestrained bar test procedure was used to determine the length change in concrete (as described in ASTM C157). The procedure is exactly the same as that of the restrained bar test except that the specimen does not contain a threaded restraining bar, and the specimen remains in its mold for 12 hours before its initial reading is taken.

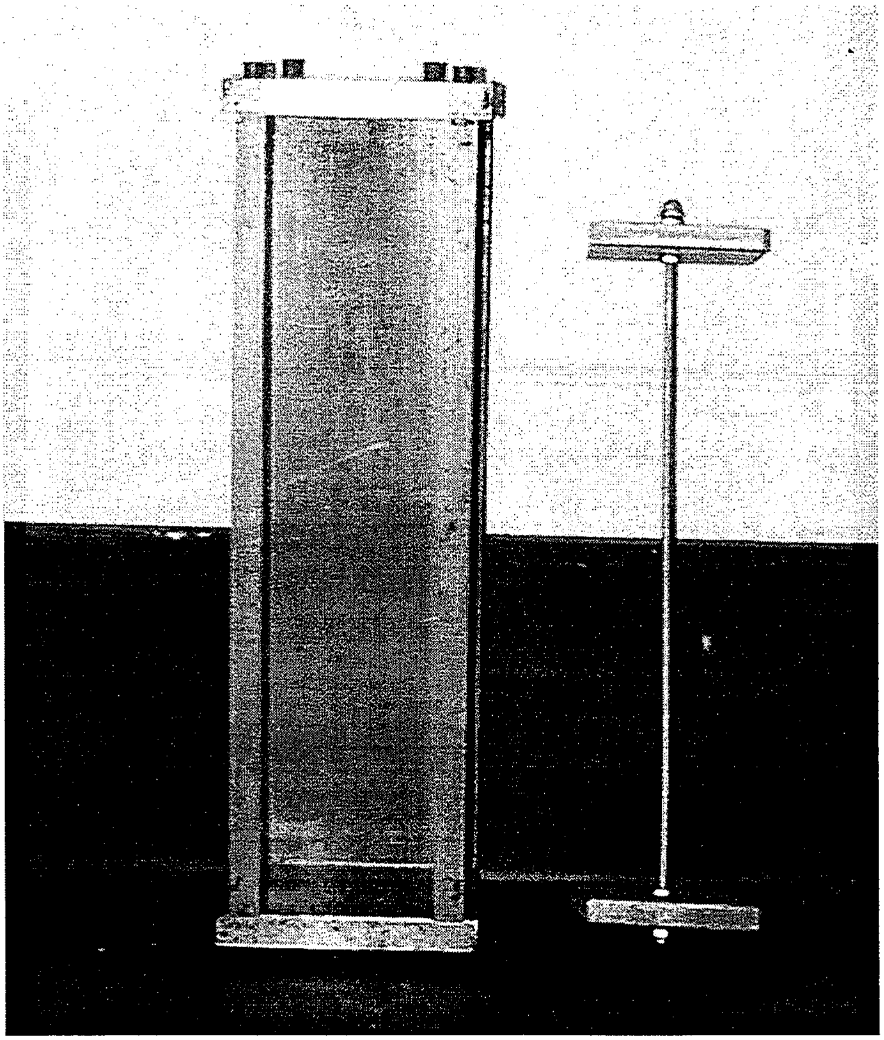
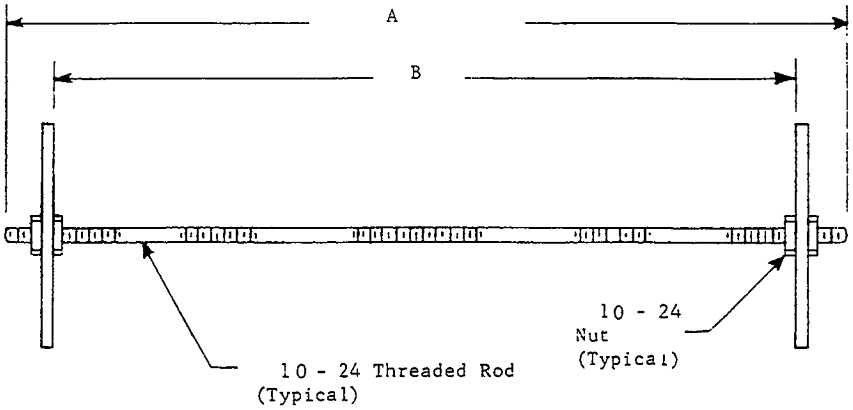
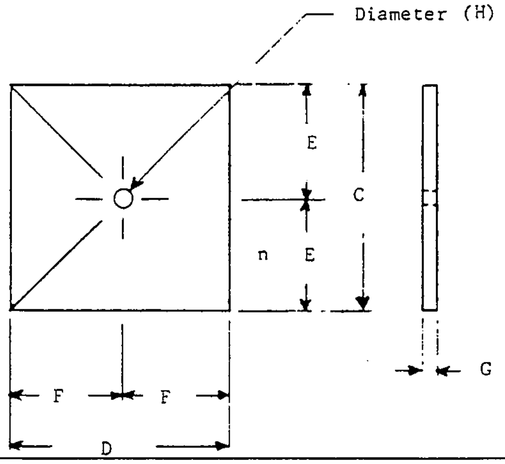


Figure 4.1 Molds for the Restrained Shrinkage Bars



(all material is mild steel, except for cap nuts)



	Dimensions	
	in.	mm
A	$11\frac{9}{16} \pm \frac{1}{16}$	294 ± 1.6
B	10	254 (gage length)
C	3	76
D	$2\frac{31}{32} \pm \frac{1}{32}$	75 ± 1
E	$1\frac{1}{2}$	38
F	$1\frac{31}{64}$	37.7
G	$\frac{3}{8}$	10
H	$\frac{3}{16}$	5

Figure 4.2 Dimensions and Hardware for Restrained Shrinkage Bars

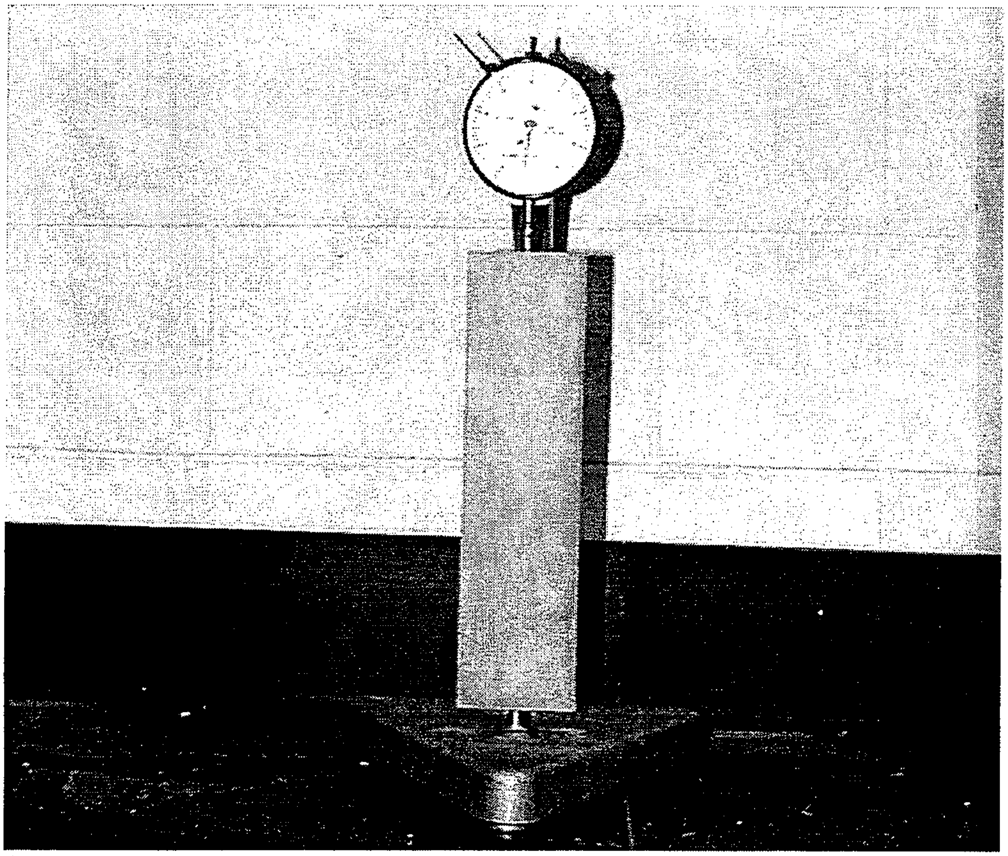


Figure 4.3 Length Comparator Instrument used to Determine the Shrinkage of the Concrete

The equation used in determining the length change percentage in the restrained and the unrestrained bar test is as follows:

$$L=(Lx-Li)/G * 100$$

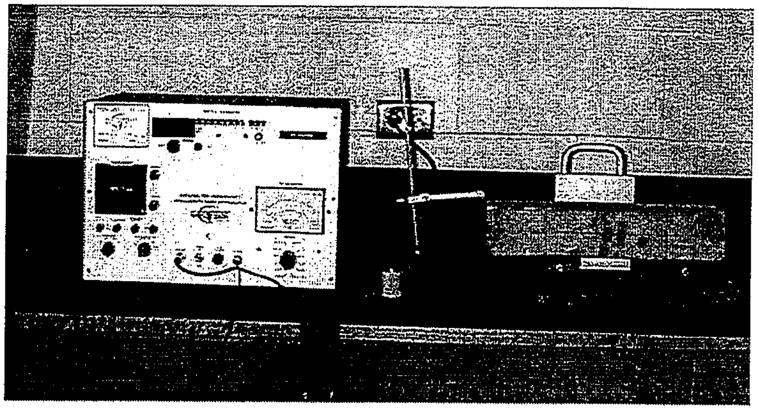
Where;

- L = Change in length at x age, %
- Lx = Comparator reading of specimen at x age minus comparator reading of reference bar at x age; in inches
- Li = Initial comparator reading of specimen minus comparator reading of reference bar at that same time; in inches
- G = Nominal gage length, 10

The unrestrained bar test was also conducted on each specimen for 61 days.

4.8 Freeze/Thaw Durability

The Freeze-Thaw Durability test was conducted in accordance with ASTM C666, Procedure A. Test samples were 3 x 4 x 16 in. cast in steel molds and initially cured according to ASTM C31. The samples were stripped from their mold upon hardening (or after 1-day) and then cured in a lime bath for 14 days. At 14 days, the specimens initial fundamental transverse frequency was recorded using a sonometer, and then they were placed into the freeze-thaw cabinet for repeated freezing and thawing cycles. The sonometer and freeze-thaw cabinet are shown in Figure 4.4. As indicated, testing was conducted according to ASTM C666, Procedure A in which the specimens were set in 1/32 in. to 1/8 in. of water throughout the freeze-thaw cycle. The specimens went through a complete freeze/thaw cycle every 3-4 hours. A freeze-thaw cycle consists of



(a)

(b)

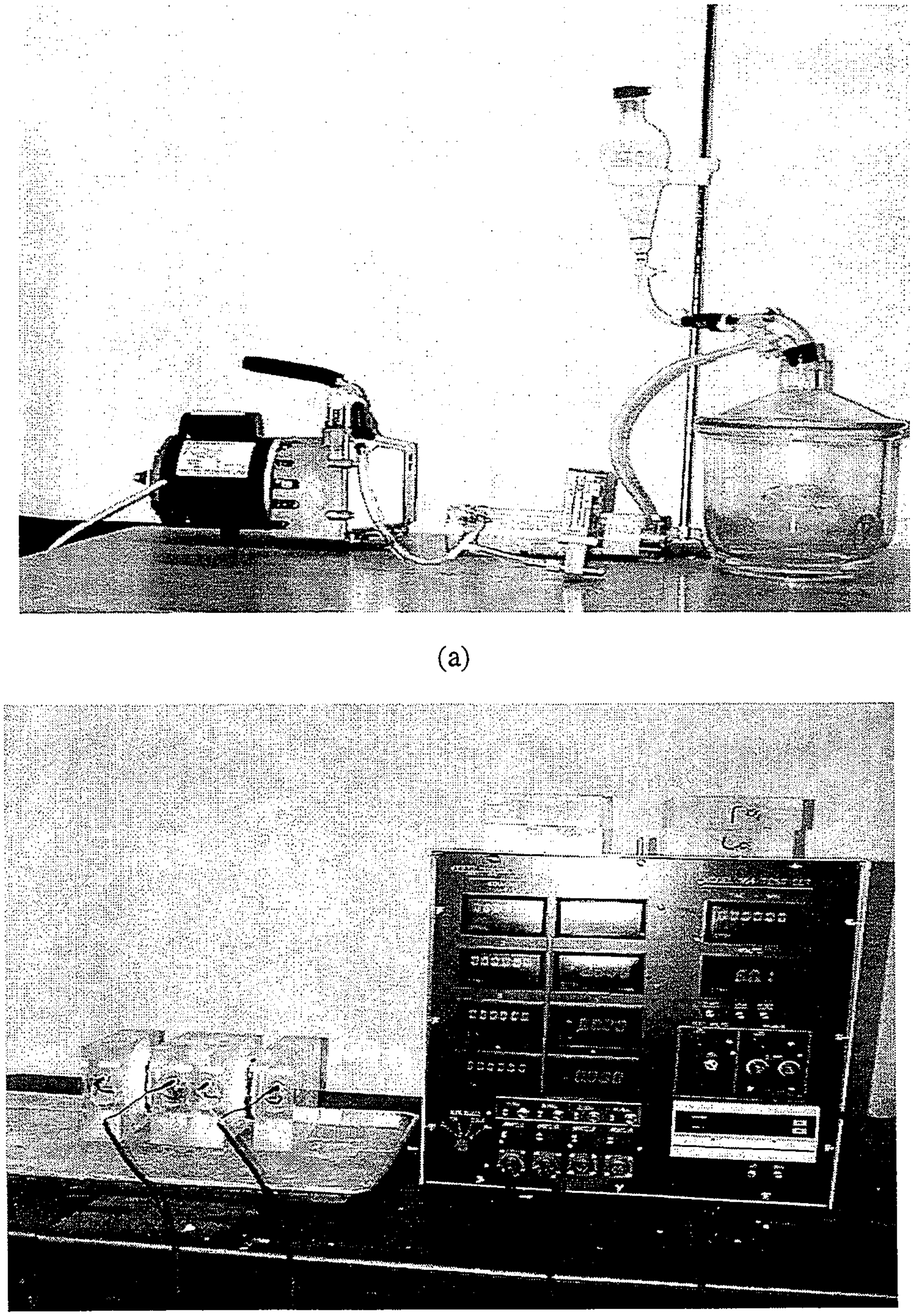
Figure 4.4 (a) Sonometer used to Obtain the Specimens Natural Tranverse Frequency
(b) Freeze-Thaw Cabinet

lowering the temperature of the specimen from 40 ° F to 0 ° F and raising it from 0 ° F to 40 ° F. Samples were tested approximately every 30 cycles in the thawed state for the fundamental transverse frequency. Tests were conducted for 300 cycles. At 300 cycles, the samples were removed from the freeze-thaw cabinet and tested for the final fundamental transverse frequency. Resistance to freeze-thaw is given as a Durability Factor (DF). The equation used to calculate the DF is shown below, where n is the fundamental transverse frequency at zero freeze-thaw cycles and n_1 is the fundamental transverse frequency at 300 cycles.

$$DF = (n_1^2)/(n^2) \text{ X } 100$$

4.9 Rapid Chloride Ion Penetration/Permeability

The permeability of the concrete was measured according to ASTM C1202, “Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration.” The apparatus used to conduct this test is shown in Figure 4.5. Conducting the chloride ion test consists of monitoring the amount of electrical current or charges in coulombs that passes through a 2 in. thick disk cut from a 4 x 8 in. cylinder during a 6 hour period. A 60 volt current is maintained across the ends of the specimen, one of which is immersed in a sodium chloride solution, and the other in a sodium hydroxide solution. The total charge passed is measured in coulombs. The amount of coulombs passed during the 6 hour long test has been found to be related to the resistance of the specimen to chloride ion penetration. As indicated, tests were conducted on 2 in. thick disks cut from 4 x 8 in. cylinders that were cured according to ASTM C31 (moist cured for 56 days). After the 56 days of moist curing the permeability of the concrete mixture was determined via the



(a)

(b)

Figure 4.5 (a) Vacuum Saturation Process (b) Instrument Used to Determine Concretes Permeability rapid chloride ion test described above. Concrete mixtures chloride ion permeability can be classified on charge passed as follows:

Charge Passed (Coulombs)	Chloride Ion Permeability Classification
>4000	High
2000 – 4000	Moderate
1000 – 2000	Low
100 – 1000	Very Low
<100	Negligible

4.10 Ring Test

The ring test is a test that accounts for all of the material factors that influence concrete shrinkage cracking from the time of casting. It simultaneously considers stress development, dimensional changes, and creep at early ages. In this test, a concrete ring was casted around a steel ring instrumented with strain gages. The steel ring had a outside diameter of 9", a radial thickness of ¼" and a height of 2". Also a temporary outer ring was placed on the outside the inner steel ring for restraint on the SCC mixture. This is needed since either external or internal restraint is needed for SCC mixtures to perform properly. To allow a fair comparison, this same restraint was placed on the ALDOT mixtures. This outside ring had a thickness of 1/16" and an outside diameter of 13". The outside ring was left on the specimens for 4 days. The form/mold for the ring test specimens is shown in Figure 4.6 and a ring specimen after removal from its mold is shown in Figure 4.7. This test was conducted on each of the four test mixtures for two different curing conditions. One of the specimens was dry cured for the entire test period and the other was wet cured for seven days and then dry cured for the remainder of the test. The strain was recorded for the specimens each day for 61 days. Additionally, the ring specimens were visually inspected daily for concrete cracking. At the end of the 61 day test period, the concrete rings were saw-cut as indicated in Figure 4.8 and visually inspected for internal cracking. It is to be noted that the specimens that produce the least amount of strain and the least amount of cracking correspond to mixtures with the best resistance to shrinkage cracking.

4.11 Heat of Hydration Test

The heat of hydration test determines the rise in temperature due to hydration of the cement over the initial 24 hour period for a concrete mixture. Each of the concrete test mixtures was mixed in an environmental chamber where the temperature was held constant at 75° F for the duration of the test. The test was conducted on each mixture by placing a thermocouple in the center of a 12" x 6" cylinder. The thermocouple was placed into the specimen immediately after the concrete was mixed and placed in the cylinder. A wet burlap bag was wrapped around the cylinder to mitigate heat loss from the specimen. The concrete temperature was recorded every 30 minutes for a period of 24 hours, at which time the test was terminated.

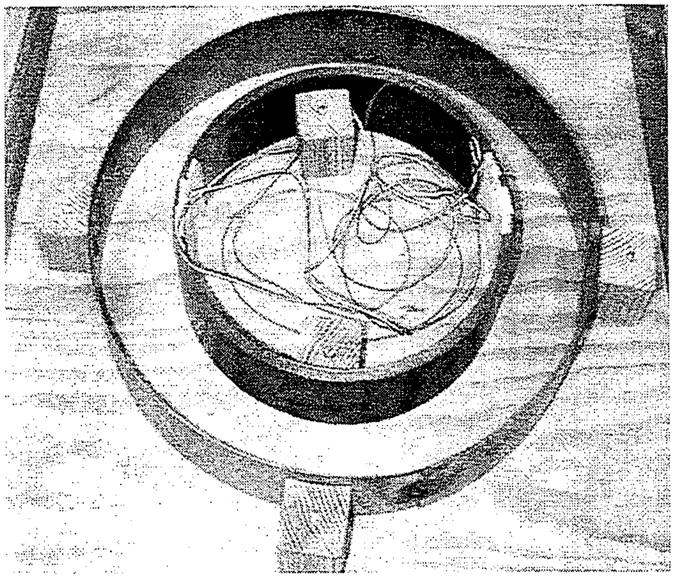


Figure 4.6 Mold for the Ring Test

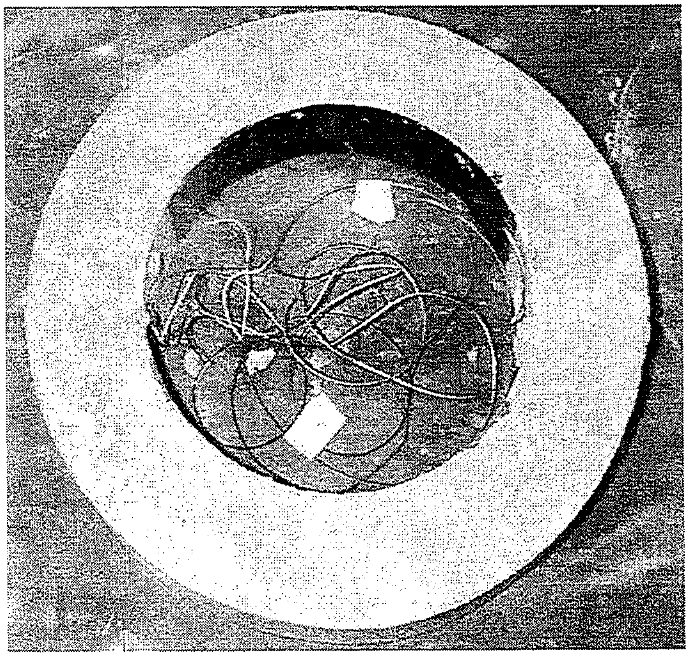


Figure 4.7 Ring Specimen After Removal From its Mold

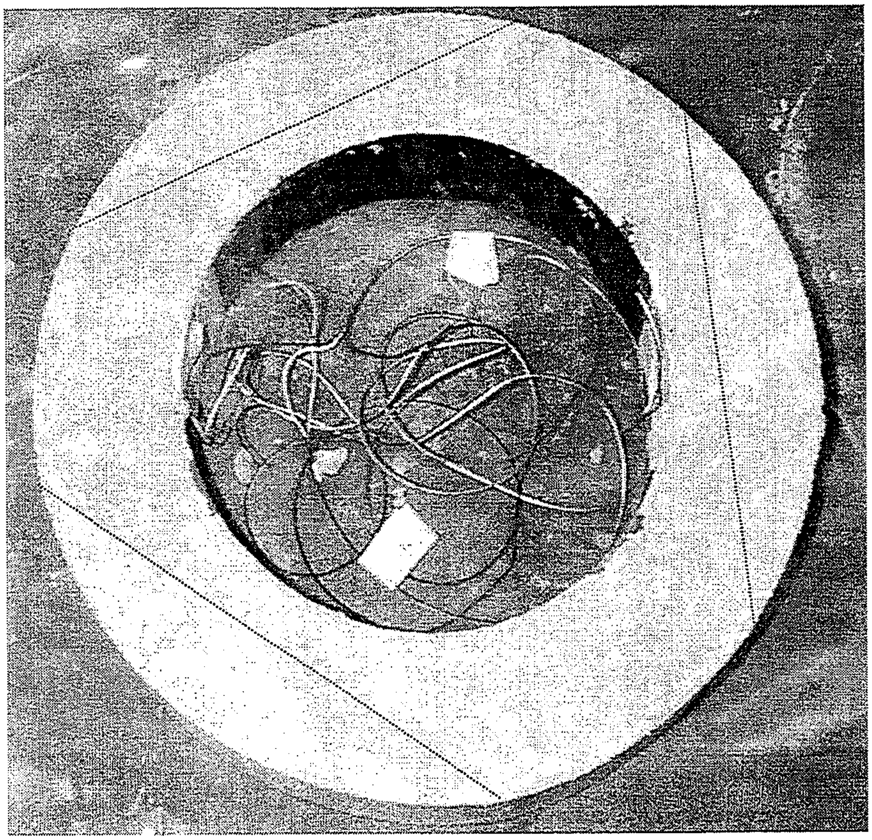


Figure 4.8 Ring Test Specimen Showing Typical Cut Sections for Visual Inspection

5. PRESENTATION OF LABORATORY RESULTS

5.1 General

As mentioned in Chapter 4, laboratory testing was conducted on the following four concrete mixture designs:

- SCC-K – Concrete mixture employing Type-K expansive cement
- SCC-K/MS – Concrete mixture employing Type-K expansive cement with the addition of micro silica
- ALDOT-SRA – Concrete mixture consisting of ALDOT's current standard mixture design with the shrinkage reducing admixture Eclipse
- ALDOT (Control) – Concrete mixture consisting of ALDOT's current standard mixture design

The testing involved a comprehensive investigation of each mixture's fresh and hardened properties in hopes of finding an effective, robust, and construction friendly concrete mixture design that would be appropriate for Alabama bridge deck applications.

In presenting the results, the fresh concrete properties are discussed first, followed by the hardened concrete properties and the results from special tests.

5.2 Fresh Concrete Property Result

The fresh properties of the concrete mixtures were observed at three different ambient temperatures (45° F, 75° F and 95° F), with the properties observed being: slump, air content, unit weight, set-time, and concrete temperature. Results for each of these are presented and discussed below.

Slump: Mixture slumps were observed 1 minute, 15 minutes, 30 minutes and 45 minutes after completion of mixing of the concrete. Results for the slump loss are shown in Tables 5.1 – 5.3 and in Figures 5.1 – 5.7. Figures 5.1 – 5.4 show the effects of the changing temperature on each of the four different mixtures. Figures 5.5 – 5.7 show the slump loss of the mixtures on the same plot for each of the mixing temperatures to facilitate comparing the mixtures. As expected the lower mixing temperature (45° F) had the least effect on slump whereas the highest mixing temperature (95° F) had the greatest effect on slump. These plots reveal that the two Type-K mixtures have the largest slump loss over time. This was expected since the expansive cement, Type-K, swells when it comes in contact with water, and mixtures water is used in the growth of the ettringite in Type-K cement mixtures. As shown in Figure 5.1, slump of the Type-K mixture at 95 ° F was significantly lower than at 45 ° F and 75 ° F. This is because at this high temperature all of the allowed water had already been used before the 20 minute rest period. This low slump would cause the concrete mixture to be very stiff, therefore a high range water reducer may be needed, as was used in the Type-K mixture with micro-silica, to make the concrete mixture more construction friendly. Also from inspection of the shrinkage reducing admixture concrete mixture (ALDOT-SRA) the Eclipse retarded the slump loss, therefore the change in slump for this mixture was lower than that for the ALDOT (Control).

Air Content: The air content was observed at the completion of mixing of the concrete. The air content was purposely held approximately constant in the laboratory by adding or reducing the amount of air entraining agent (MB AE90) to the concrete mixture design. This allowed observing how the change in temperature directly effected the air content of the concrete mixture. The results revealed that the air entrainment dosage was relatively the same (as specified in Table3.1) for each specified mixture at the changing temperatures except for the mixture design containing Eclipse (ALDOT-SRA). It was observed that the air content fluctuated greatly with this mixture regardless of the mixing temperature, and it appears that Eclipse tends to "kill" the air in the concrete. Therefore large dosages of MB AE90 were used to reach the specified air content of 3% to 5%, this can also be shown in Table 3.1 by comparing the ALDOT-SRA air entrainment admixture dosage to the ALDOT (Control) dosage. The specified air content was 3 – 5% for the ALDOT mixtures and was 4 – 6% for the SCC mixtures. For this reason the air entrainment dosage for the SCC mixtures were higher than the ALDOT mixtures.

Results for the air content testing is shown in Tables 5.1 – 5.3 and in Figures 5.8 – 5.14. Figures 5. 8 – 5.11 show the effect of the changing temperature on each of the four different mixture designs. Figure 5.12 – 5.14 show the percentage of air content for each mixture on the same plot for each of the mixing temperatures to facilitate comparing the mixtures.

Unit Weight: The unit weight was observed at the completion mixing of the concrete. The results for the unit weight are shown in Tables 5.1 – 5.3 and in Figures 5.15 – 5.21. Figures 5.15 – 5.17 show the effect of the changing temperature on each of the four different mixtures. Figures 5.18 – 5.21 show the unit weight for each mixture on the same plot for each of the mixing temperatures to facilitate comparing the mixtures. The unit weight for the concrete stayed relatively the same when the mixing temperature was held at 75° F and 95° F. But as the mixing temperature decreased from 75° F to 45° F it is evident that as the temperature decreased so did the unit weight. When the mixing temperature was at 75° F and 95° F the entire specified amount of water was used, due to hydration, but at 45° F all of the water was not used therefore the unit weight was lower. Figures 5.19 – 5.21 indicate that the SCC mixtures (SCC-K and SCC-K/MS) produce lower unit weight values. The expansive characteristics of these mixtures resulted in lower unit weights which in turn may adversely affect the concrete permeability.

Set-Time: The set-time was observed at the completion of mixing of the concrete. The results for the set-time are shown in Tables 5.1 – 5.3 and in Figures 5.22 – 5.28. Figures 5.22 – 5.25 show the effect of changing temperature on each of the four different mixtures. Figures 5.26 – 5.28 show the set-time for each mixture on the same plot for each of the mixing temperatures to facilitate comparing the mixtures. The initial set-time is reached when the penetration resistance reaches 500 psi and the final set-time is reached when the penetration resistance reaches 4000 psi. The penetration resistance is not to be confused with the compressive strength. The penetration resistance is the concrete's resistance to a 1 inch needle penetrating the concrete's surface 1 inch. It is evident from the figures listed above that the SCC-K and the SCC-K/MS sets-up much faster than the two ALDOT mixtures. It is also evident that the shrinkage reducing admixture Eclipse prolongs the set-time, especially in colder temperature. Therefore, one should avoid placing concrete with SRA at low temperatures and should place the concrete early in the morning when the temperature is warm due to the amount of time needed for the concrete mixture to set up.

Concrete Temperature: The concrete temperature was observed at the completion of mixing of the concrete. The results for the concrete temperature are shown in Tables 5.1 – 5.3 and in Figures 5.29 – 5.31. Figures 5.29 – 5.31 show the effect of mixing ambient temperature on the concrete internal temperature. From these figures, it is evident that as the concrete is mixed, heat has been generated through friction. Therefore, on hot summer days the concrete mixtures should be placed either in the morning or late in the evening. The concrete's temperature increases during the mixing process due to friction generated between the concrete's ingredients. This increase in temperature causes the concrete's temperature to be above the ambient temperature. This was not shown in Figure 5.31. The water was not exposed to the 95° F ambient temperature prior to mixing the concrete (as discussed in the fresh concrete property section in Chapter 4), therefore the temperature of the water (approximately 70° F) caused the concrete to be slightly lower than 95° F ambient temperature.

5.3 Hardened Concrete Property Results

The following hardened concrete properties of the concrete mixtures were observed: compressive strength, split tensile strength, drying shrinkage (restrained and unrestrained), elastic modulus, freeze-thaw durability, and rapid chloride ion penetration/permeability. The compressive strength, split tensile strength and the drying shrinkage tests were all observed at four different curing conditions (Lab Standard, Excellent, Fair and Poor as defined in Chapter 4). The elastic modulus, freeze-thaw durability and the rapid chloride ion penetration/permeability were observed only at the lab standard (LS) curing condition. Results for each of these testings are presented below.

Compressive Strength: The compressive strength of each of the concrete mixtures were observed at 3, 7, 28 and 56 days for each of the four curing conditions. Results of the compressive strength are shown in Tables 5.4 – 5.7 and in Figures 5.32 – 5.39. Figures 5.32 – 5.35 show the effect of the different curing conditions on each of the four different test mixtures. Figures 5.36 – 5.39 show the compressive strength of each mixture on the same plot for each of the curing conditions to facilitate comparing the mixtures. The compressive strength data used in these tables and figures where obtained by averaging the compressive strength of three specimens of each mixture at each curing condition.

Both Type-K mixtures, SCC-K and SCC-K/MS, and the ALDOT (Control) mixture had very similar compressive strengths for the different curing conditions. The ALDOT-SRA mixture exhibited considerably lower compressive strengths than the other mixtures, leading to the conclusion the SRA-Eclipse decreased the compressive strength. This is consistent with other SRA testing. It has been reported [15] that SRA-Eclipse reduces the compressive strength by approximately 10%.

Comparing the four different curing conditions, the excellent curing condition provided considerable higher compressive strengths than the lab standard, fair and poor curing conditions.

Splitting Tensile Strength: The splitting tensile strength of each of the concrete mixtures were observed at 7 days and at 28 days for each of the four curing conditions. Results of the splitting tensile strength are shown in Tables 5.4 – 5.7 and in Figures 5.40 – 5.47. Figures 5.40 – 5.43 show the effect of the different curing conditions on each of the four different mixtures. Figures 5.44 – 5.47 show the splitting tensile strength of each mixture on the same plot for each of the curing conditions to facilitate comparing the mixtures. The splitting tensile data used in these tables and figures where obtained by averaging the splitting tensile strength of three specimens of each mixture at each curing condition.

In comparing the four concrete mixtures the ALDOT (Control) mixture produced higher split tensile strengths than the other concrete mixtures followed by SCC-K, SCC-K/MS and ALDOT – SRA. The ALDOT-SRA mixture exhibited considerably lower tensile strengths than the other mixtures, leading to the conclusion that SRA-Eclipse decreased the split tensile strength in concrete. This is very important since concrete cracks when the stress exceeds its tensile strength. From comparing the results in Tables 5.4 – 5.7, the ALDOT-SRA mixture split tensile strengths are 8- 34 % lower than the other mixtures. The four different curing conditions did not seem to have a significant effect on the split tensile strength of the mixtures, except for the lab standard curing condition which produced lower tensile strengths than the other curing conditions.

Drying Shrinkage (Restrained): The restrained bar drying shrinkage was observed on each of the four concrete mixtures daily for each of the four curing conditions. Results for the restrained bar drying shrinkage are shown in Table 5.8 and in Figures 5.48 – 5.55. Figures 5.48 – 5.51 show the effect of the different curing conditions on each of the four mixtures. Figures 5.52 – 5.55 show the restrained bar shrinkage results of each mixture on the same plot for each of the curing conditions to facilitate comparing the mixtures. The restrained bar drying shrinkage data used in these tables and figures where obtained by averaging two specimens from each mixture at each of the four curing conditions.

In comparing the four concrete mixtures, SCC-K produced the best shrinkage results followed by ALDOT-SRA, SCC-K/MS and ALDOT (Control) with the last providing the worst case scenario. The results show that the success of the SCC-K mixture relied greatly upon wet curing of the concrete for 7 days, to allow the ettringite to properly form. Figures 5.52 and 5.53 shows the success of the SCC-K mixture with the 7-day wet cure and Figure 5.54 and 5.55 shows that without the 7-day wet cure, Type-K cement does not have a positive effect on concrete shrinkage. Results indicate that the micro-silica in the SCC-K/MS mixture may inhibit swelling effect of the Type-K cement therefore causing this mixture to shrink more than the Type-K mixture. Figure 5.48 and Figure 5.49 show that the test for the SCC-K mixture was terminated at 49 days and the SCC-K/MS mixture was terminated at 50 days due to instrumentation failure to the instrument shown in Figure 4.3. This mishap did not alter the results of the restrained bar test since the mixtures shrinkage curves had already leveled off prior to the termination of the test. The ALDOT-SRA mixture also had good shrinkage characteristics with its best result occurring at the excellent curing condition. This was also the best curing condition for the SCC-K mixture which had better results than the ALDOT-SRA mixture. The best fit lines in Figure 5.50 show a downward slope at 61 days, but a close examination of the individual plots show that the shrinkage plots are starting to level off towards the end of the testing period. The ALDOT-SRA mixture postpones shrinkage up to 30 days but then the concrete shrinks until the concrete reaches approximately 58 days. One positive result for the ALDOT-SRA mixture is that the data show that this mixture does not rely heavily on the curing condition. This corresponds to information in the literature. The ALDOT (Control) mixture provided the worst shrinkage results.

Drying Shrinkage (Unrestrained): The unrestrained bar drying shrinkage was observed on each of the four concrete mixtures daily for each of the four curing conditions. Results for the unrestrained bar drying shrinkage are shown in Table 5.9 and in Figures 5.56 – 5.63. Figures 5.56 – 5.59 show the effect of the different curing conditions on each of the four mixtures. Figures 5.60 – 5.63 show the unrestrained bar shrinkage results of each mixture on the same plot for each of the curing conditions to facilitate comparing the mixtures. The unrestrained bar drying shrinkage data used in these tables and figures were obtained by averaging two specimens of each mixture at each of the four curing conditions.

The results for the unrestrained bar shrinkage were very similar to the results of the restrained bar shrinkage, with the Type-K mixtures producing the best results. This is as expected since Type-K cement expands due to wet curing of the concrete. The unrestrained bar test results also shows the importance in wet curing of Type-K cement. This is shown in Figure 5.56. The lab standard and excellent curing condtions produced low shrinkage results where as the fair and poor curing conditions produced high shrinkage results. The results also show that the ALDOT-SRA mixture provides similar results whether restrained or unrestrained. The ALDOT (Control) mixture again produced the worst shrinkage results with shrinkage occuring throughout the test.

Elastic Modulus: The elastic modulus was observed on each of the four concrete mixtures at 7, 28 and 56 days at the lab standard curing condition. Results for the elastic modulus are shown in Table 5.10 and in Figures 5.64 – 5.68. The elastic modulus data used were obtained by averaging two specimens of each mixture. Figure 5.64 shows the modulus of elasticity for each concrete mixture at the three specified days. Figures 5.65

– 5.68 show how each mixture relates to the theoretical approximations of ACI 318 and ACI 363. These approximations are empirical relationships that can be used for design when the modulus of elasticity has not been determined experimentally, and are

ACI 318

$$E_c = 33w^{1.5}\sqrt{f_c'} \quad \text{(psi)}$$

ACI 363

$$E_c = 1.0x10^6 + 40{,}000\sqrt{f_c'} \quad \text{(psi)}$$

where w = unit weight of concrete (pcf), f_c' = compressive strength of concrete at specified number of days.

In comparing the four concrete mixtures in Figure 5.64 the ALDOT (Control) produced the highest modulus of elasticity followed by the ALDOT-SRA mixture. The two Type-K mixtures produced very similar results with lower moduli values than the ALDOT mixtures. This appears to be consistent with Type-K cement providing expansive characteristics and lower unit weight concrete. Figures 5.65 – 5.68 show that the modulus of elasticity results compare reasonably well with the ACI approximations. The results show that the ACI equations are good approximations of the modulus of elasticity.

Freeze-Thaw Durability: The freeze-thaw durability results were observed approximately every 30 cycles for a test period of 300 cycles. Results for the freeze-thaw durability are shown in Table 5.11 and in Figure 5.69. The freeze-thaw durability data used were obtained by averaging the results from two specimens of each mixture.

The durability factor for each mixture was very similar. The durability factor dropped the first 30 cycles but in some of the mixtures it rose over the rest of the testing period. This is due to the aging of the concrete. As the test period increased the concrete's strength became stronger and its stiffness greater, and therefore the durability of the concrete became a little better. Even though the durability factor was acceptable for all four concrete mixtures, the ALDOT-SRA mixture scaled significantly more than the ALDOT (Control) mixture. The two Type-K mixtures, SCC-K and SCC-K/MS, had little tendency to scale. This can be seen in Figure 5.70. Therefore, the results of the freeze-thaw durability test showed that the SRA-Eclipse tended to cause the concrete surface to scale. This is very important since northern Alabama experiences numerous freeze-thaw cycle every year.

Rapid Chloride Ion Penetration/Permeability:

The rapid chloride ion penetration/permeability test was conducted on 2 specimens of each mixture. Each specimen was wet cured for 52 days as described in ASTM 1202. Results of the rapid chloride ion permeability test are shown in Table 5.12. The results show that the SCC-K/MS mixture had by far the lowest permeability. This agrees with the literature, which indicate that the addition of micro silica significantly reduces the permeability of concrete. The other three mixtures were very similar. Even though the SCC-K mixture has a high permeability rating it is quite comparable with the ALDOT (Control) mixture. It has been reported that Type-K cement may increase the permeability of concrete; however, these data show that the SCC-K mixture permeability is about the same as the standard ALDOT (Control) mixture.

Ring Test: The ring test was conducted on 2 specimens of each concrete mixture. One specimen experienced a 7 day wet cure while the other specimen experienced no curing. The ring tests were conducted for 61 days, and the results are shown in Figures 5.71 – 5.75.

The shrinkage strains for each of the four concrete mixtures are shown in Figures 5.71 – 5.74. Figures 5.75 – 5.76 show the four concrete mixtures for each of the curing conditions on the same plots to facilitate comparing the four mixtures. The results were very similar to those described under the drying shrinkage section of this chapter, with the Type-K mixtures providing the best results. It is to be noted that the concrete mixture producing the lowest shrinkage strains should provide the most resistance to drying shrinkage.

The intent of a ring test is to integrate the drying shrinkage strain and tensile strength characteristics of a mixture in a single test since concrete shrinkage cracking is a function of both of these characteristics. However, ring test results in this investigation did not turn out as expected, and did not provide any significantly useful results. Strain gage readings on the inner steel ring in the test increased at a rapid rate initially, and leveled off after approximately 20 days as can be seen in Figures 5.71 and 5.76. The strain gage data did not indicate any ring cracking nor was any cracking evident from visual inspections. Additionally, at the end of the ring tests, the ring specimens were saw-cut for internal visual inspections (see Figure 5.77 and Figure 5.78), and again no cracking was found. Since shrinkage bar testing for these same mixtures showed continued shrinkage at 20 days and beyond, it appears that in the ring specimens that creep and/or microcracking of the mixtures resulted in an upper limit of radial stress applied to the inner steel ring as reflected by the ring strain gage data.

Others have reported successful results with the ring test when using 6" tall by 3" thick concrete ring specimens. More research needs to be done on this test to develop it into a practical and viable test for accessing shrinkage cracking potential of concrete mixtures.

Heat of Hydration: The heat of hydration test was conducted on each of the four concrete mixtures at a ambient mixing temperature of 70° F, and the results are shown in Figure 5.79. The results for this test were very similar to the mixture set-time results. The Type-K mixtures SCC-K and SCC-K/MS generated the most heat due to the hydration of the water in the concrete followed by the ALDOT (Control) and ALDOT-SRA mixtures. It is important to note the SRA-Eclipse, generated the least amount of heat, and at a slower rate. Because of this, the concrete temperature was still above ambient room temperature at the completion of the test (24 hours). This result is consistent with the set-time results. That is, since the ALDOT-SRA mixture produces a lower heat of hydration temperature and prolongs the hydration period, the set-time would be expected to be longer.

Table 5.1 Fresh Concrete Property Testing Results at Ambient Temperature of 45° F

Concrete[1] Property/Parameter		**Concrete Mixture**			
		SCC-K	**SCC-K/MS**	**ALDOT-SRA**	**ALDOT (Control)**
Slump ASTM C143 (inches)	1 – min.	7.5	8	4	4.5
	15 – min.	6	7.5	2	3
	30 – min.	4.25	5.75	1	2
	45 – min.	3	5	0.5	1.5
Air Content ASTM C231		5.5	5.8	6.3	6
Unit Weight ASTM C138 (lbs/cf)		138.7	138.6	142.9	143.7
Set-Time ASTM C403	Initial (500 psi)	10 hrs.	10 hrs. 45 min.	14 hrs. 50 min.	13 hrs. 40 min.
	Final (4000 psi)	13 hrs. 40 min.	13 hrs. 50 min.	17 hrs. 15 min.	16 hrs.
Concrete Temperature ASTM C1064 (°F)		58	60	52	51

[1] Values shown are the average of 2 replica tests.

Table 5.2 Fresh Concrete Property Testing Results at Ambient Temperature of 75° F

Concrete Property/Parameter		Concrete Mixture			
		SCC-K	SCC-K/MS	ALDOT-SRA	ALDOT (Control)
Slump[1] ASTM C143 (inches)	1 – min.	7.75	8.5	4	4
	15 – min.	6	7.5	3	2
	30 – min.	4.75	4.5	2	1.5
	45 – min.	3.25	2.75	0.75	1
Air Content[1] ASTM C231		4.7	5	4.3	5
Unit Weight[1] ASTM C138 (lbs/cf)		139.5	140.2	146.89	145.38
Set-Time[2] ASTM C403	Initial (500 psi)	6 hrs. 35 min.	7 hrs. 20 min.	9 hrs. 45 min.	8 hrs. 30 min.
	Final (4000 psi)	8 hrs. 20 min.	8 hrs. 23 min.	11 hrs. 5 min.	9 hrs. 39 min.
Concrete Temperature[1] ASTM C1064 (°F)		87	86	86	83

[1] Values shown are the average of 6 replica tests.

[2] Values shown are the average of 2 replica tests.

Table 5.3 Fresh Concrete Property Testing Results at Ambient Temperature of 95° F

Concrete[1] Property/Parameter		Concrete Mixture			
		SCC-K	**SCC-K/MS**	**ALDOT-SRA**	**ALDOT (Control)**
Slump ASTM C143 (inches)	1 – min.	1.5	7.0	3.25	2.75
	15 – min.	.25	2	1	.25
	30 – min.	0	.25	.25	0
	45 – min.	0	0	0	0
Air Content ASTM C231		5.6	4.3	3.8	3.6
Unit Weight ASTM C138 (lbs/cf)		142.3	142.7	146.91	145.41
Set-Time ASTM C403	Initial (500 psi)	3 hrs. 25 min.	3 hrs. 30 min.	6 hrs. 35 min.	4 hrs. 17 min.
	Final (4000 psi)	4 hrs. 25 min.	4 hrs. 40 min.	7 hrs. 10 min.	6 hrs. 40 min.
Concrete Temperature ASTM C1064 (°F)		94	94	91.5	93

[1] Values are the average of 2 replica tests.

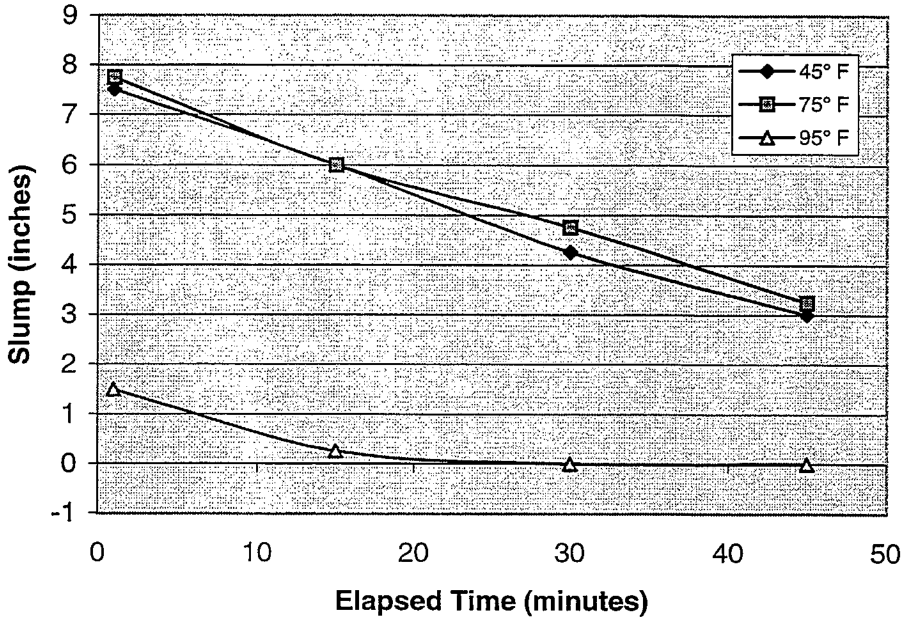


Figure 5.1 Change in Slump for SCC-K

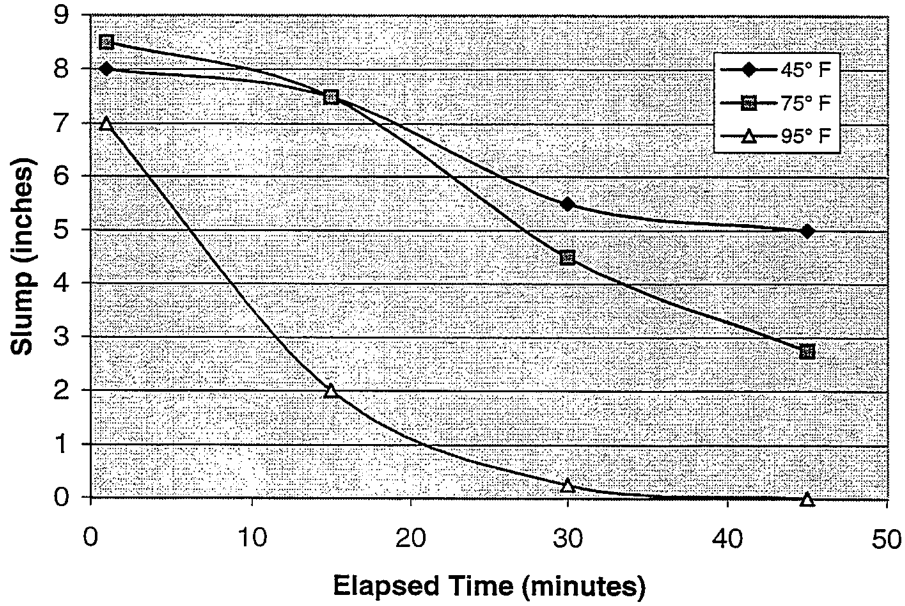


Figure 5.2 Change in Slump for SCC-K/MS

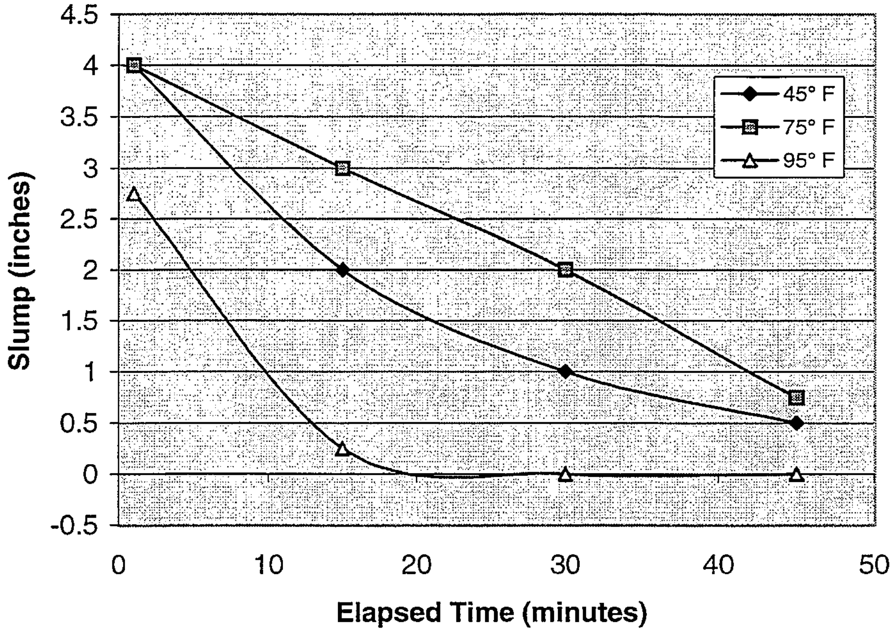


Figure 5.3 Change in Slump for ALDOT-SRA

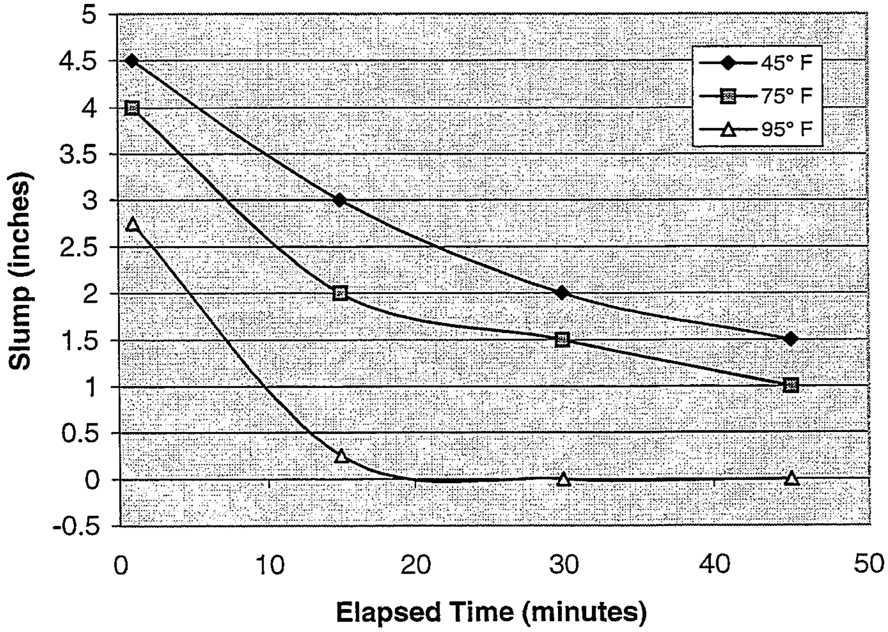


Figure 5.4 Change in Slump for ALDOT (Control)

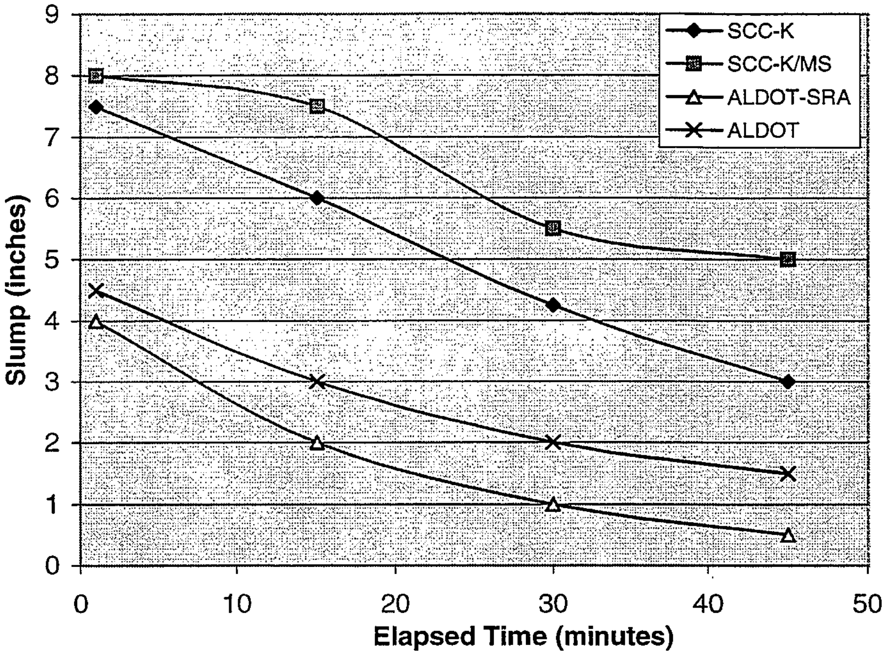


Figure 5.5 Change in Slump @ 45° F.

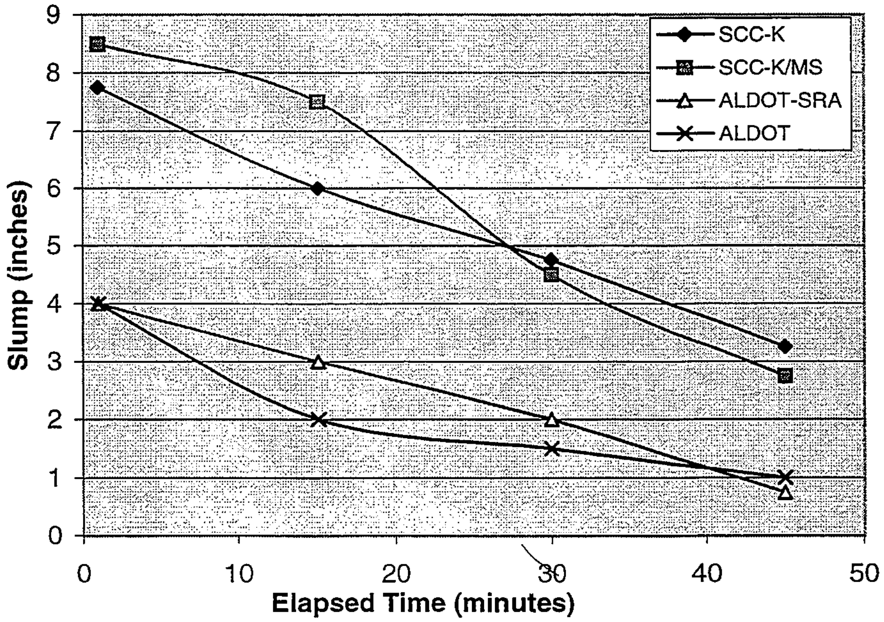


Figure 5.6 Change in Slump @ 75° F

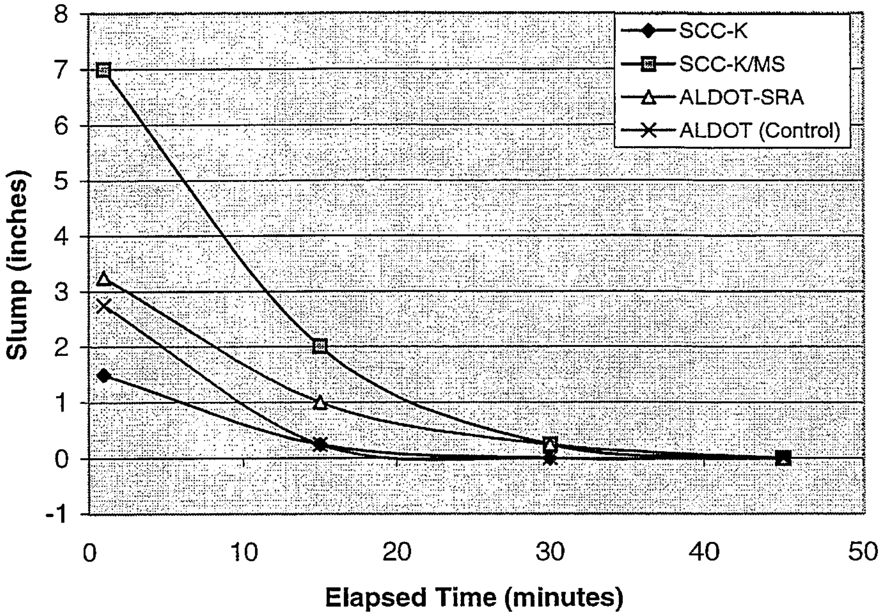


Figure 5.7 Change in Slump @ 95° F

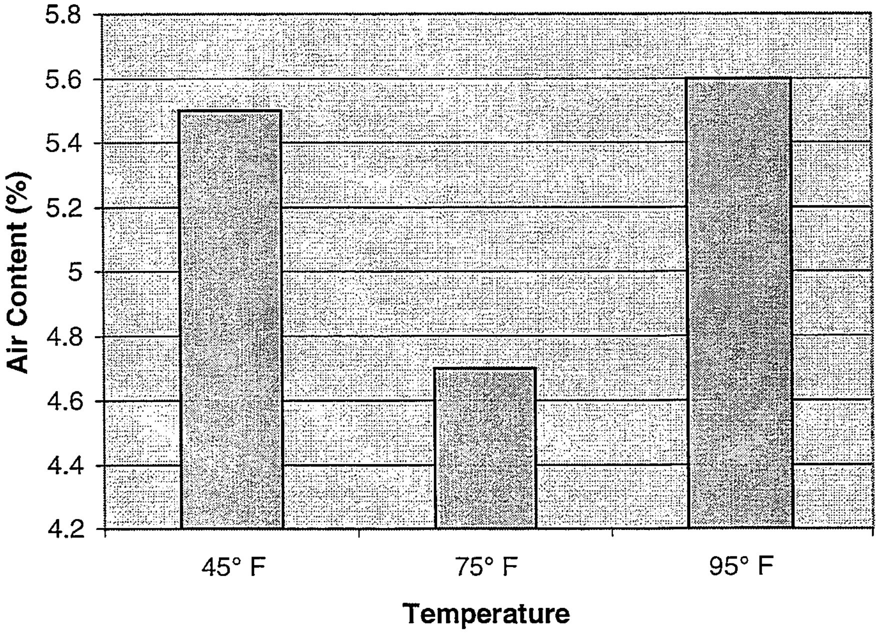


Figure 5.8 Air Content for SCC-K

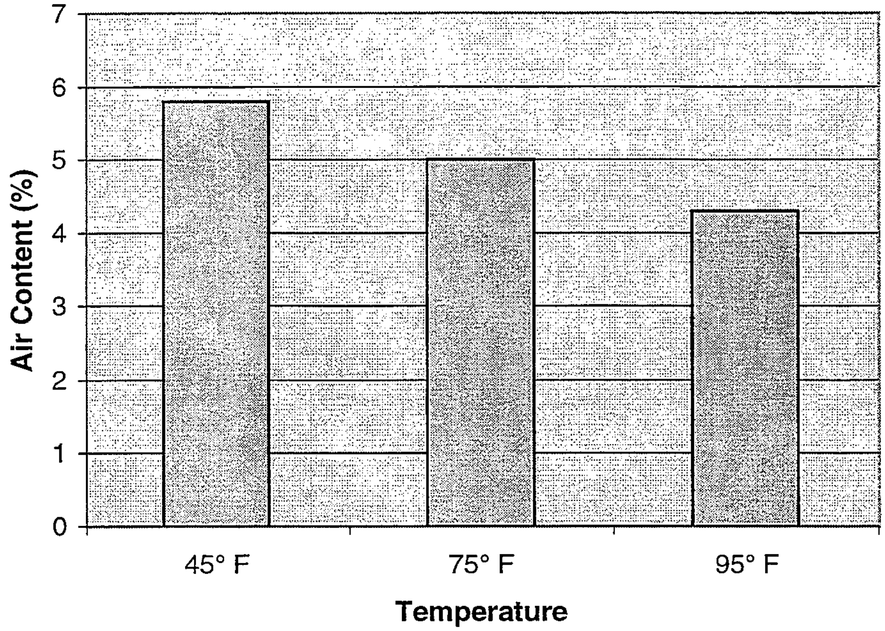


Figure 5.9 Air Contnet for SCC-K/MS

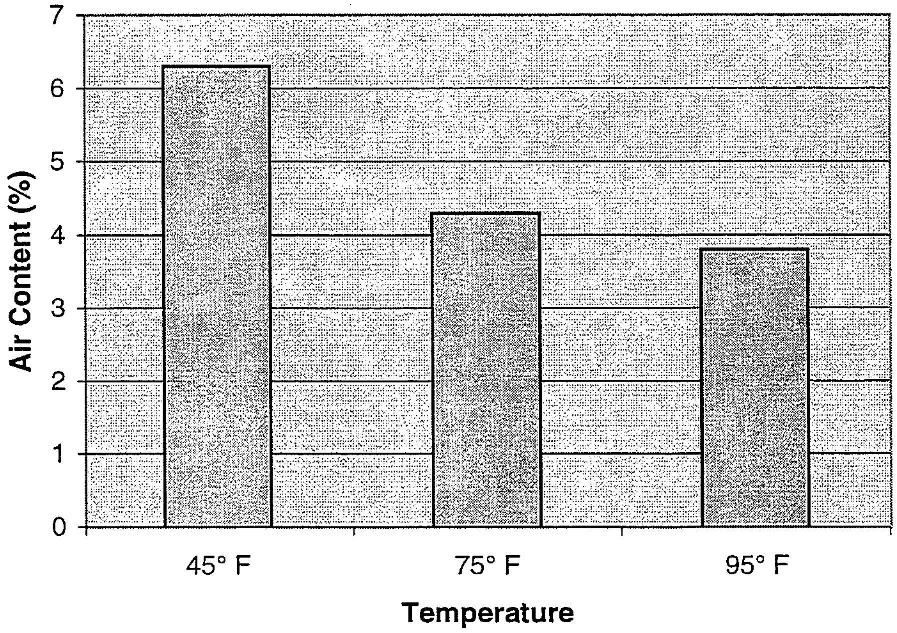


Figure 5.10 Air Content % for ALDOT-SRA

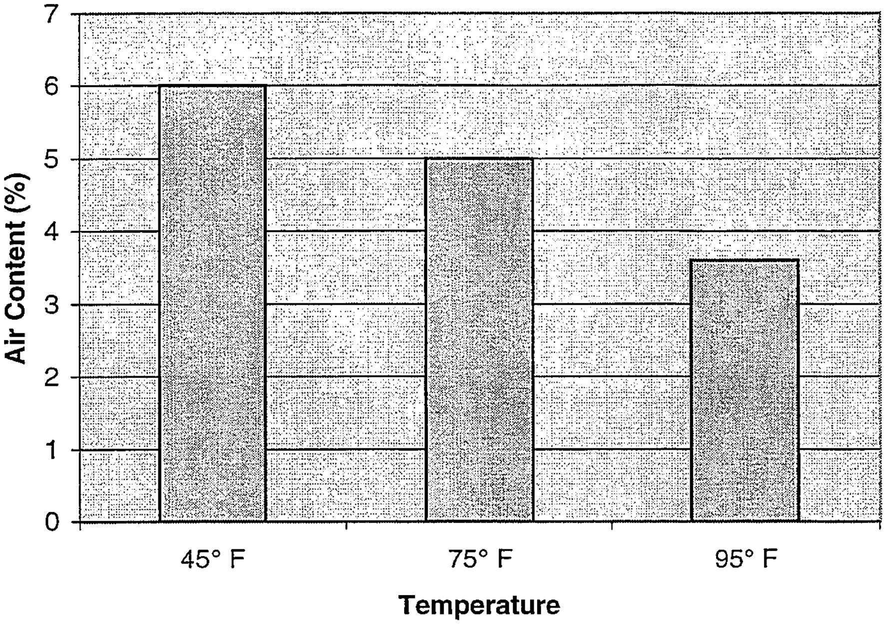


Figure 5.11 Air Content for ALDOT (Control)

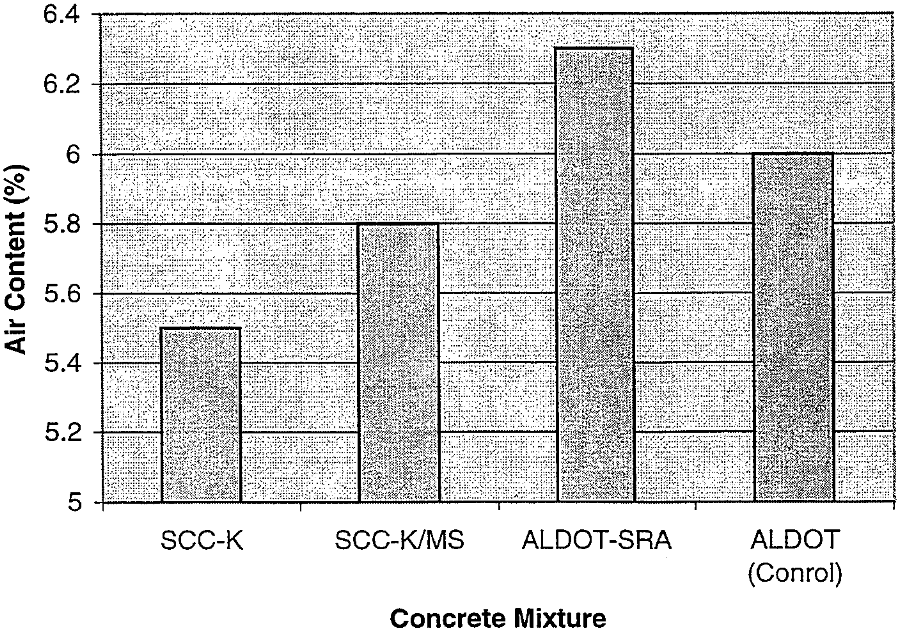


Figure 5.12 Air Content @ 45° F

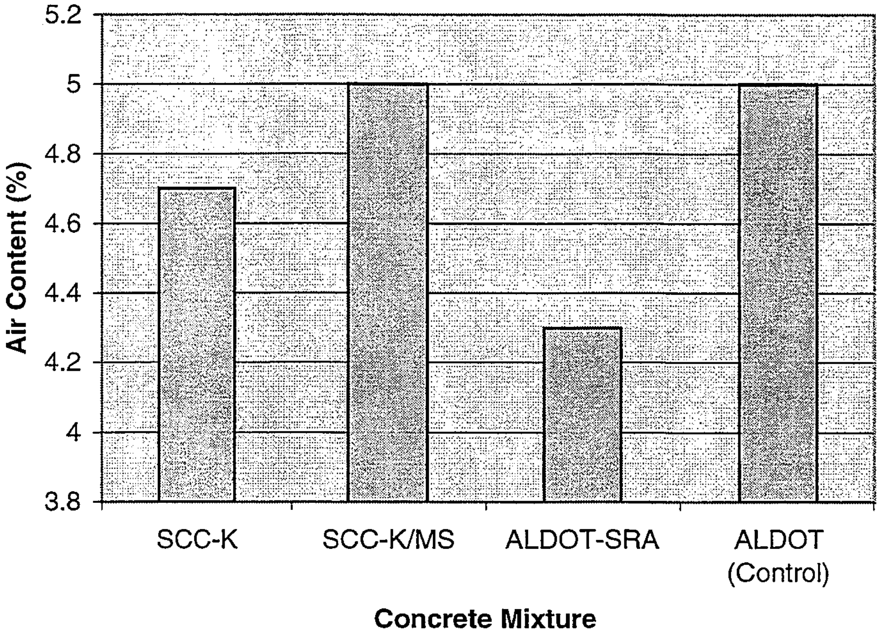


Figure 5.13 Air Content @ 75° F

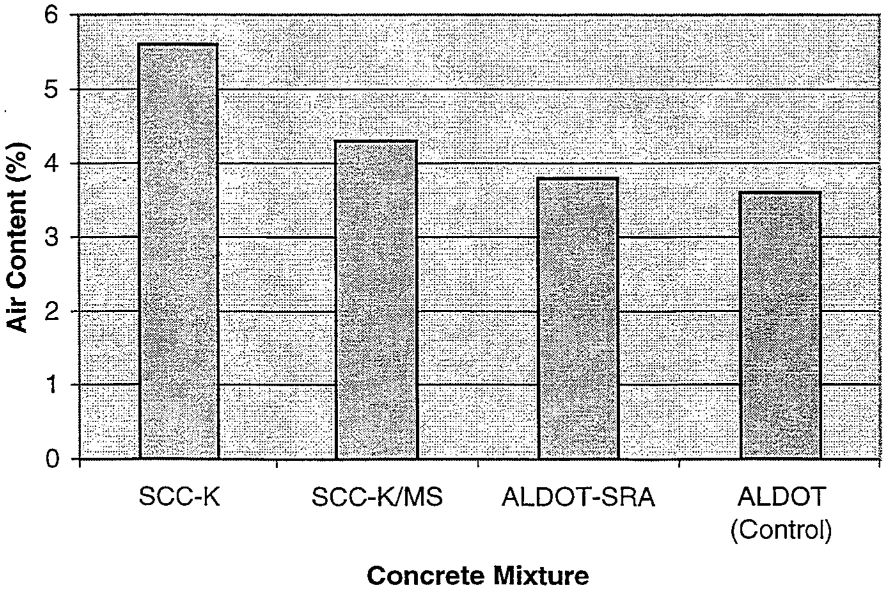


Figure 5.14 Air Content @ 95° F

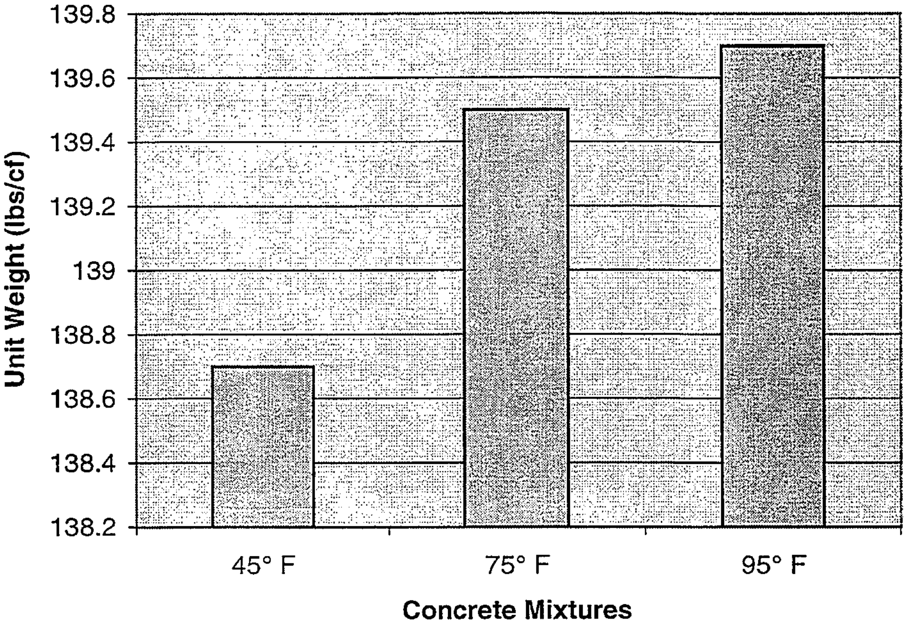


Figure 5.15 Unit Weight of SCC-K Mixture at Different Mixing Temperatures

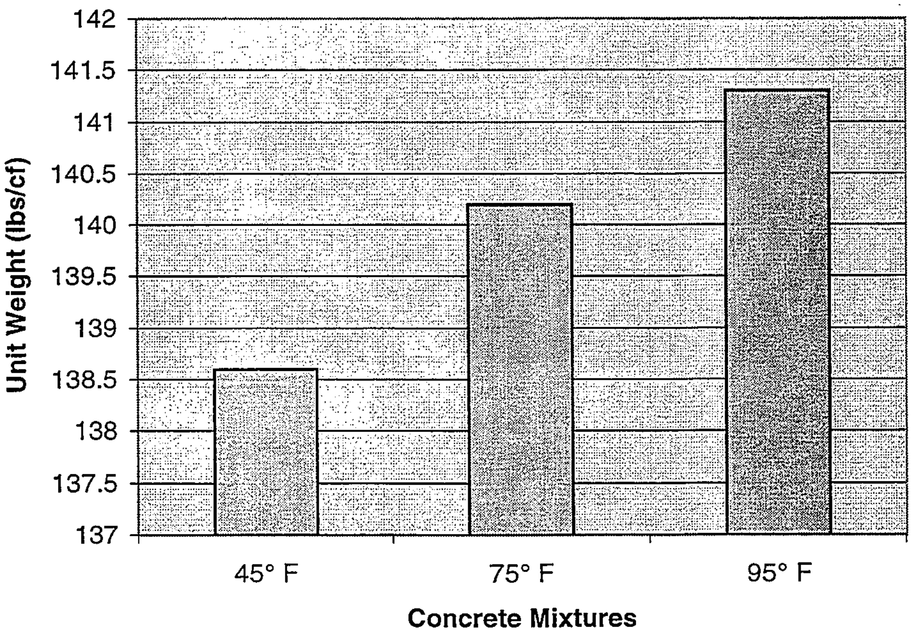


Figure 5.16 Unit Weight of SCC-K/MS Mixture at Different Mixing Temperatures

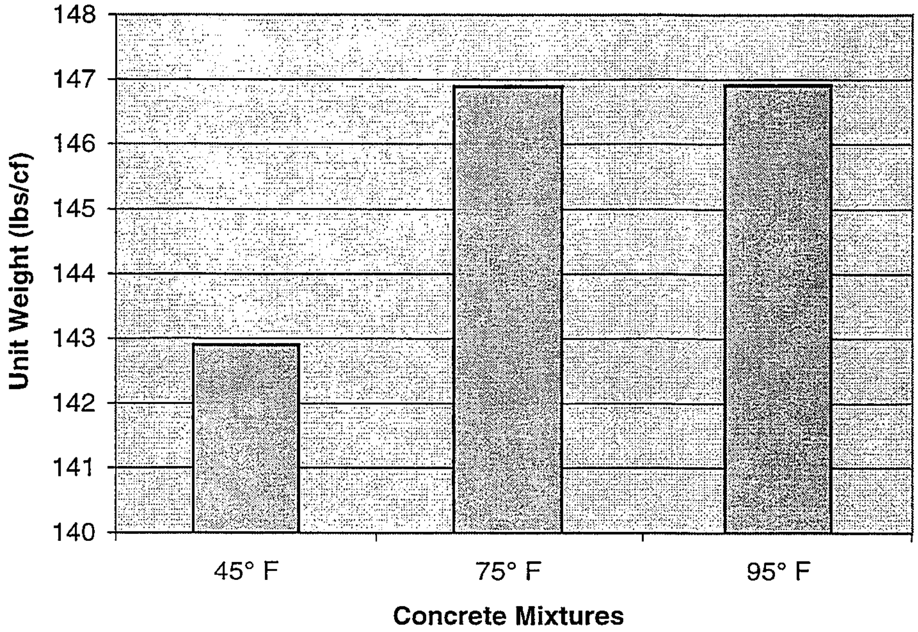


Figure 5.17 Unit Weight of ALDOT-SRA Mixture at Different Mixing Temperatures

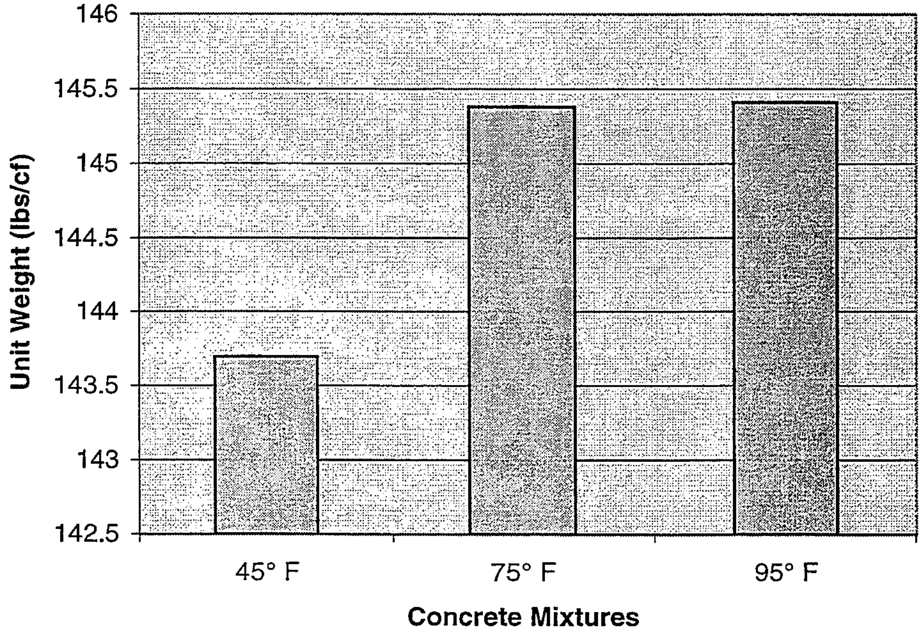


Figure 5.18 Unit Weight of ALDOT (Control) Mixture at Different Mixing Temperatures

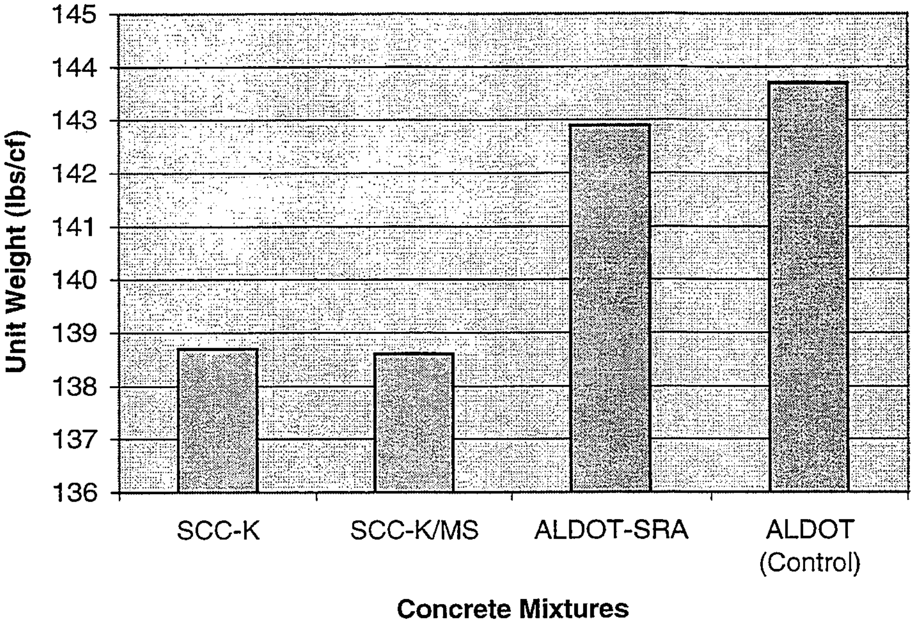


Figure 5.19 Unit Weight of Concrete Mixtures at 45° F

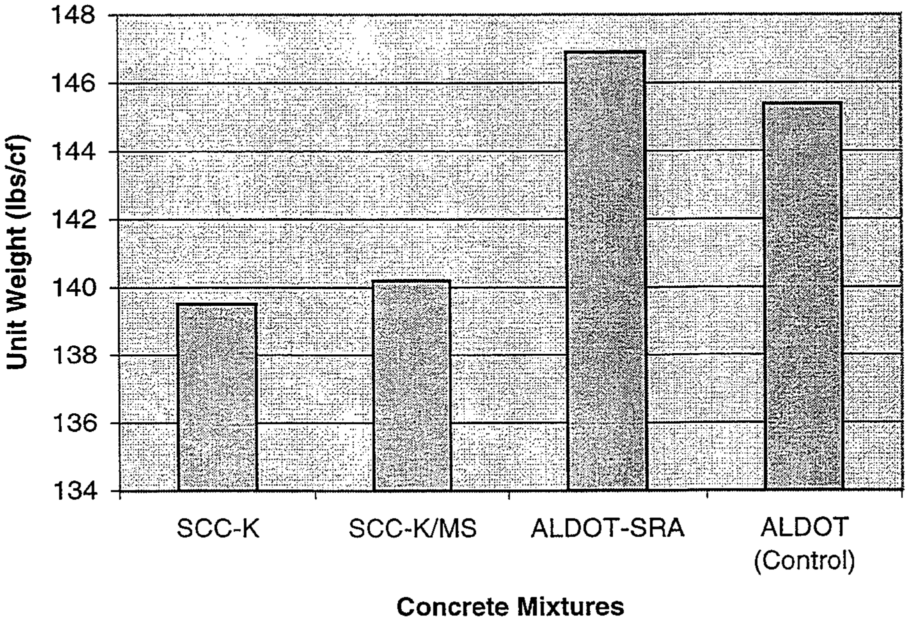


Figure 5.20 Unit Weight of Concrete Mixtures at 75° F

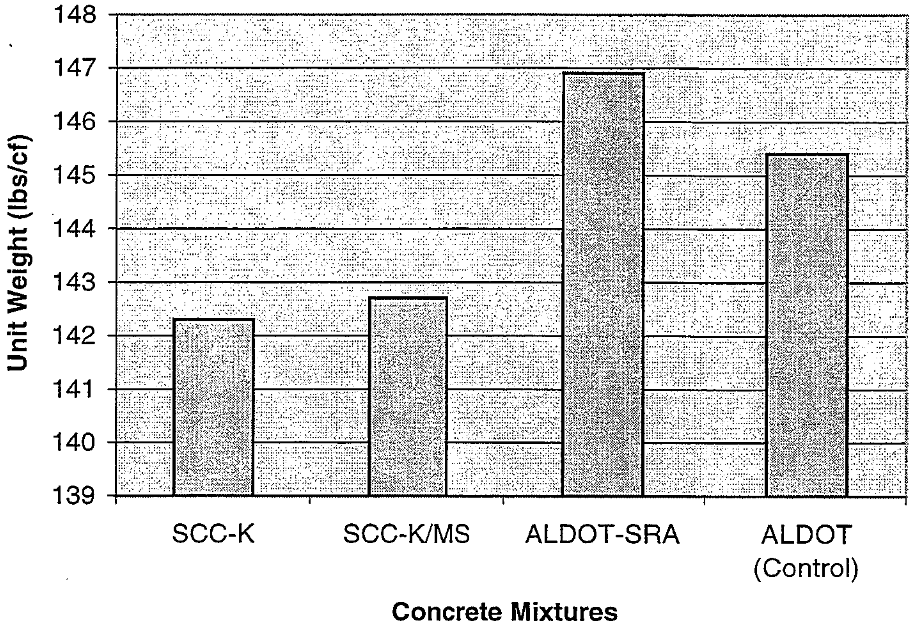


Figure 5.21 Unit Weight of Concrete Mixtures at 95° F

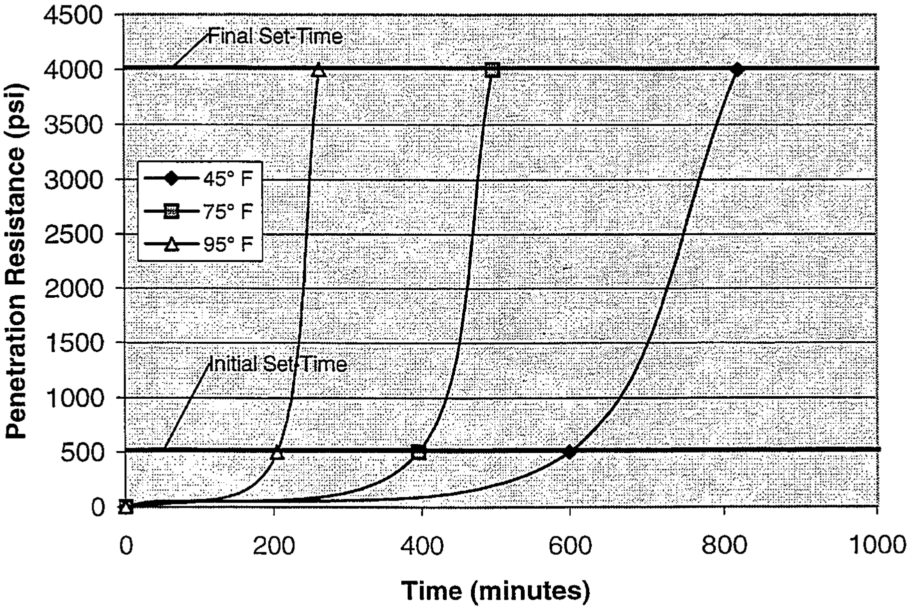


Figure 5.22 Initial and Final Set-Time for SCC-K at Different Mixing Temperatures

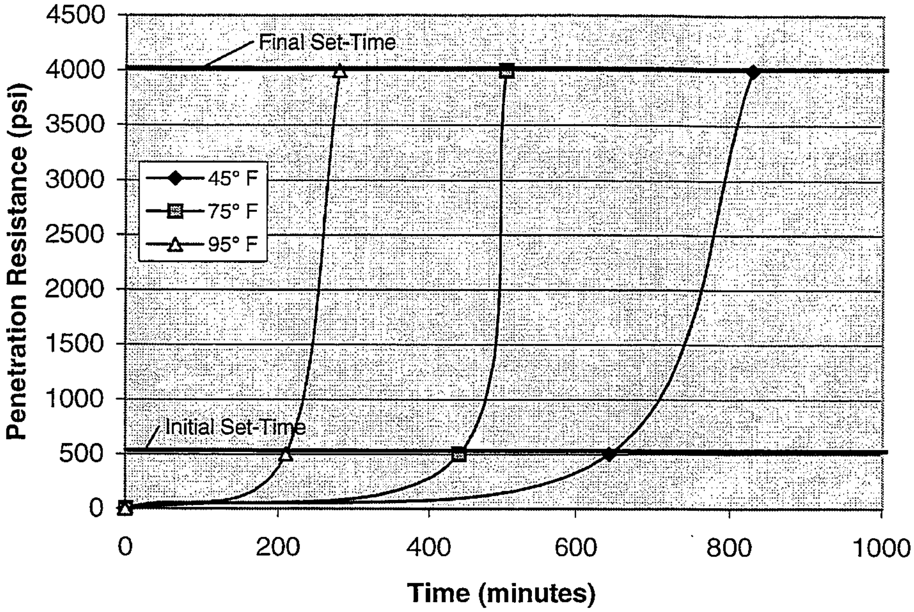


Figure 5.23 Initial and Final Set-Time for SCC-K/MS at Different Mixing Temperatures

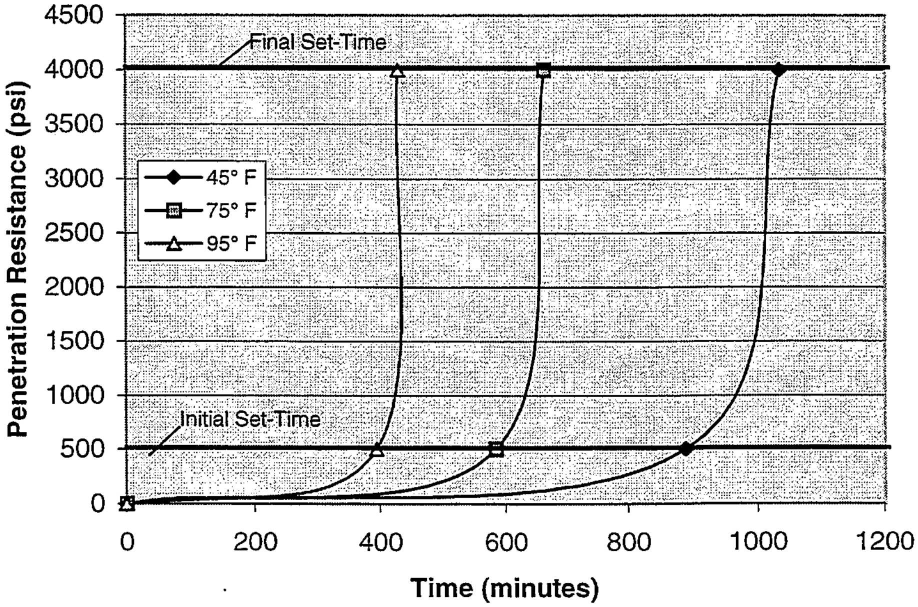


Figure 5.24 Initial and Final Set-Time for ALDOT-SRA at Different Mixing Temperatures

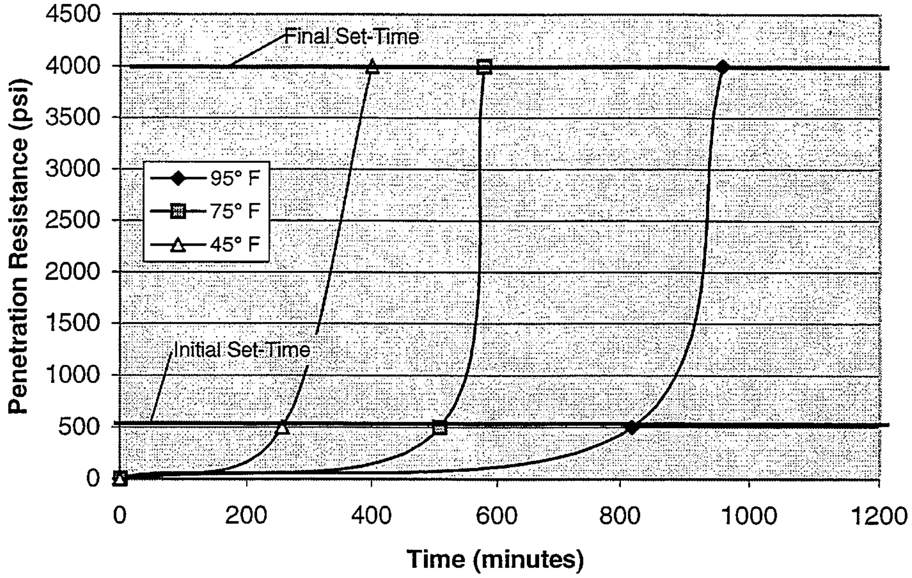


Figure 5.25 Initial and Final Set-Time for ALDOT (Control) at Different Mixing Temperatures

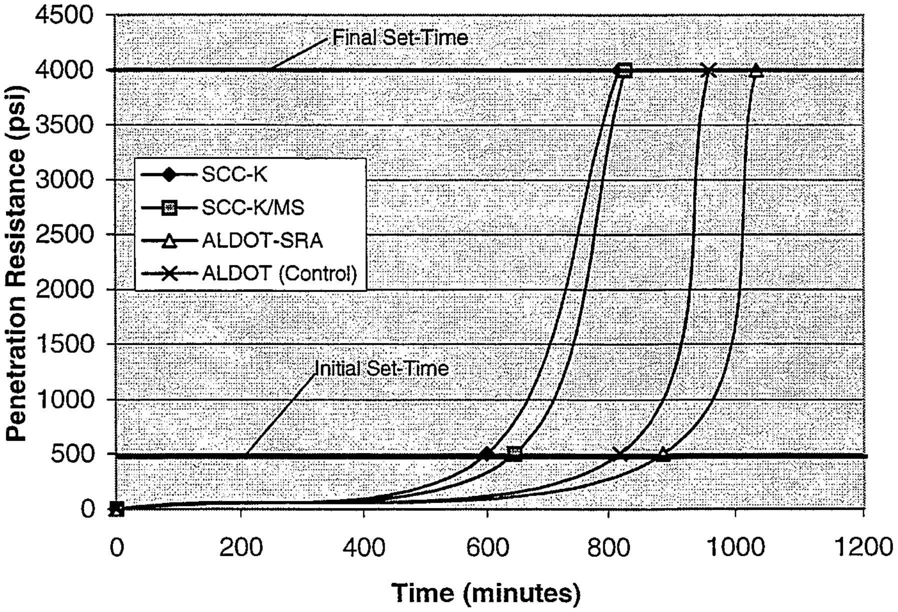


Figure 5.26 Initial and Final Set-Time for the Concrete Mixtures at 45° F

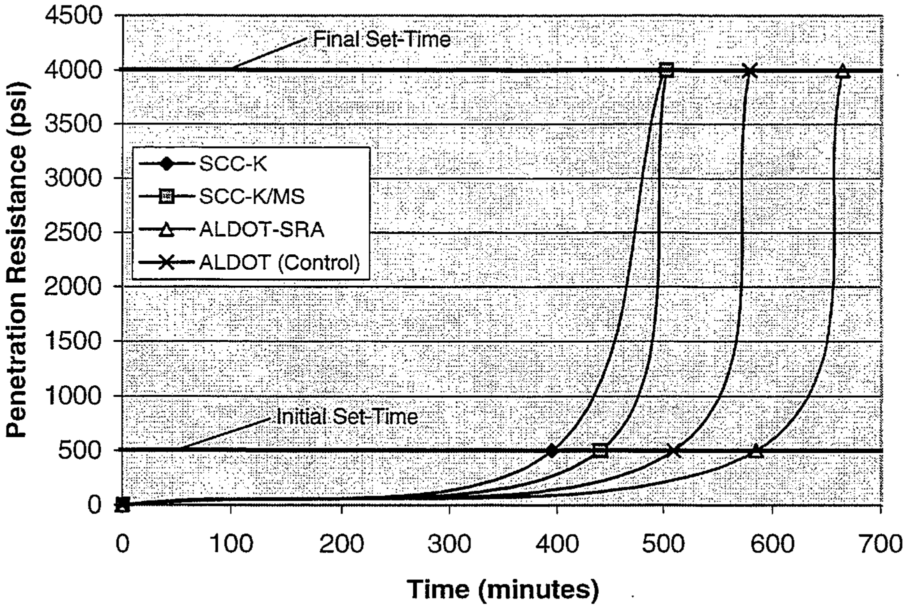


Figure 5.27 Initial and Final Set-Time for the Concrete Mixtures at 75° F

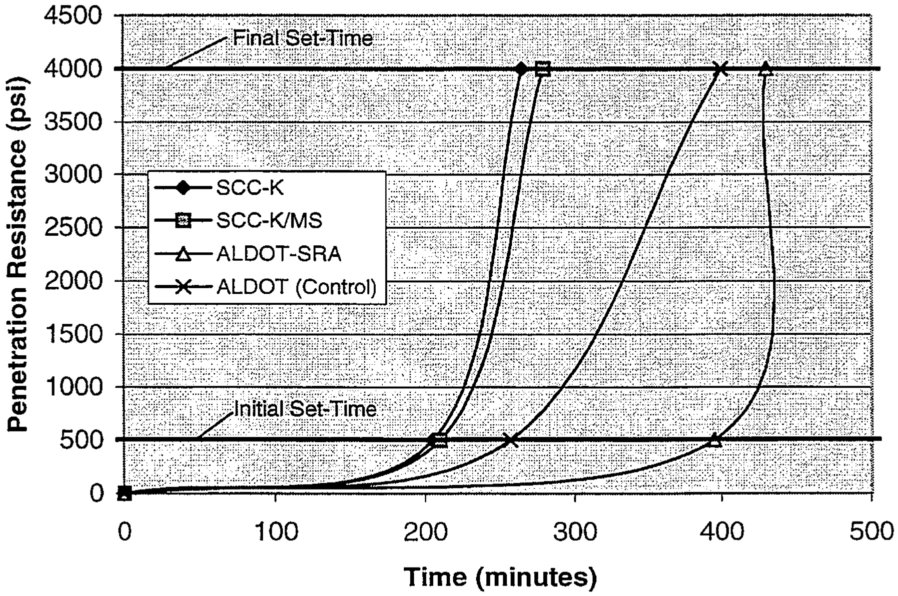


Figure 5.28 Initial and Final Set-Time for the Concrete Mixtures at 95° F

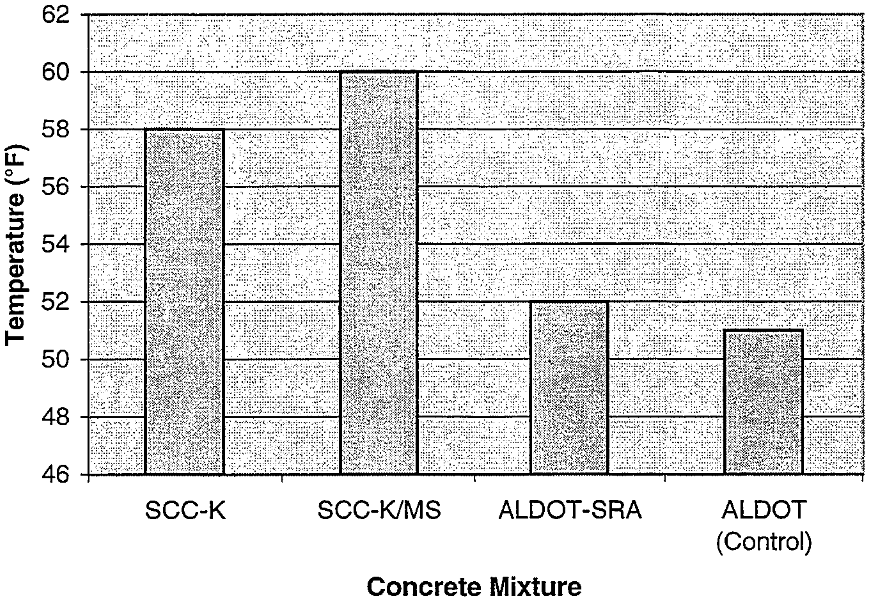


Figure 5.29 Temperature of Concrete Mixtures at 45° F Ambient Temperature

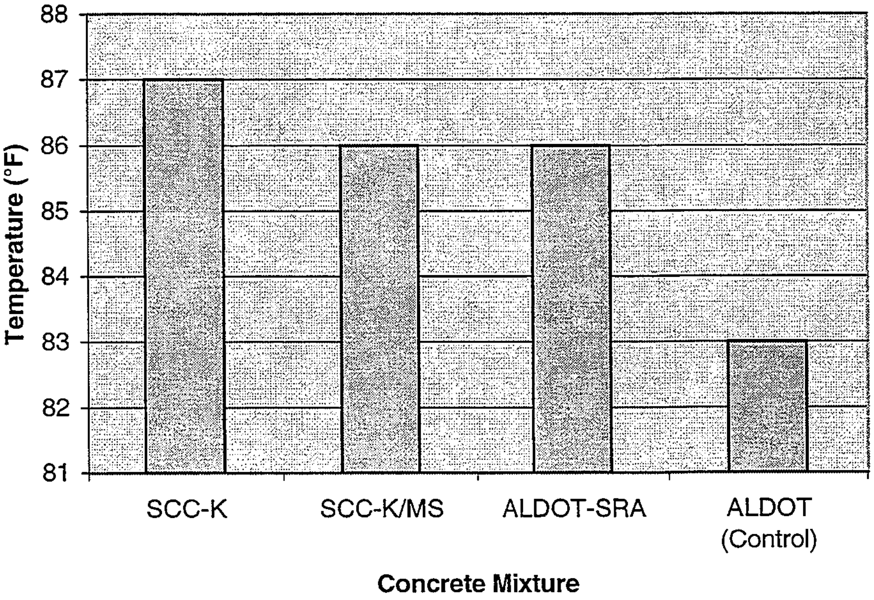


Figure 5.30 Temperature of Concrete Mixtures at 75° F Ambient Temperature

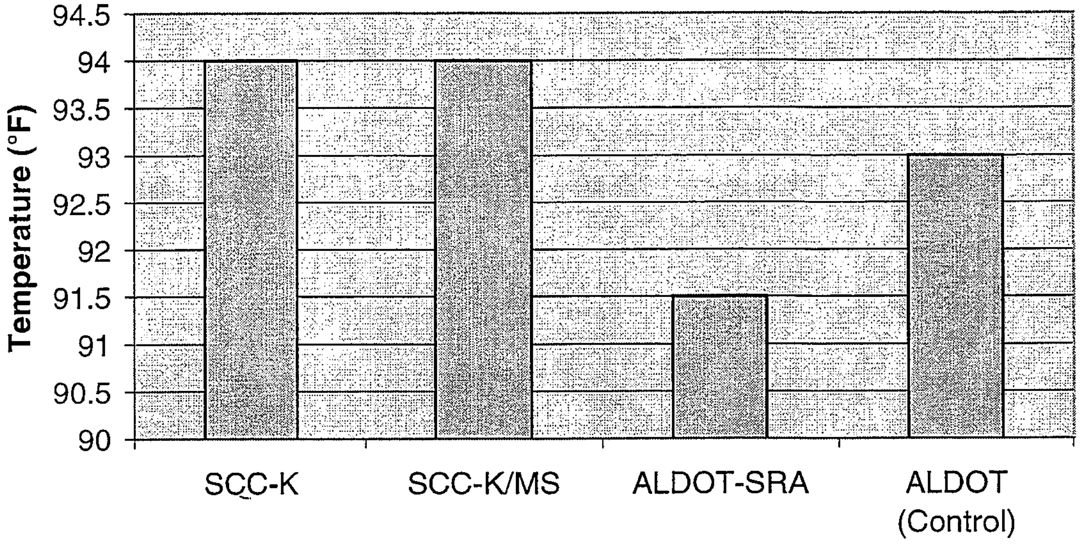


Figure 5.31 Temperature of Concrete Mixtures at 95° F Ambient Temperature

Table 5.4 Compressive Strength and Split Tensile Results for Lab Standard Curing Condition.

Curing Condition	**Concrete Property**		**Concrete Mixture**			
			SCC-K	**SCC-K/MS**	**ALDOT-SRA**	**ALDOT (Control)**
LS	Compressive* Strength ASTM C39 (psi)	3 – day	3827	3060	3260	3860
		7 – day	4480	3910	3870	5025
		28 – day	5270	5690	4755	5935
		56 - day	5665	5720	5100	6125
	Splitting ** Tensile Strength ASTM C496 (psi)	7 – day	310	327	301	402
		28 – day	376	345	312	415

*Values are the average of three specimens.

**Values are the average of two specimens.

*** Values of the specimens incorporated in the averages above are shown in Table A.1 and A.2 in the Appendix.

Table 5.5 Compressive Strength and Split Tensile Results for Excellent Curing Condition.

Curing Condition	**Concrete Property**		**Concrete Mixture**			
			SCC-K	**SCC-K/MS**	**ALDOT-SRA**	**ALDOT (Control)**
E	Compressive* Strength ASTM C39 (psi)	3 – day	3785	3020	3200	4110
		7 – day	4500	3840	3835	4960
		28 – day	5950	6455	5095	6485
		56 – day	6430	6630	5600	6505
	Splitting** Tensile Strength ASTM C496 (psi)	7 – day	366	296	324	355
		28 – day	453	303	339	499

*Values are the average of three specimens

**Values are the average of two specimens

** Values of the specimens incorporated in the averages above are shown in Table A.1 and A.2 in the Appendix

Table 5.6 Compressive Strength and Split Tensile Results for Fair Curing Condition.

Curing Condition	Concrete Property		Concrete Mixture			
			SCC-K	SCC-K/MS	ALDOT-SRA	ALDOT (Control)
F	Compressive* Strength ASTM C39 (psi)	3 – day	4448	3480	3225	4110
		7 – day	4875	4810	3750	4935
		28 – day	5950	5120	4500	5400
		56 – day	6430	5900	4780	5600
	Splitting ** Tensile Strength ASTM C496 (psi)	7 – day	353	368	328	475
		28 – day	503	389	329	502

*Values are the average of three specimens.

**Values are the average of two specimens.

*** Values of the specimens incorporated in the averages above are shown in Table A.1 and A.2 in the Appendix

Table 5.7 Compressive Strength and Split Tensile Results for Poor Curing Condition.

Curing Condition	Concrete Property		Concrete Mixture			
			SCC-K	SCC-K/MS	ALDOT-SRA	ALDOT (Control)
P	Compressive* Strength ASTM C496 (psi)	3 – day	4285	3255	3265	4105
		7 – day	4975	4580	3825	4800
		28 – day	5245	5100	4700	5140
		56 – day	5710	5275	4755	5510
	Splitting** Tensile Strength ASTM C496 (psi)	7 – day	453	488	303	445
		28 – day	465	492	346	522

*Values are the average of three specimens

**Values are the average of two specimens

***Values of the specimens incorporated in the averages above are shown in Table A.1 and A.2 in the Appendix

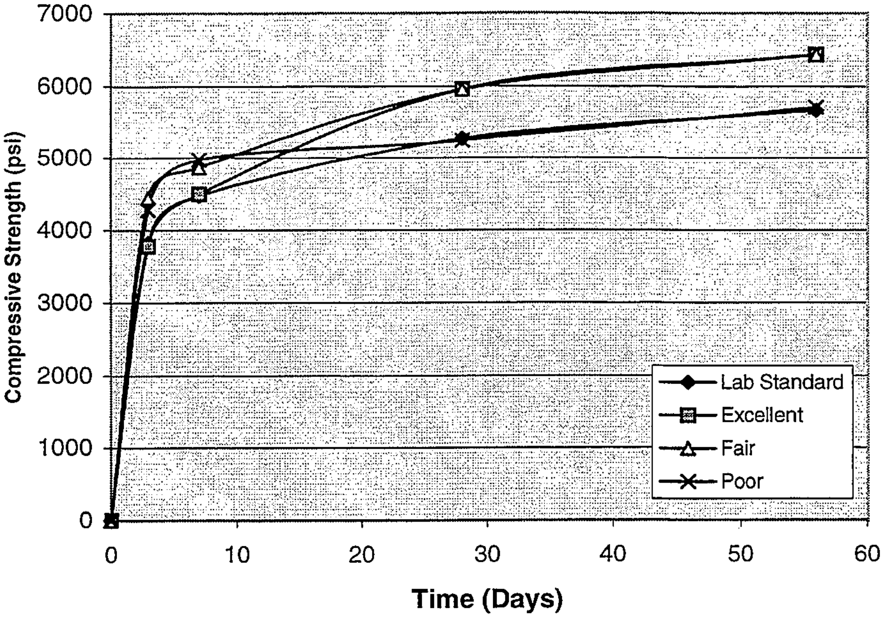


Figure 5.32 Compressive Strength for SCC-K at the Four Different Curing Conditions

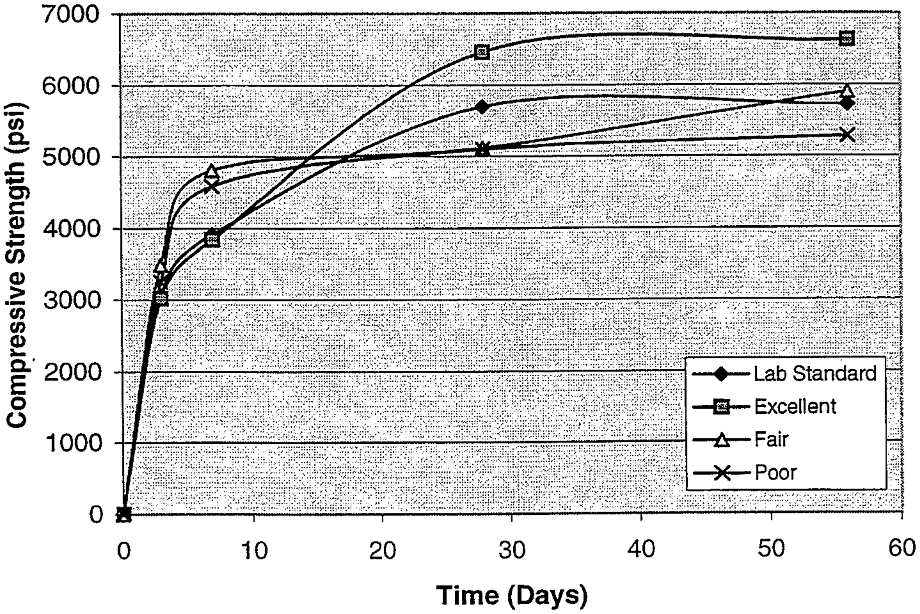


Figure 5.33 Compressive Strength for SCC-K/MS at the Four Different Curing Conditiions

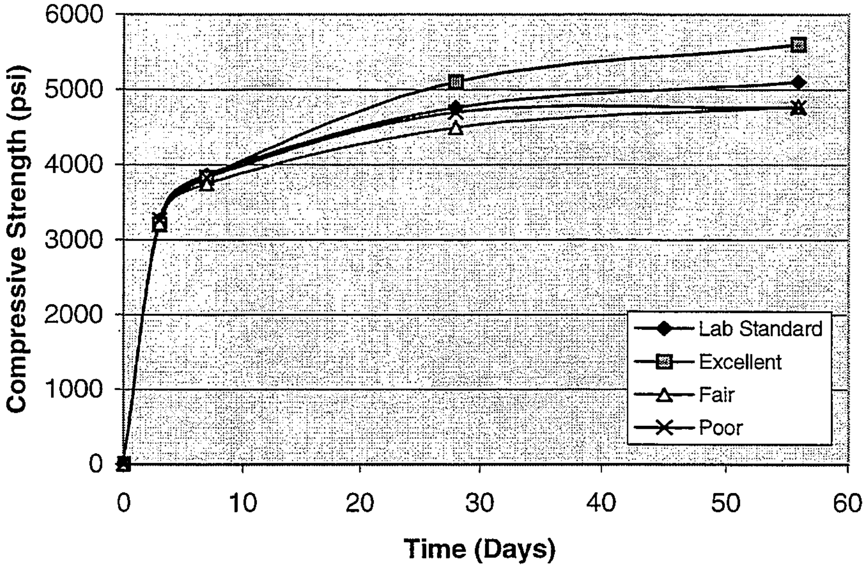


Figure 5.34 Compressive Strength for ALDOT-SRA at the Four Different Curing Conditions

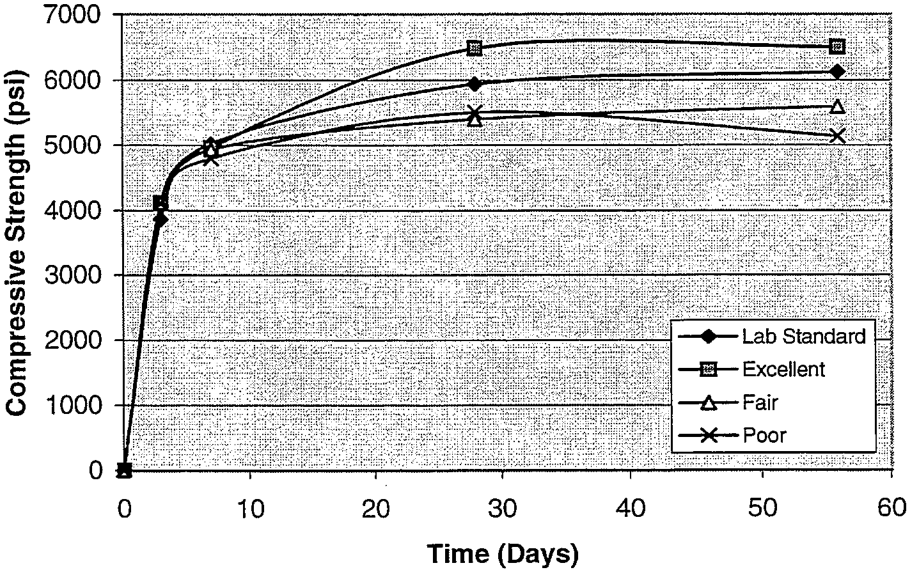


Figure 5.35 Compressive Strength for ALDOT (Control) at the Four Different Curing Conditions

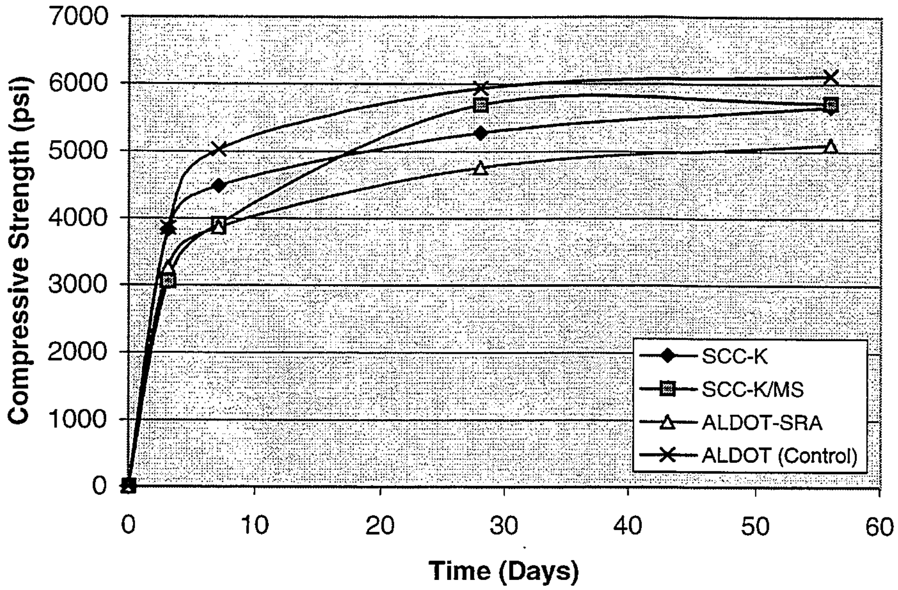


Figure 5.36 Compressive Strength for Lab Standard Curing Condition

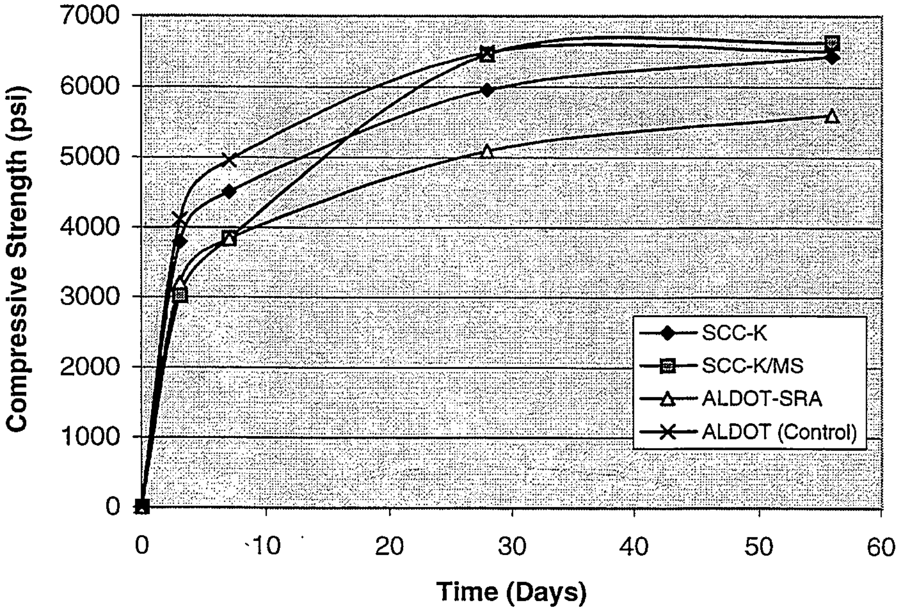


Figure 5.37 Compressive Stregth for Excellent Curing Condition

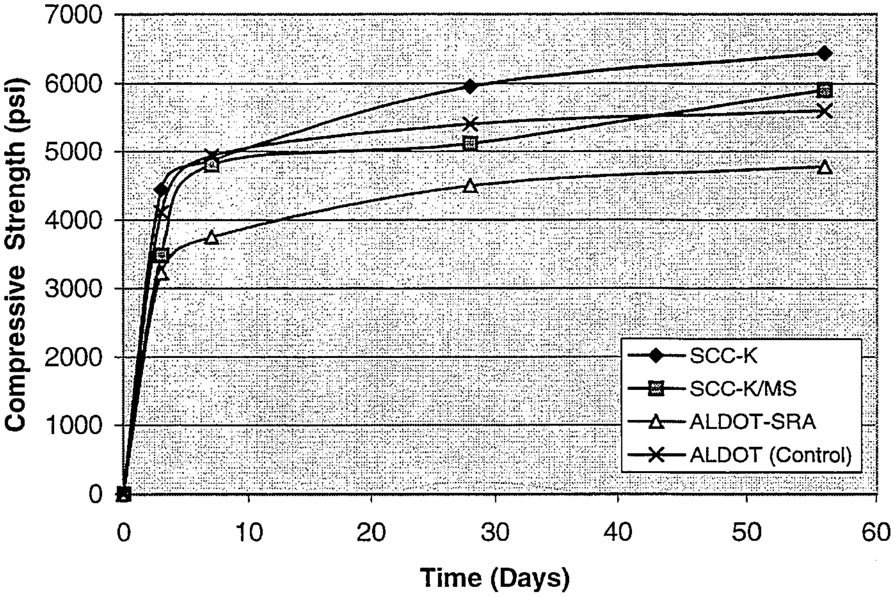


Figure 5.38 Compressive Strength for Fair Curing Condition

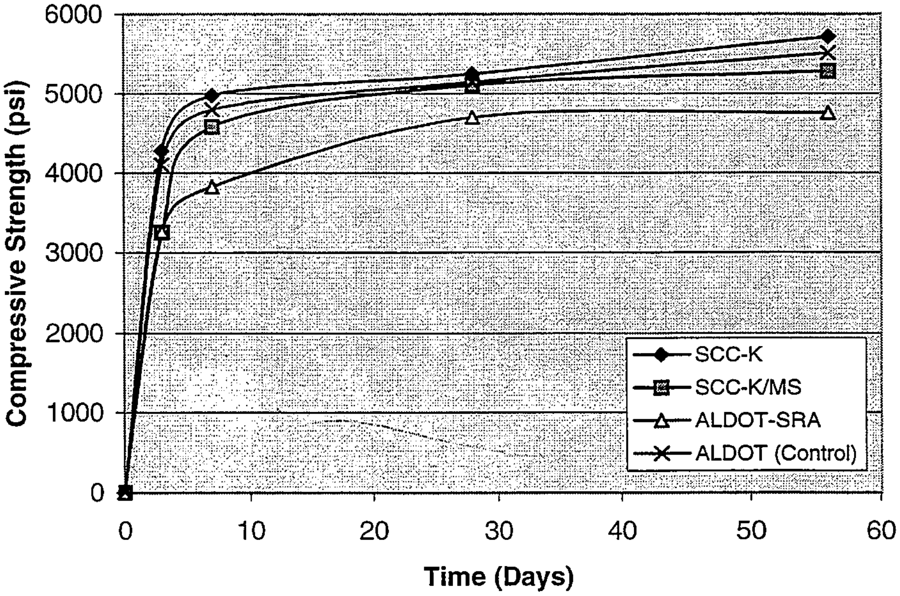


Figure 5.39 Compressive Strength at Poor Curing Conditions

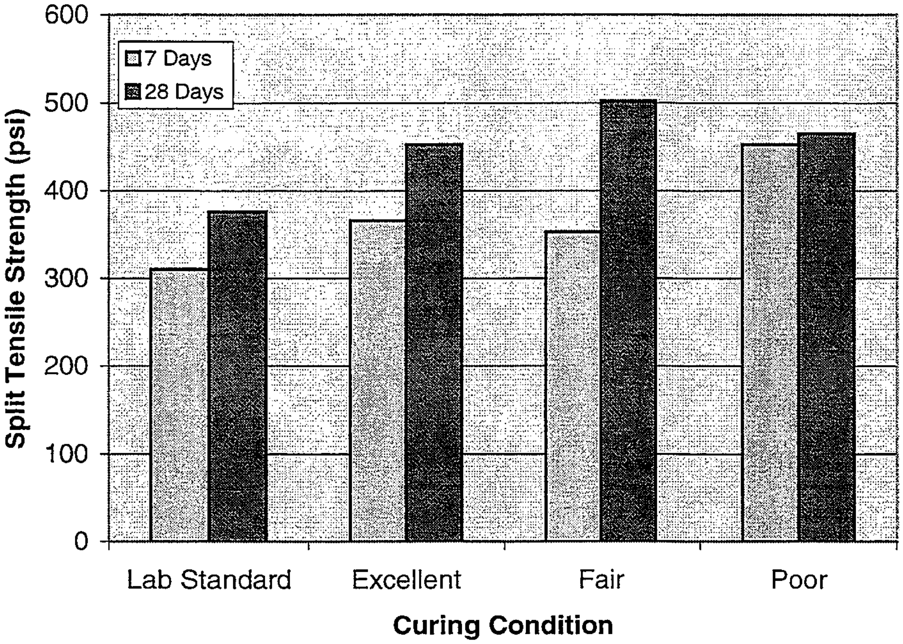


Figure 5.40 Split Tensile Strength for SCC-K

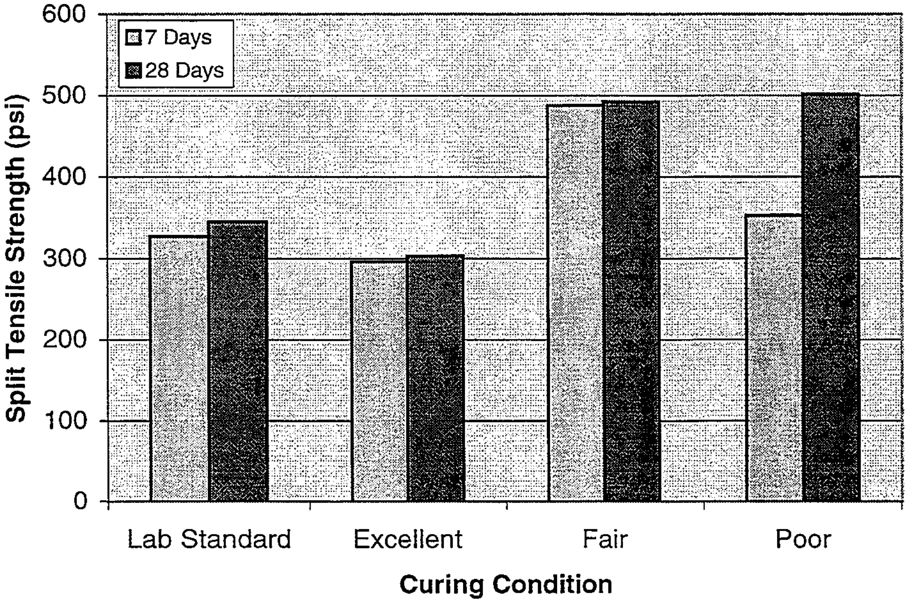


Figure 5.41 Split Tensile Strength for SCC-K/MS

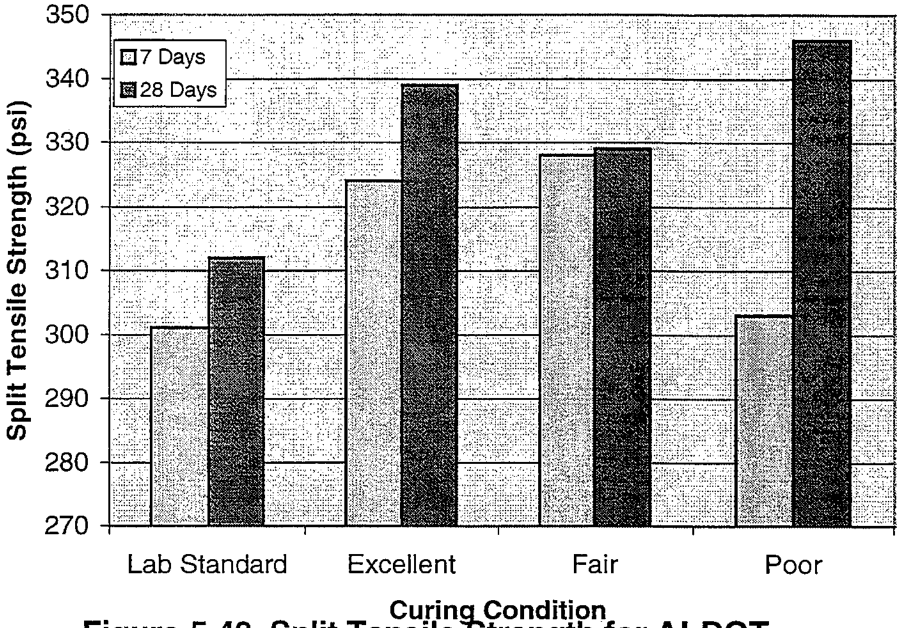


Figure 5.42 Split Tensile Strength for ALDOT-SRA

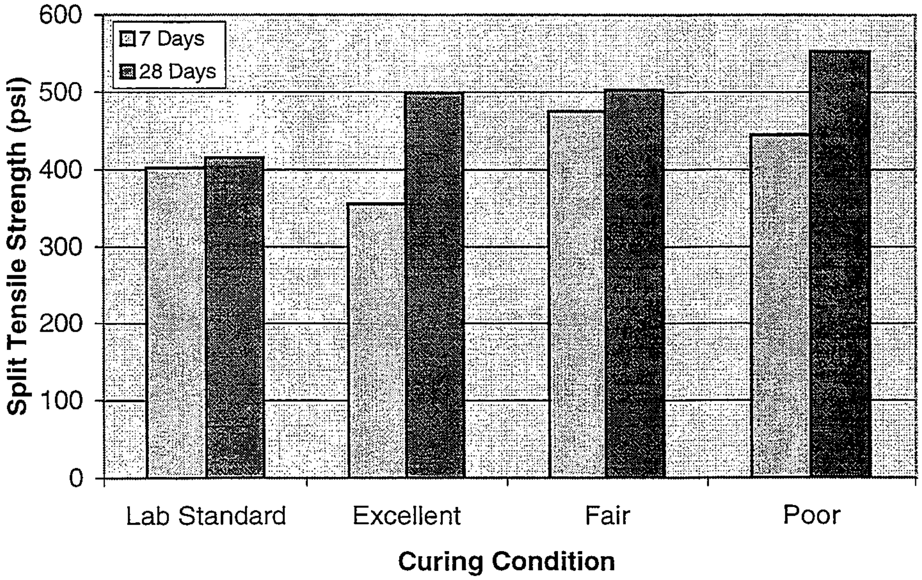


Figure 5.43 Split Tensile Strength for ALDOT (Control)

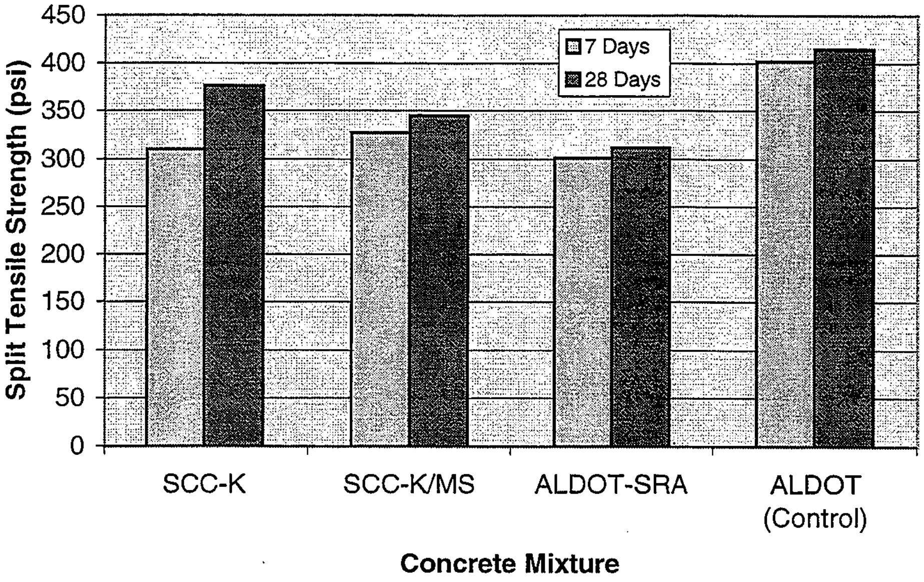


Figure 5.44 Split Tensile Strength for Lab Standard Curing Conditon

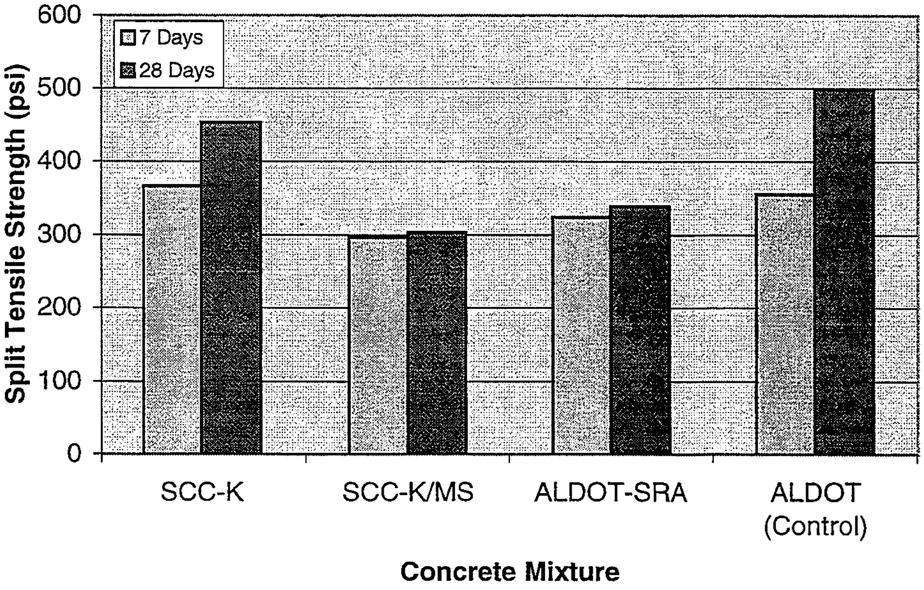


Figure 5.45 Split Tensile Strength for Excellent Curing Condition

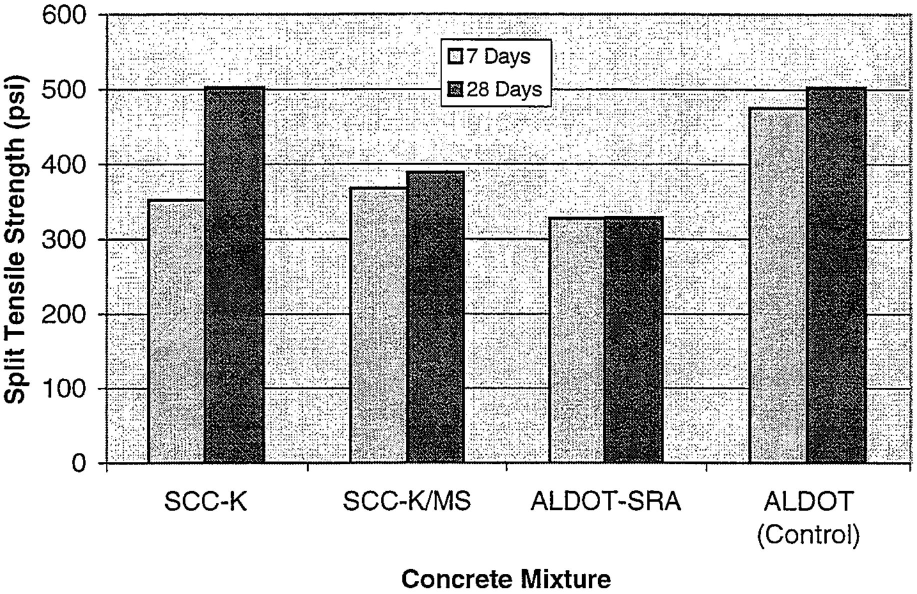


Figure 5.46 Split Tensile Strength for Fair Curing Condition

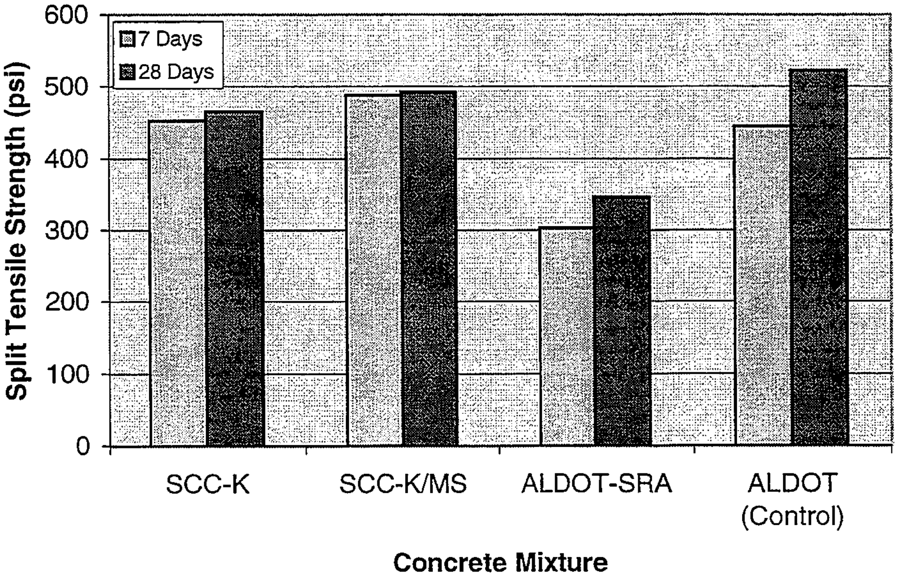


Figure 5.47 Split Tensile Strength for Poor Curing Condition

Table 5.8 Restrained Bar Shrinkage Results for the Four Concrete Mixtures at Each of the Four Different Curing Conditions.

Concrete Mixture	Curing Condition	% of Length Change @ 61 days[3]	Shrinkage Classification
SCC-K[1]	Lab Standard	.005	No Shrinkage
	Excellent	-.0015	No Shrinkage
	Fair	-.053	Moderate Shrinkage
	Poor	-.0415	Moderate Shrinkage
SCC-K/MS[2]	Lab Standard	-.032	Low Shrinkage
	Excellent	-.049	Moderate Shrinkage
	Fair	-.0755	Moderate Shrinkage
	Poor	-.077	Moderate Shrinkage
ALDOT-SRA	Lab Standard	-.029	Low Shrinkage
	Excellent	-.028	Low Shrinkage
	Fair	-.03	Low Shrinkage
	Poor	-.056	Moderate Shrinkage
ALDOT (Control)	Lab Standard	-.078	Moderate Shrinkage
	Excellent	-.064	Moderate Shrinkage
	Fair	-.082	High Shrinkage
	Poor	-.065	Moderate Shrinkage

[1] Test was terminated at 49 days.

[2] Test was terminated at 50 days.

[3] Values shown are the averages for two specimens.

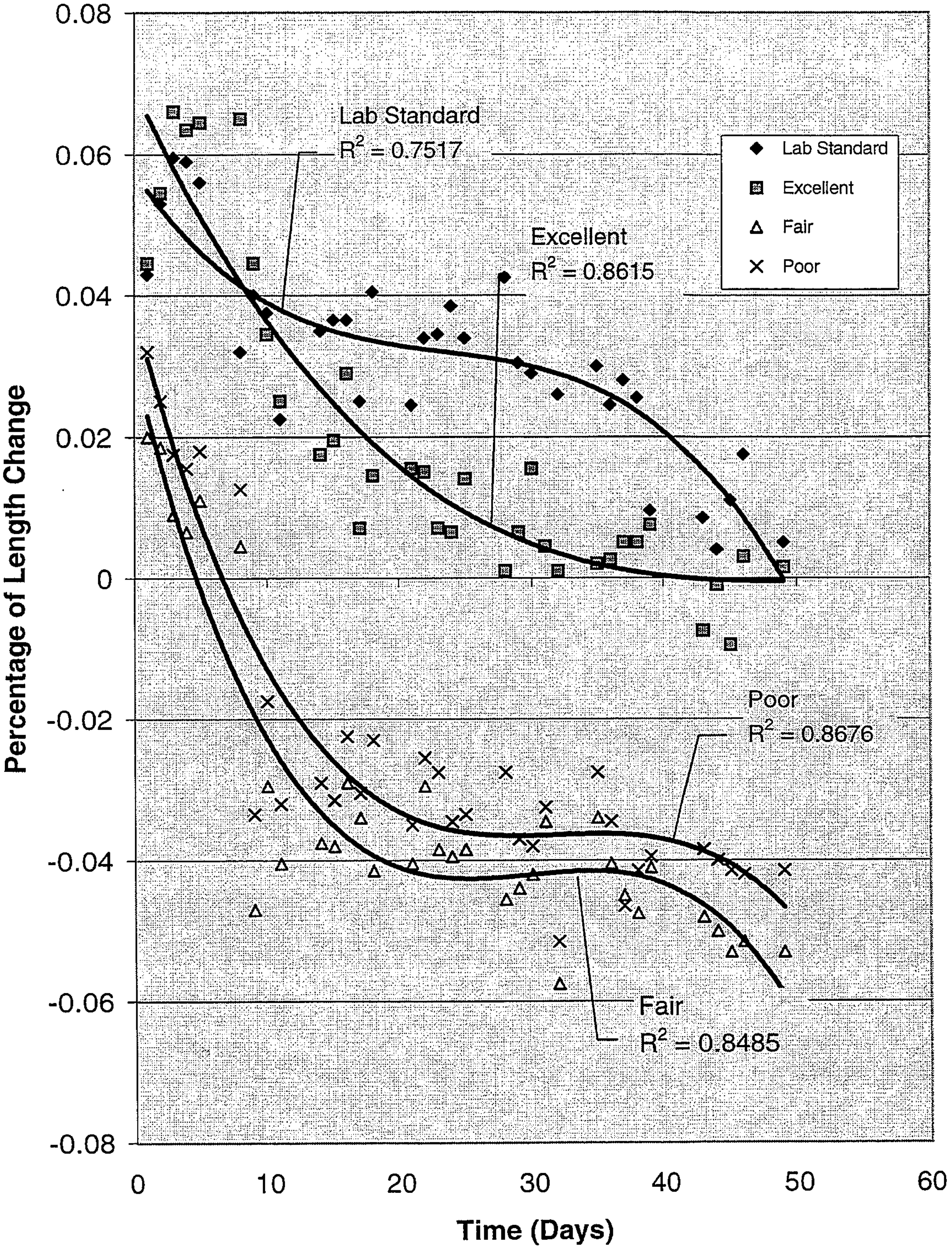


Figure 5.48 Restrained Bar Shrinkage Results from SCC-K Mixture at the Four Different Curing Conditions

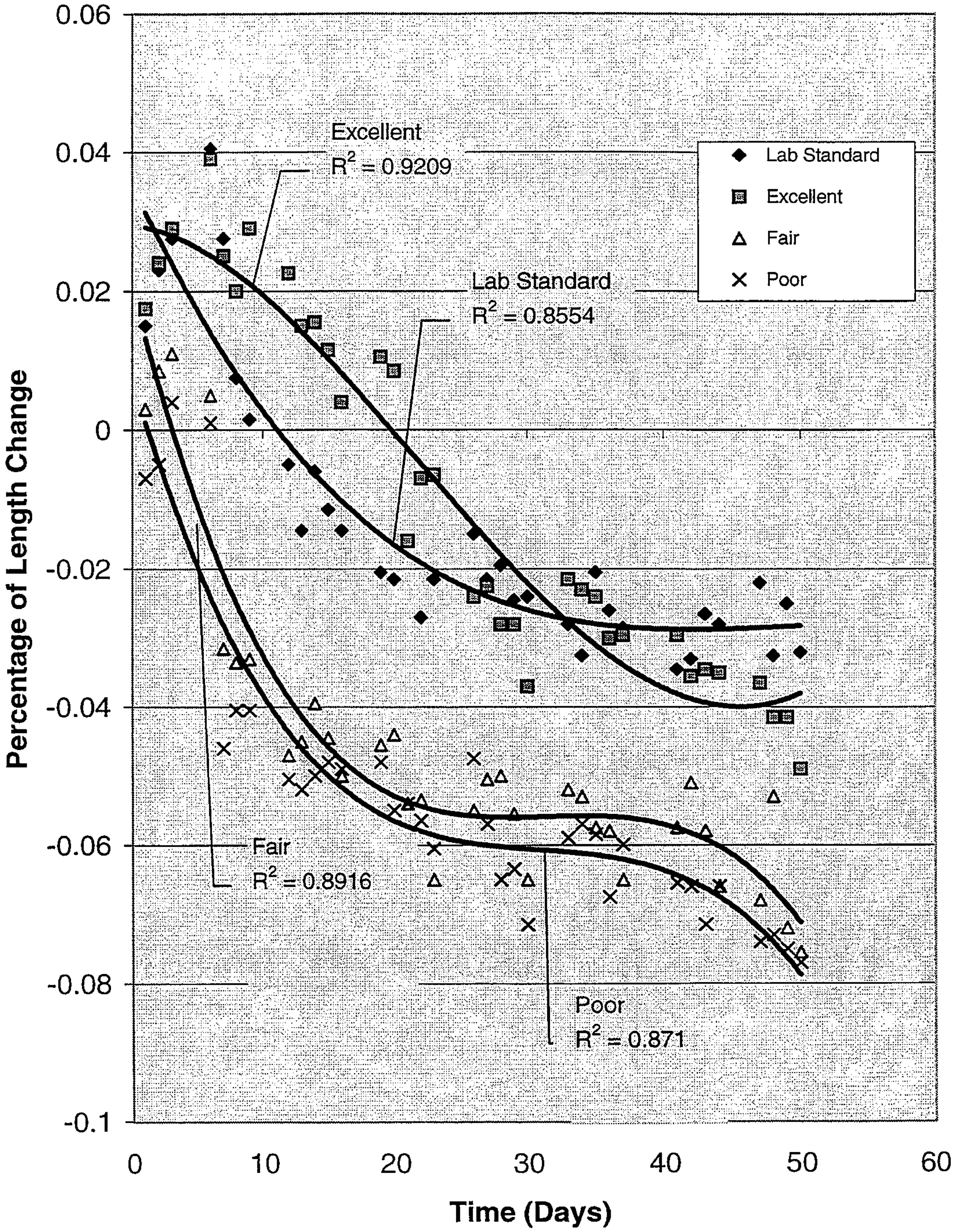


Figure 5.49 Restrained Bar Shrinkage Results from SCC-K/MS Mixture at the Four Different Curing Conditions

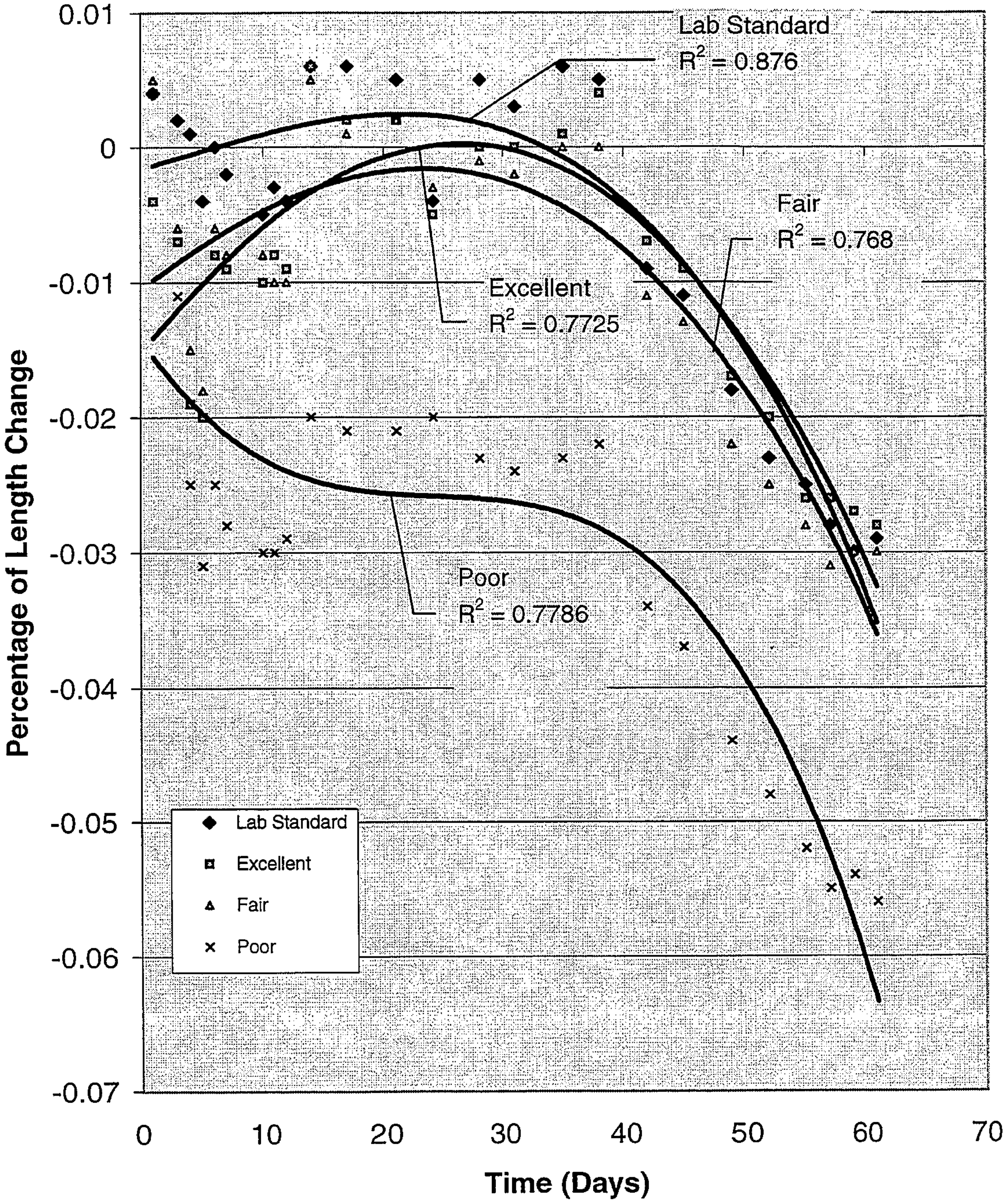


Figure 5.50 Restrained Bar Shrinkage Results from ALDOT-SRA Mixture at the Four Different Curing Conditions

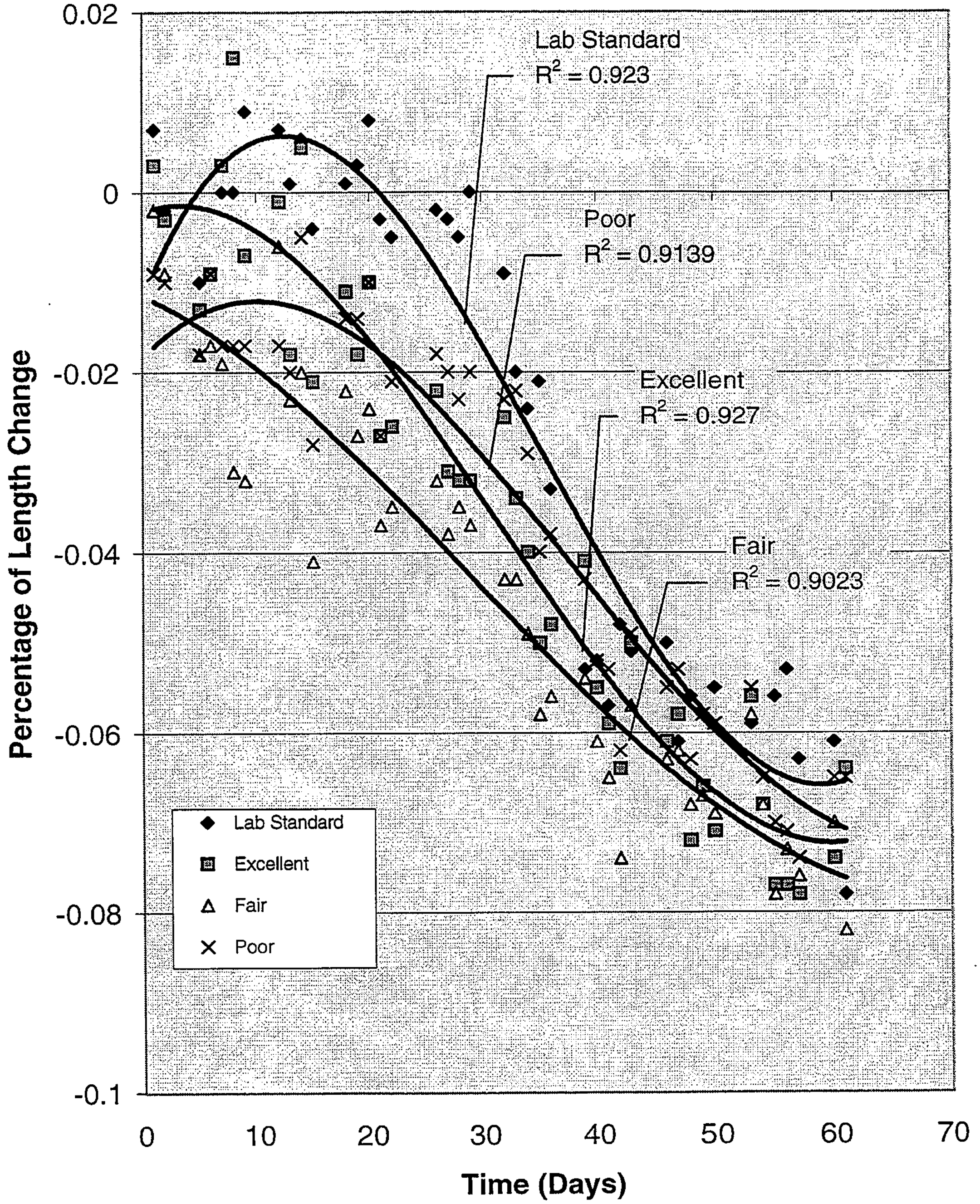


Figure 5.51 Restrained Bar Shrinkage Results from ALDOT (Control) Mixtrure at the Four Different Curing Conditions

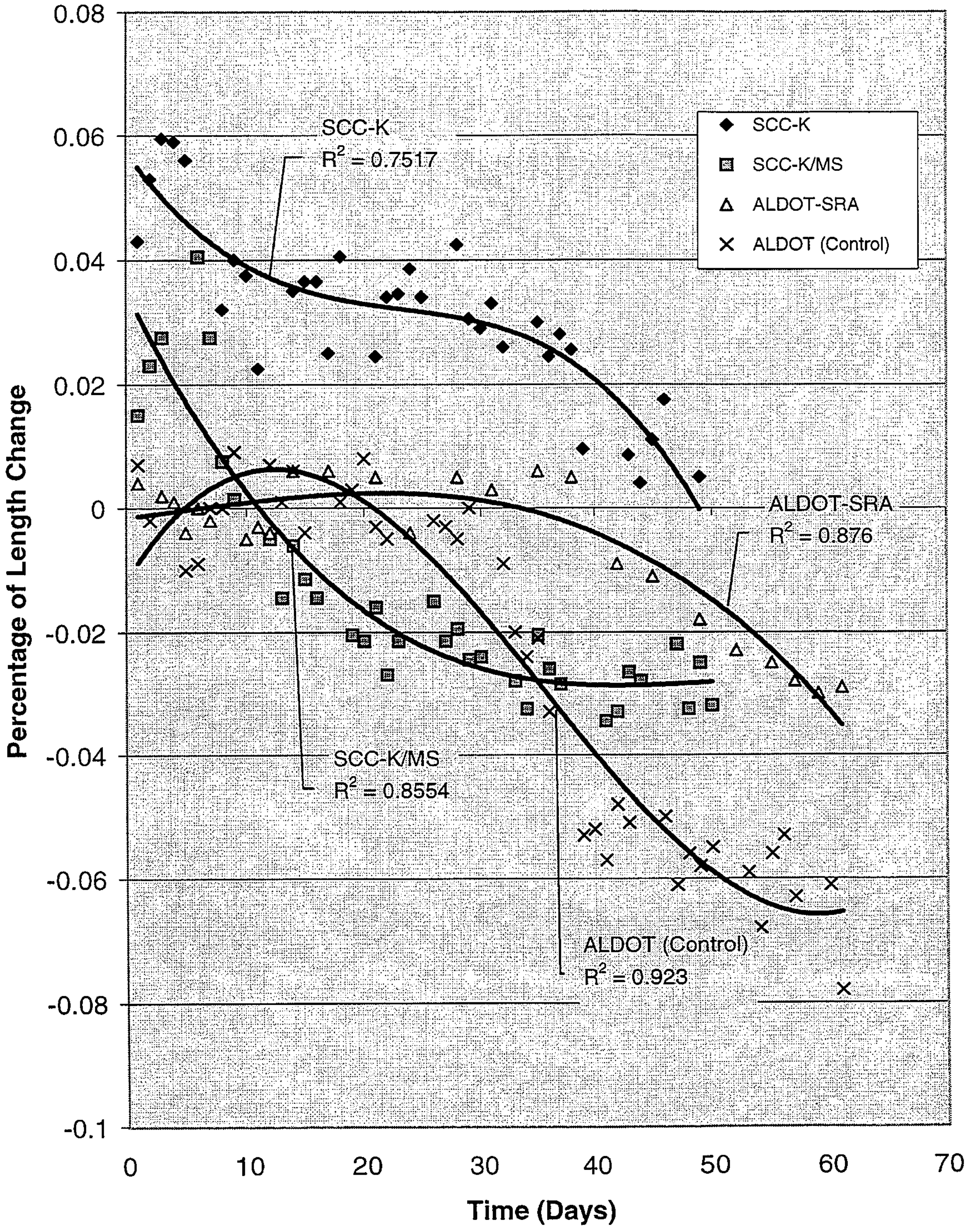


Figure 5.52 Restrained Bar Shrinkage Results for Lab Standard Curing Conditions

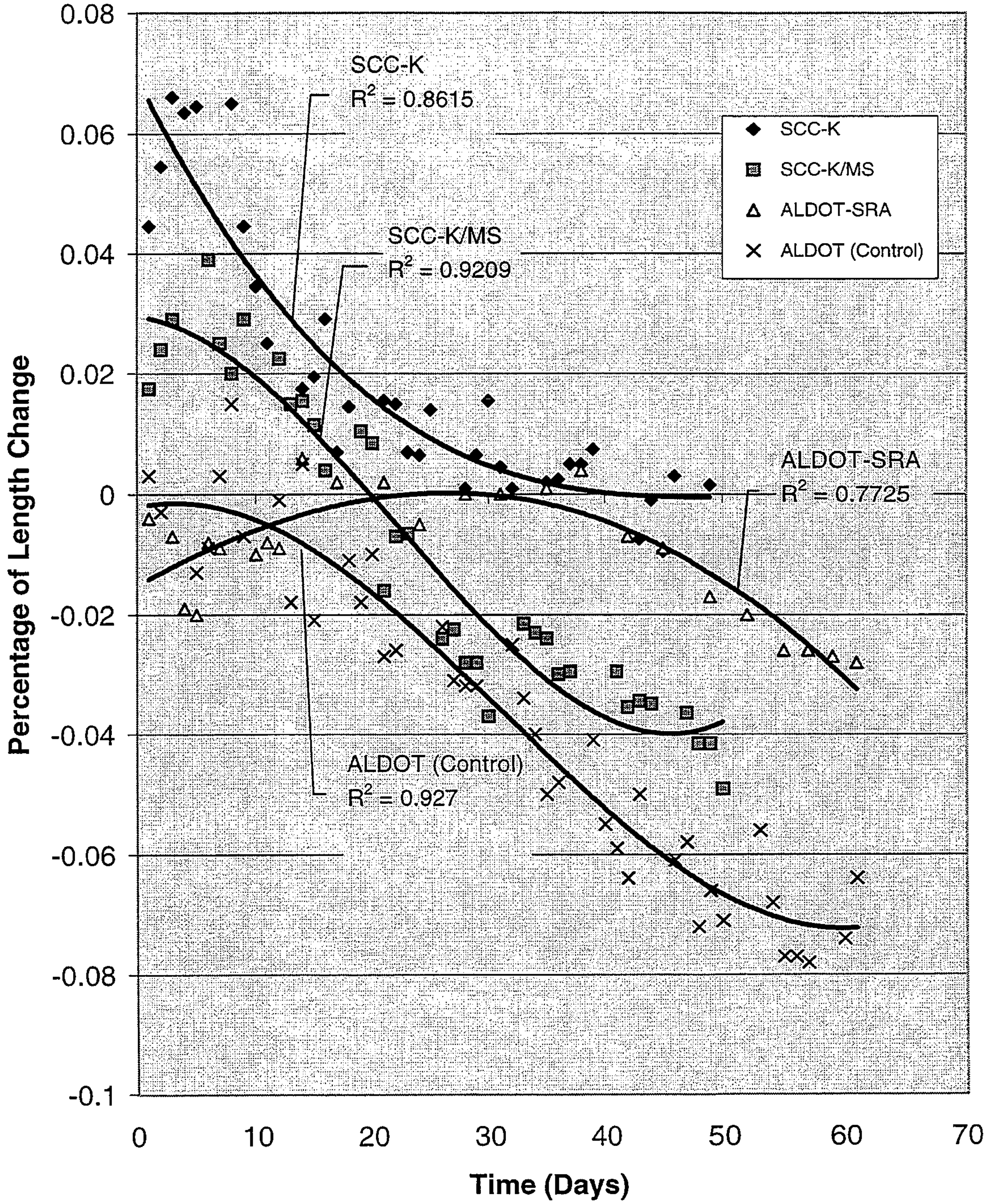


Figure 5.53 Restrained Bar Shrinkage Results for Excellent Curing Conditions

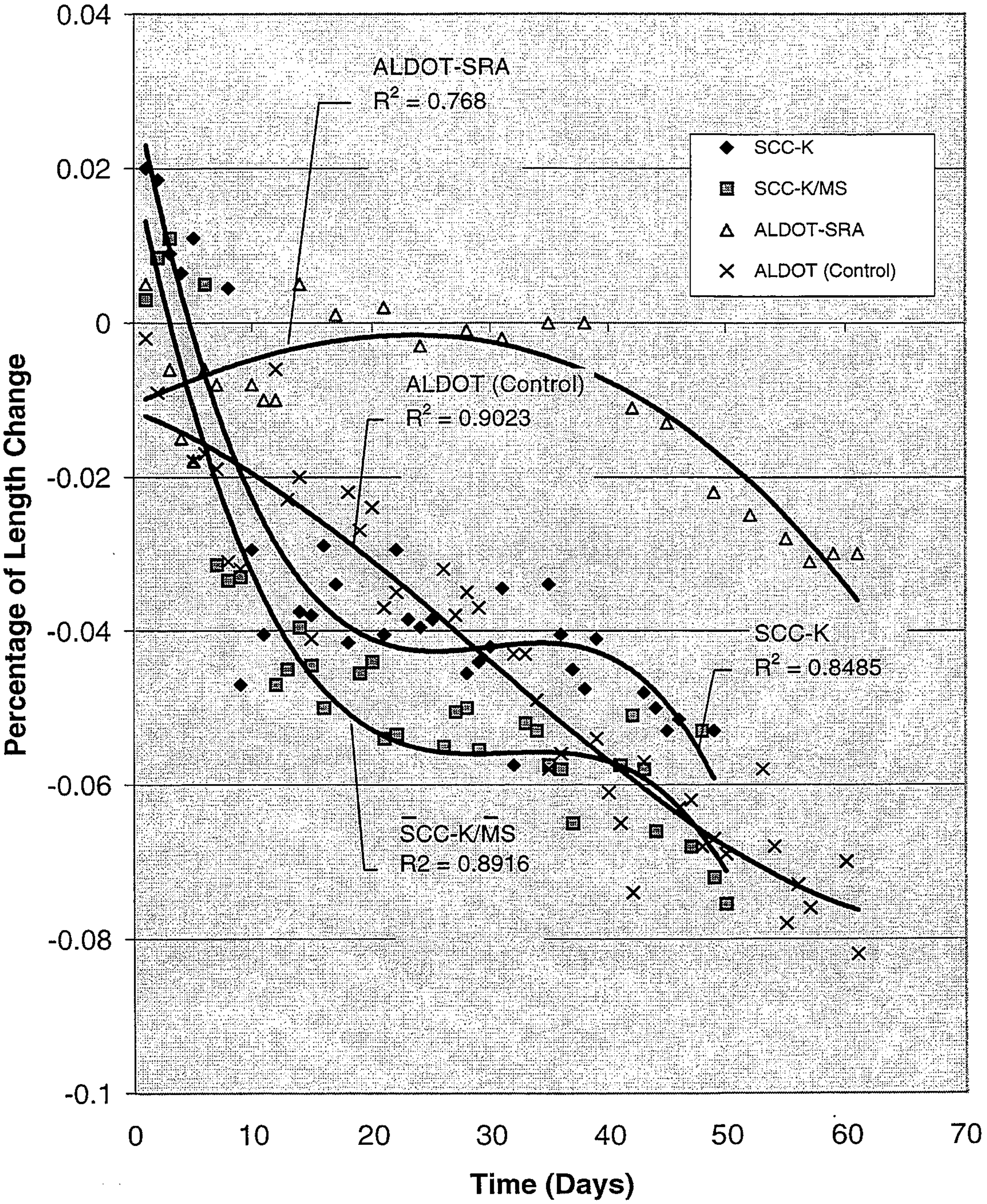


Figure 5.54 Restrained Bar Shrinkage Results for Fair Curing Conditions

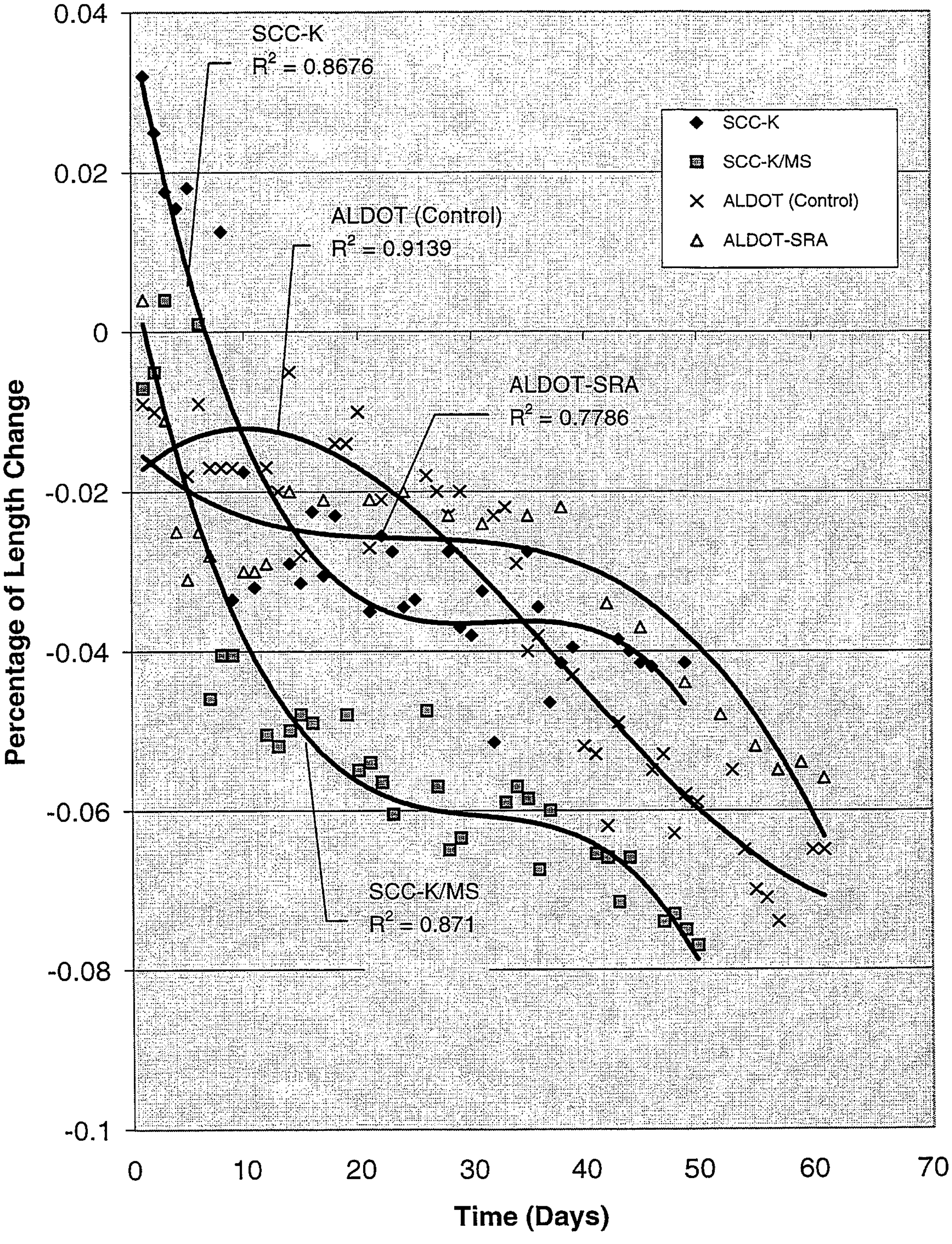


Figure 5.55 Restrained Bar Shrinkage Results for Poor Curing Conditions

Table 5.9 Unrestrained Bar Shrinkage Results for the Four Concrete Mixtures at Each of the Four Different Curing Conditions.

Concrete Mixture	Curing Condition	% of Length Change @ 61 days[1]	Shrinkage Classification
SCC-K	Lab Standard	-.017	Low Shrinkage
	Excellent	-..009	Low Shrinkage
	Fair	-.051	Moderate Shrinkage
	Poor	-.045	Moderate Shrinkage
SCC-K/MS	Lab Standard	-.014	Low Shrinkage
	Excellent	-.011	Low Shrinkage
	Fair	-.059	Moderate Shrinkage
	Poor	-.062	Moderate Shrinkage
ALDOT-SRA	Lab Standard	-.029	Low Shrinkage
	Excellent	-.031	Low Shrinkage
	Fair	-.064	Moderate Shrinkage
	Poor	-.075	Moderate Shrinkage
ALDOT (Control)	Lab Standard	-.052	Moderate Shrinkage
	Excellent	-.063	Moderate Shrinkage
	Fair	-.076	Moderate Shrinkage
	Poor	-.0865	High Shrinkage

[1] Values shown are the averages for two specimens.

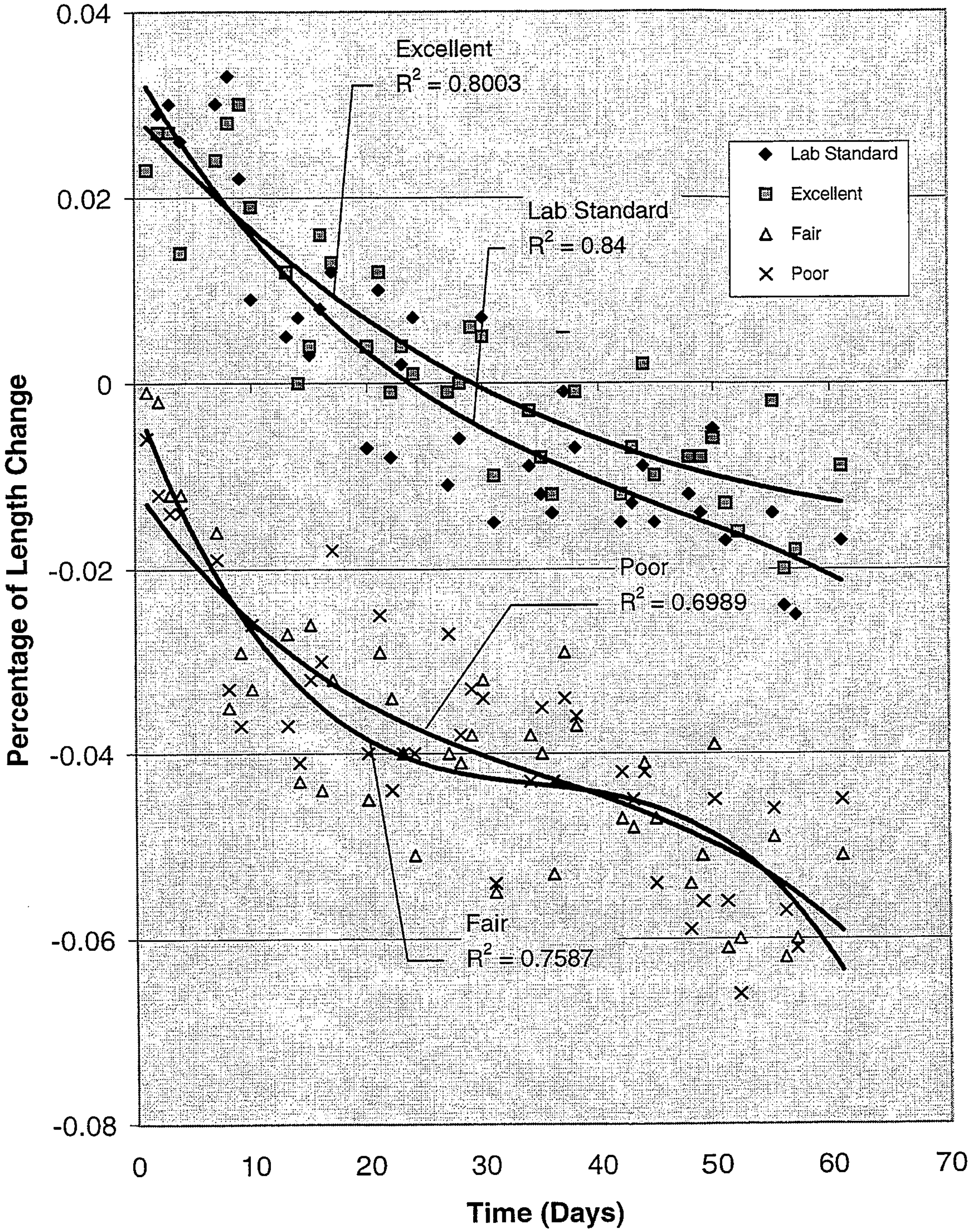


Figure 5.56 Unrestrained Bar Shrinkage Results from SCC-K Mixture at the Four Different Curing Conditions

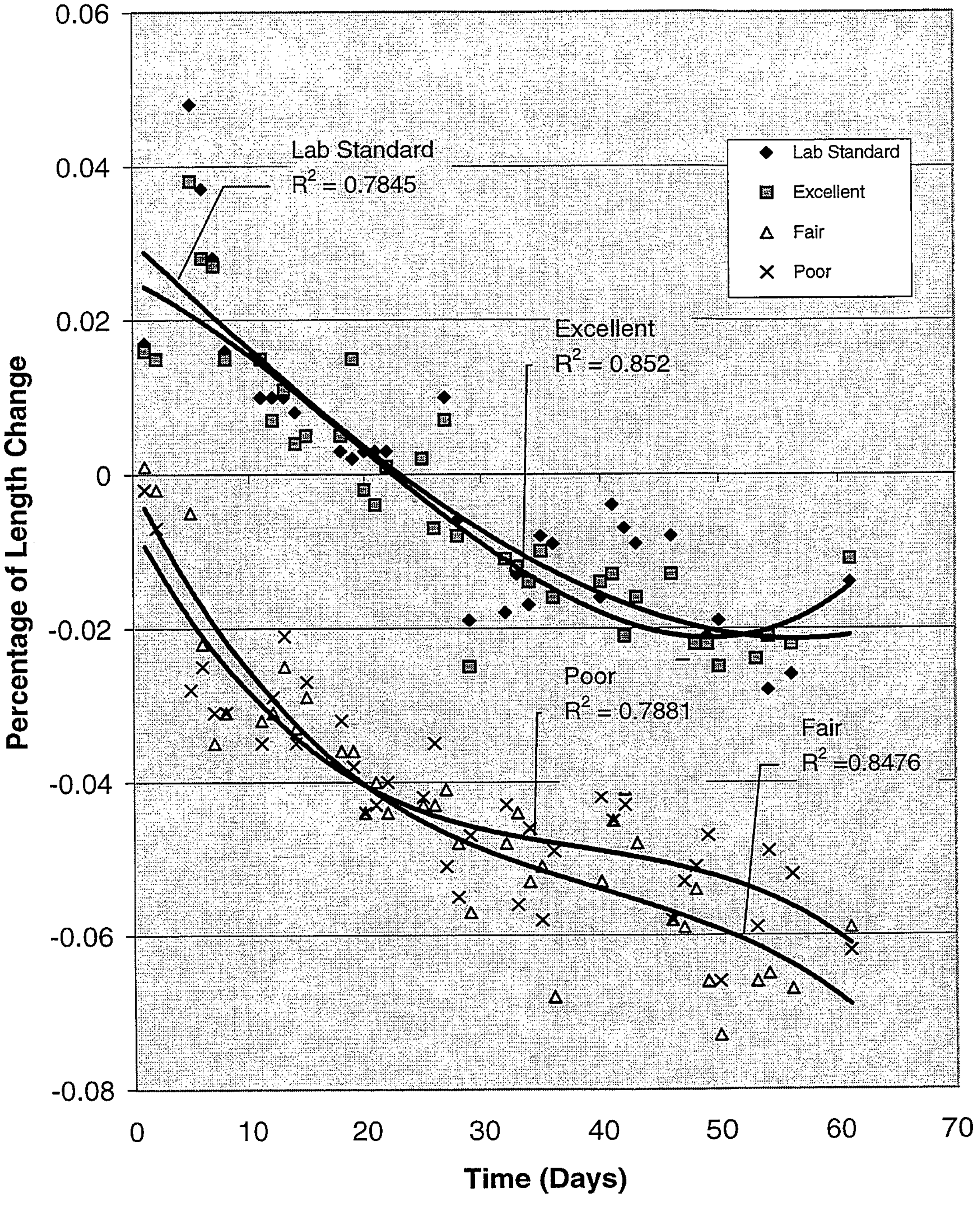


Figure 5.57 Unrestrained Bar Shrinkage Results from SCC-K/MS Mixture at the Four Different Curing Conditions

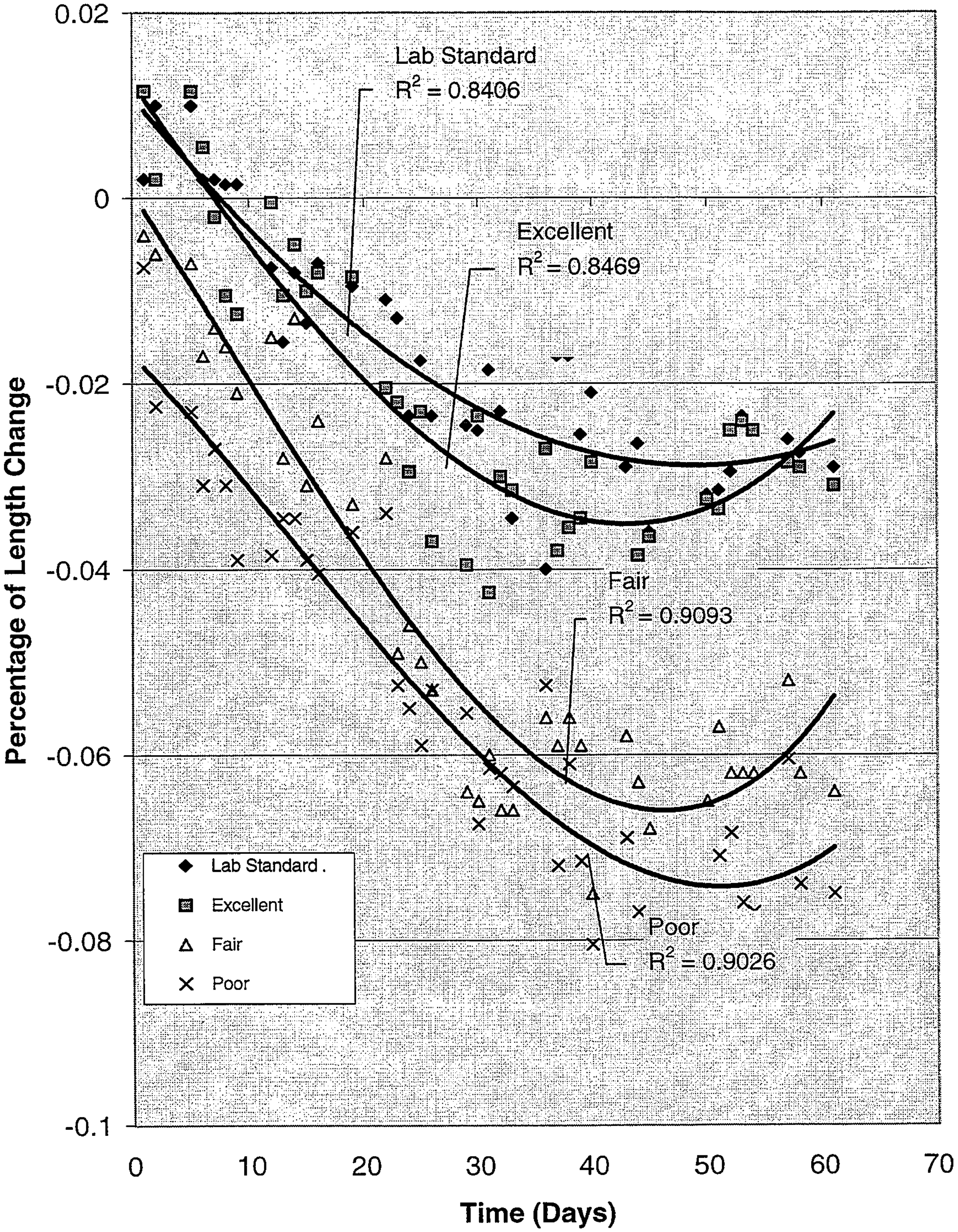


Figure 5.58 Unrestrained Bar Shrinkage Results from ALDOT-SRA Mixture at the Four Different Curing Conditions

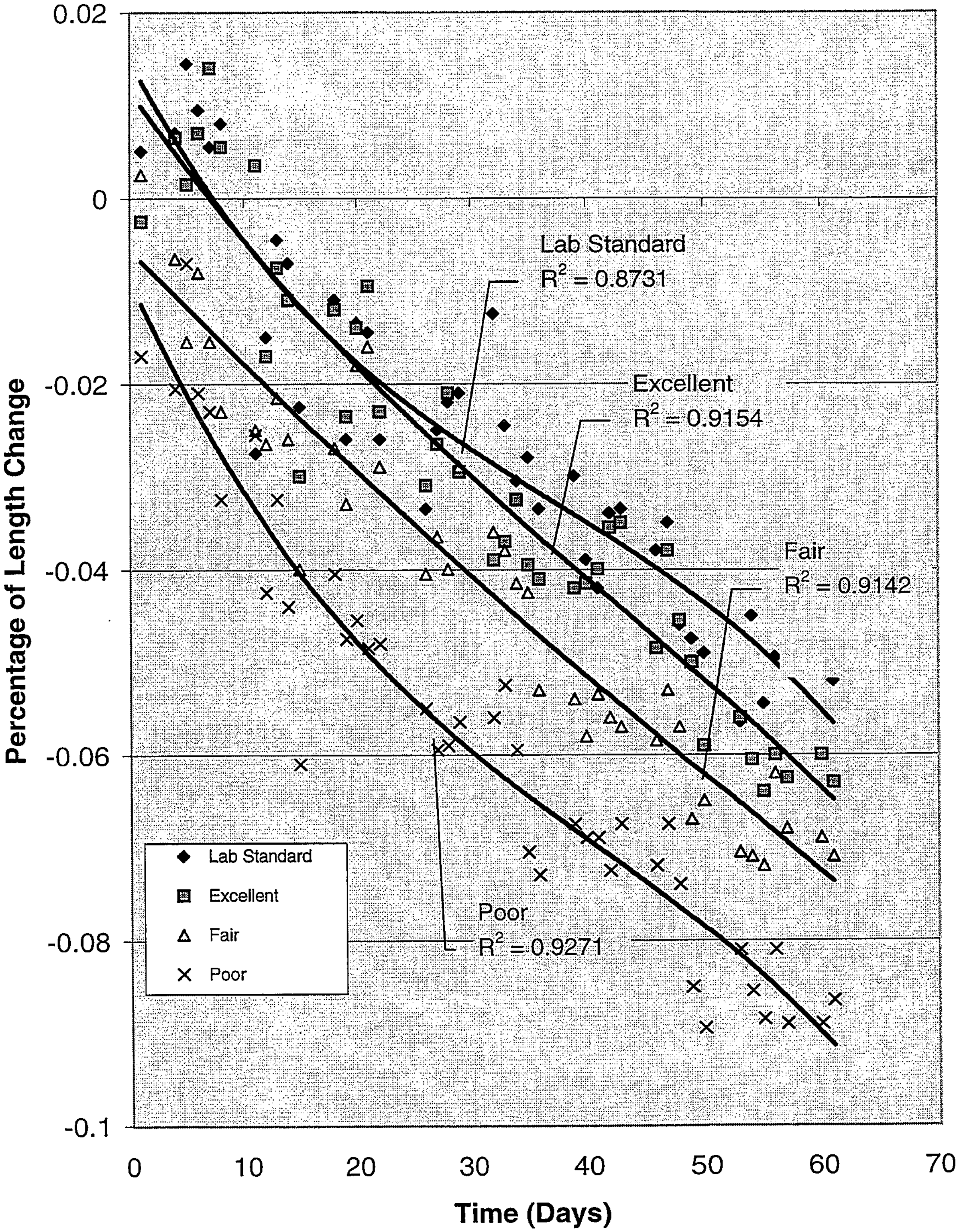


Figure 5.59 Unrestrained Bar Shrinkage Results from ALDOT (Conrol) Mixture at the Four Different Curing Conditions

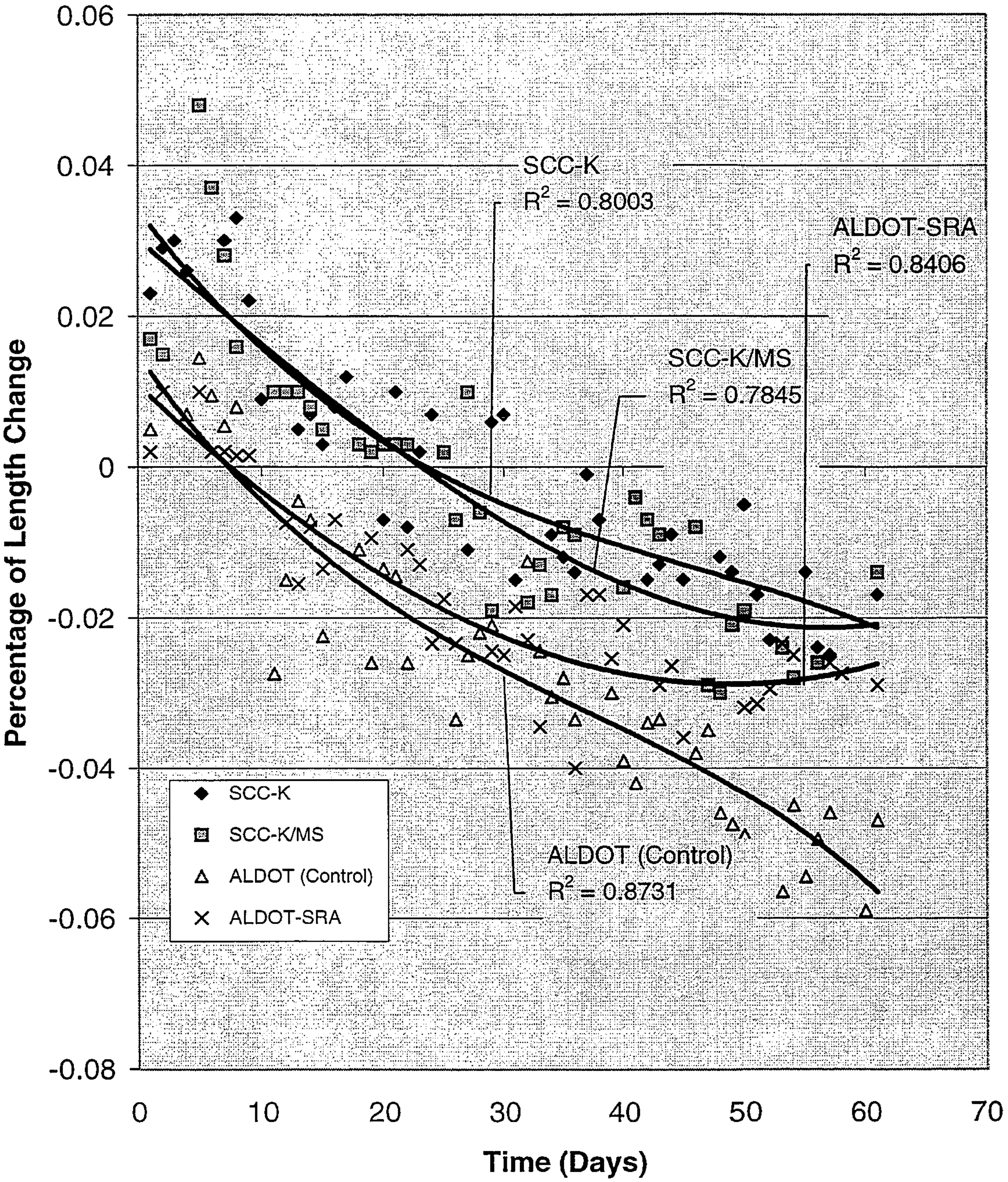


Figure 5.60 Unrestrained Bar Shrinkage Results for Concrete Mixtures Cured at Lab Standard Curing Conditon

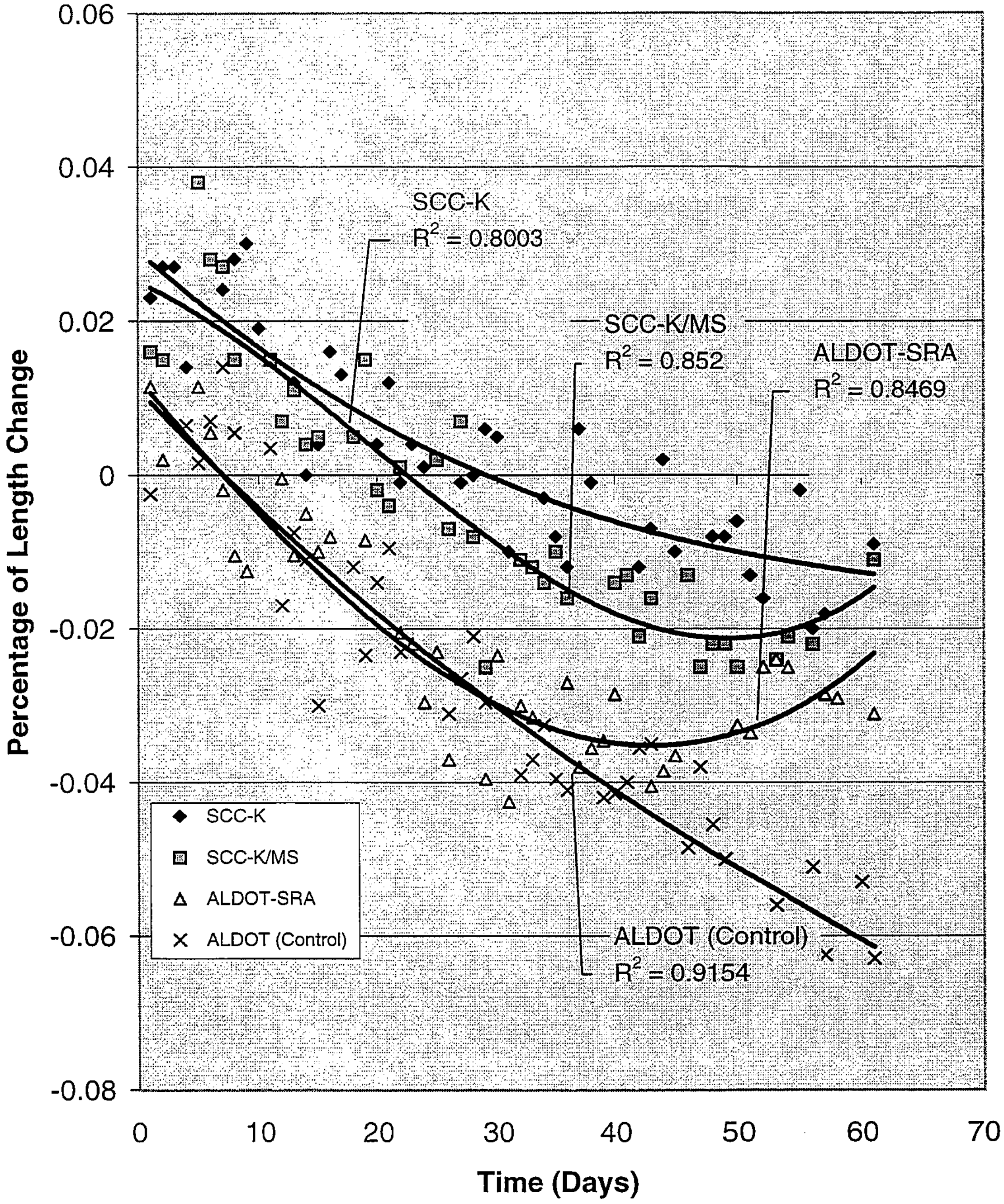


Figure 5.61 Unrestrained Bar Shrinkage Results for Concrete Mixtures Cured at Excellent Curing Conditon

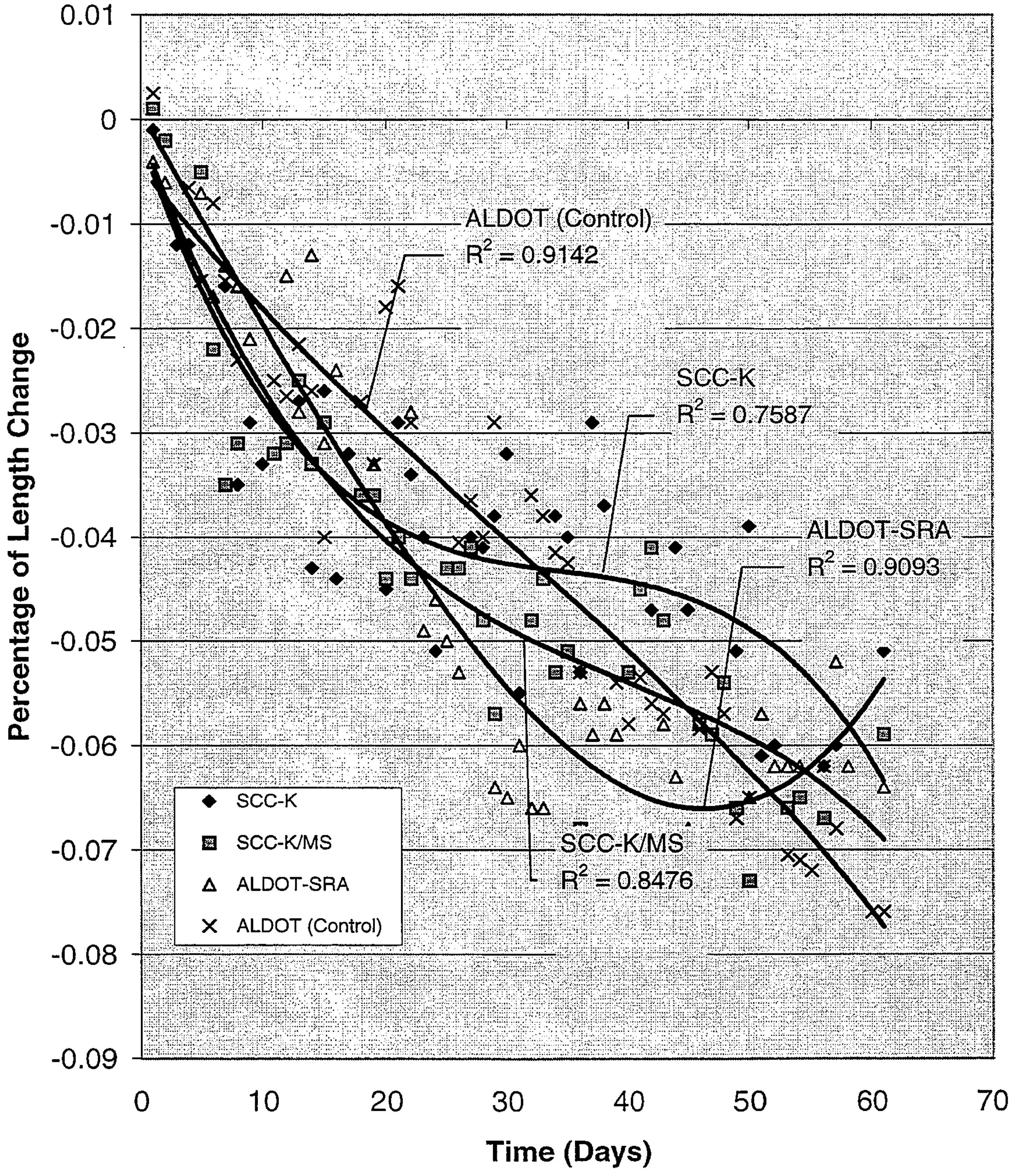


Figure 5.62 Unrestrained Bar Shrinkage Results for Concrete Mixtures Cured at Fair Curing Conditon

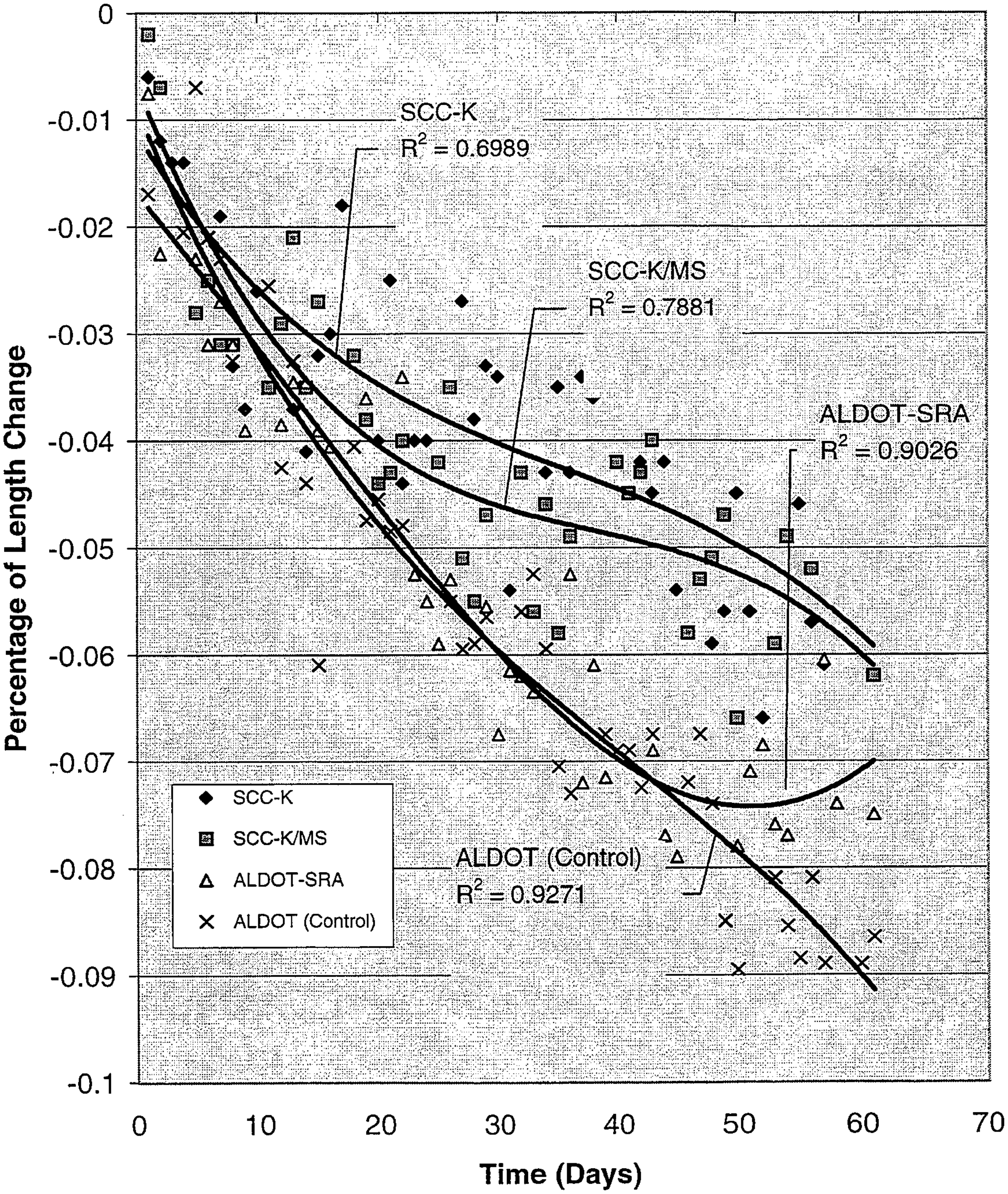


Figure 5.63 Unrestrained Bar Shrinkage Results for Concrete Mixtures Cured at Poor Curing Conditon

Table 5.10 Elastic Modulus Results for Concrete Mixtures at Lab Standard Curing Condition.

Days	Elastic Modulus[1]			
	SCC-K (psi)	SCC-K/MS (psi)	ALDOT-SRA (psi)	ALDOT (Control) (psi)
7	3,850,000	4,550,000	4,400,000	5,150,000
28	4,100,000	4,100,000	4,700,000	5,250,000
56	4,000,000	4,000,000	4,950,000	4,850,000

[1] Values shown are the average for two specimens

*Values of the specimens incorporated in the averages above are shown in Table A.3 in the Appendix

Table 5.11 Freeze-Thaw Durability Results for Concrete Mixtures.[1]

Concrete Mixture	Initial Frequency (Hz)	Final Frequency (Hz)	Durability Factor (%)
SCC-K	2025	1960	93.68
SCC-K/MS	2005	1970	96.54
ALDOT-SRA	2155	2075	92.7
ALDOT (Control)	2105	2060	95.77

[1] Values shown are the average for two specimens

*Values of the specimens incorporated in the averages above are shown in Table A.4 in the Appendix

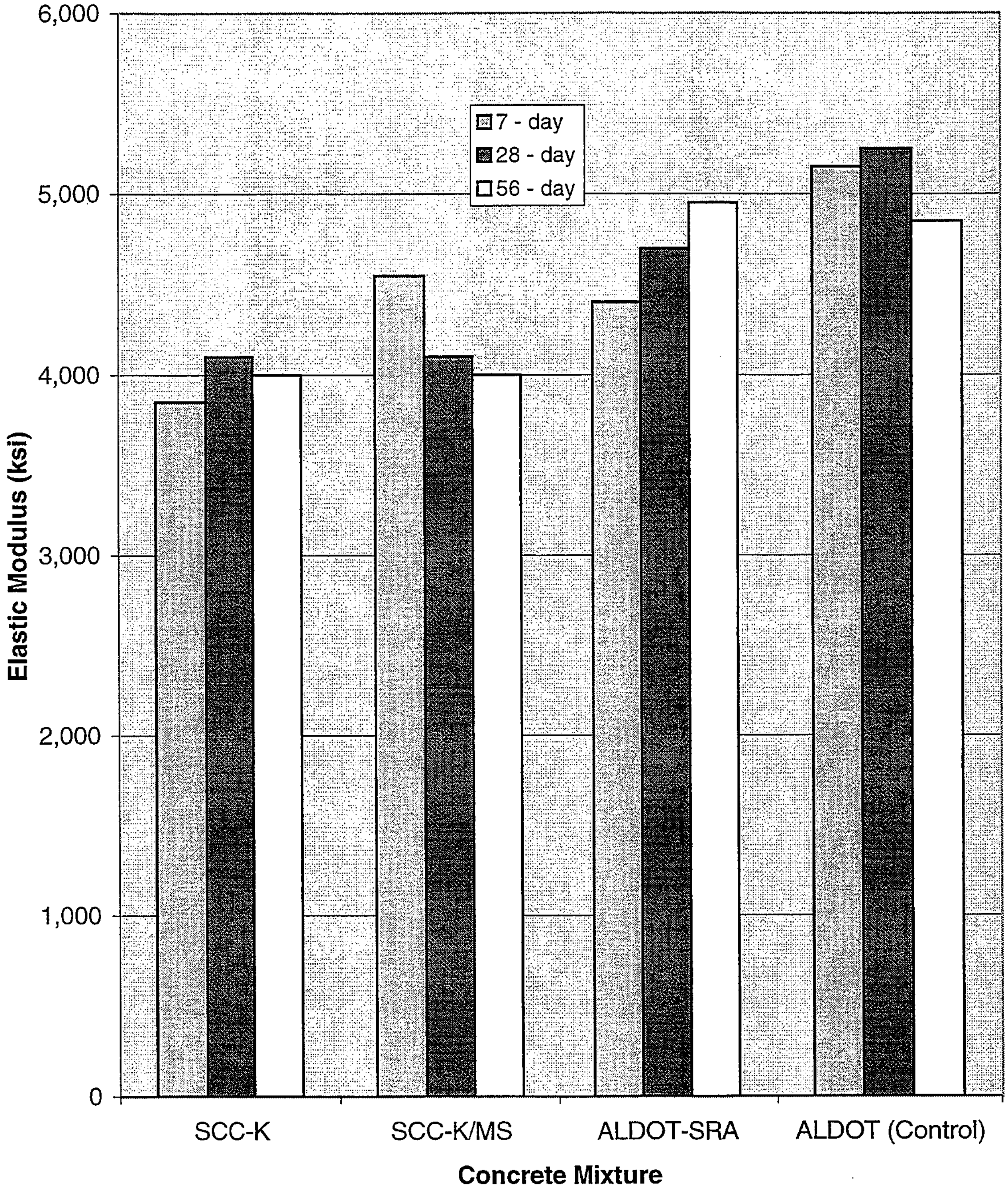


Figure 5.64 Elasitic Modulus at Lab Standard Curing Condition

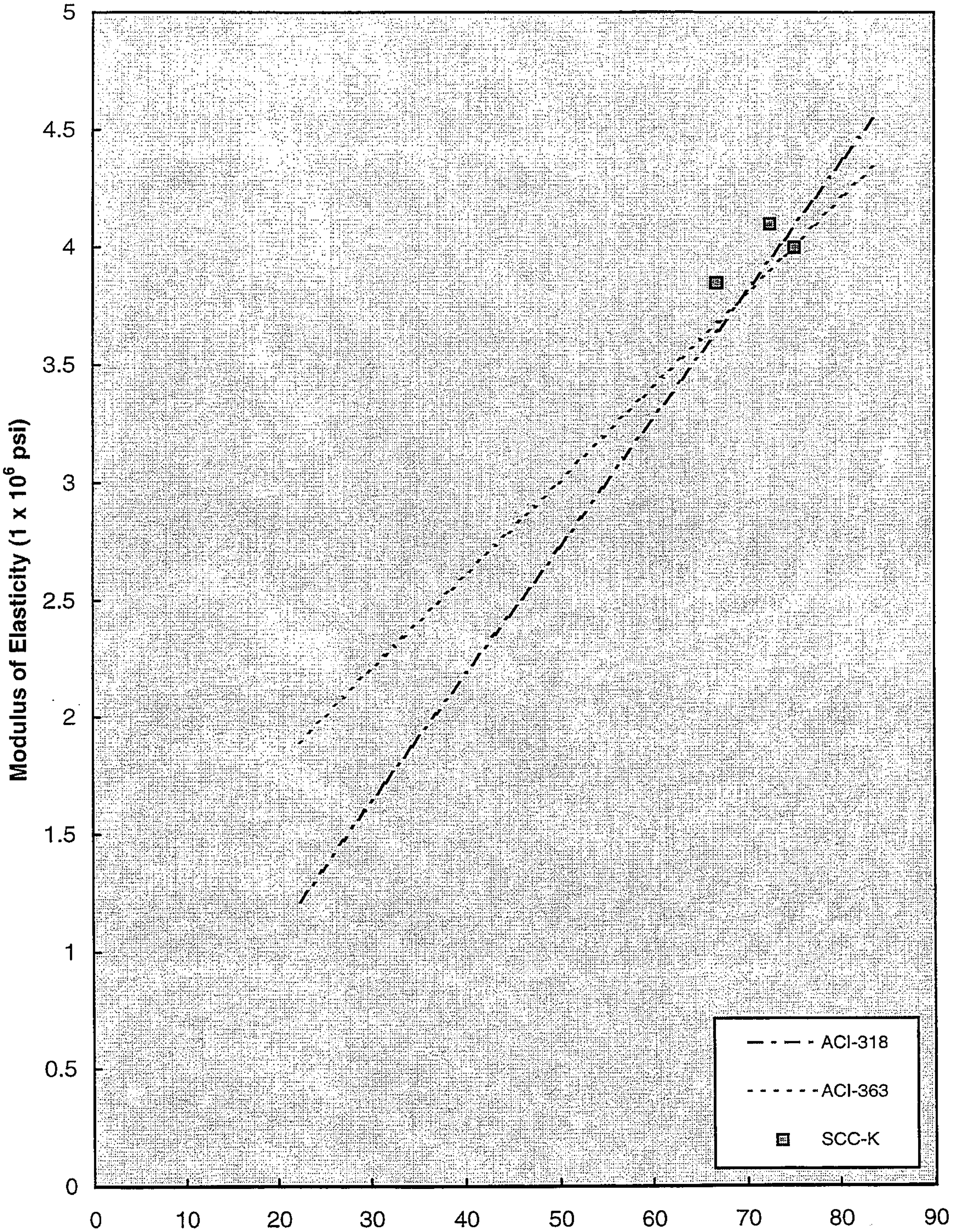


Figure 5.65 Comparison of Modulus of Elasticity Results of SCC-K Mixture with ACI-318 and ACI-363

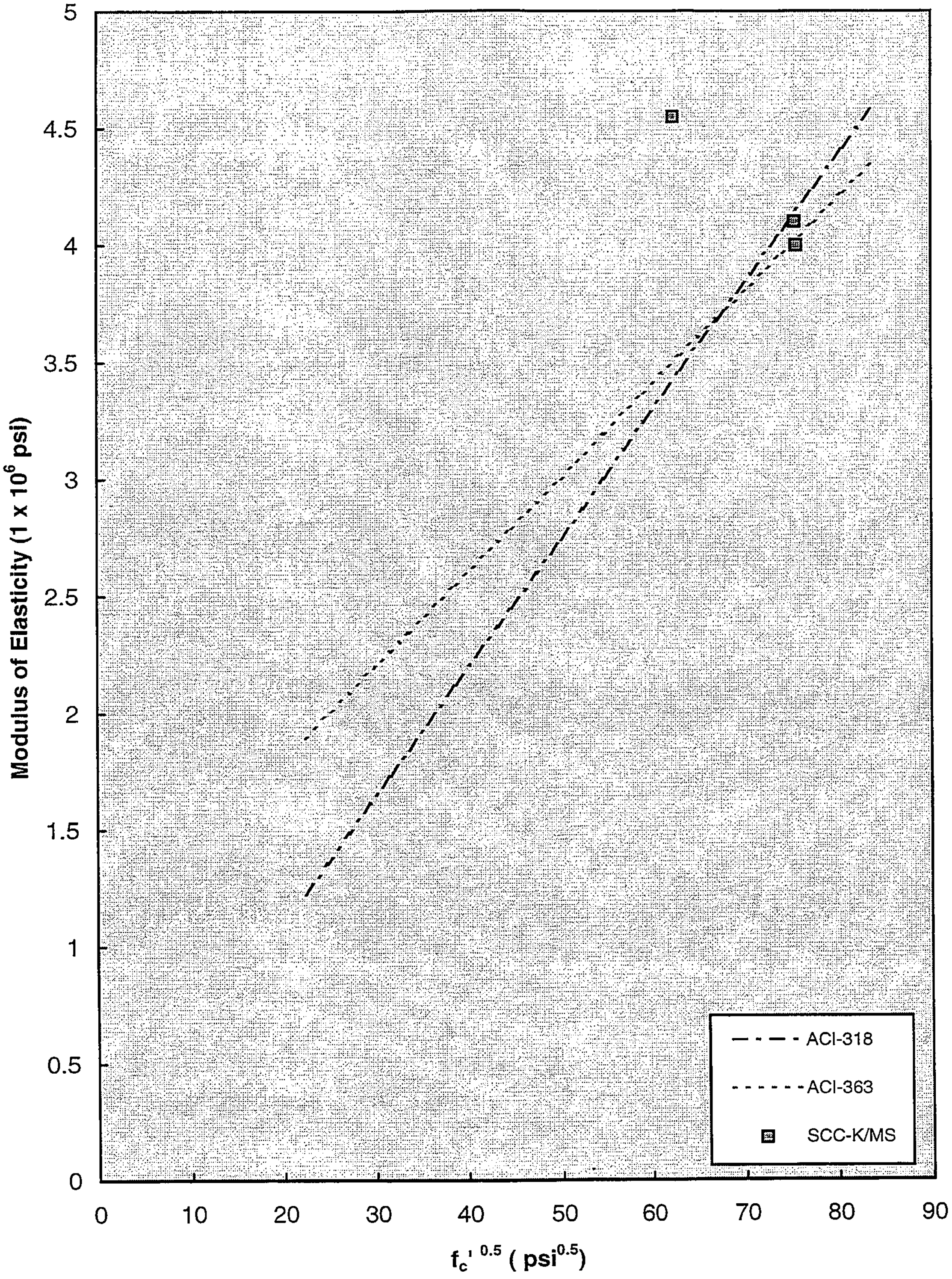


Figure 5.66 Comparison of Modulus of Elasticity Results of SCC-K/MS Mixture with ACI-318 and ACI-363

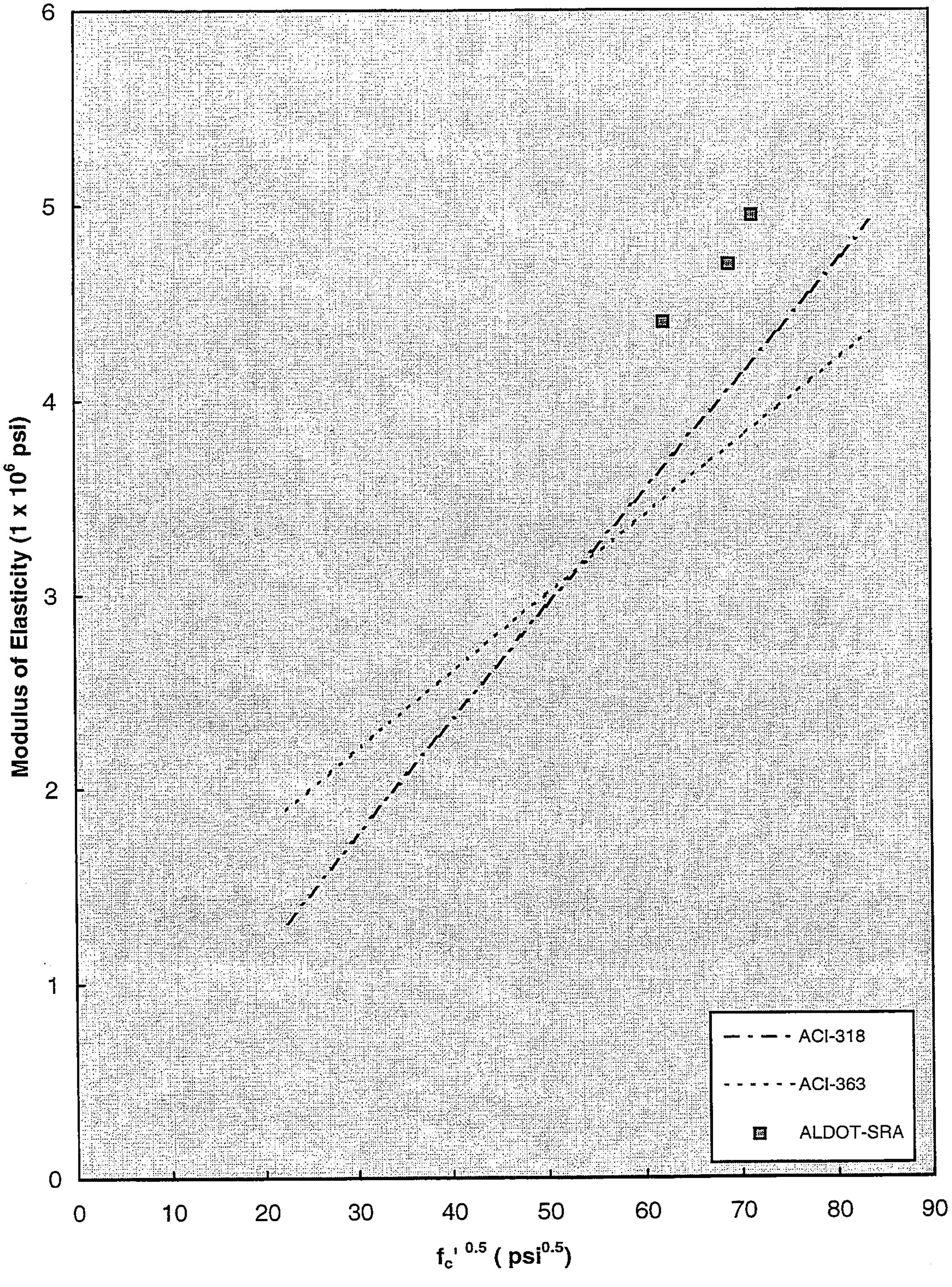


Figure 5.67 Comparison of Modulus of Elasticity Results of ALDOT-SRA Mixture with ACI-318 and ACI-363

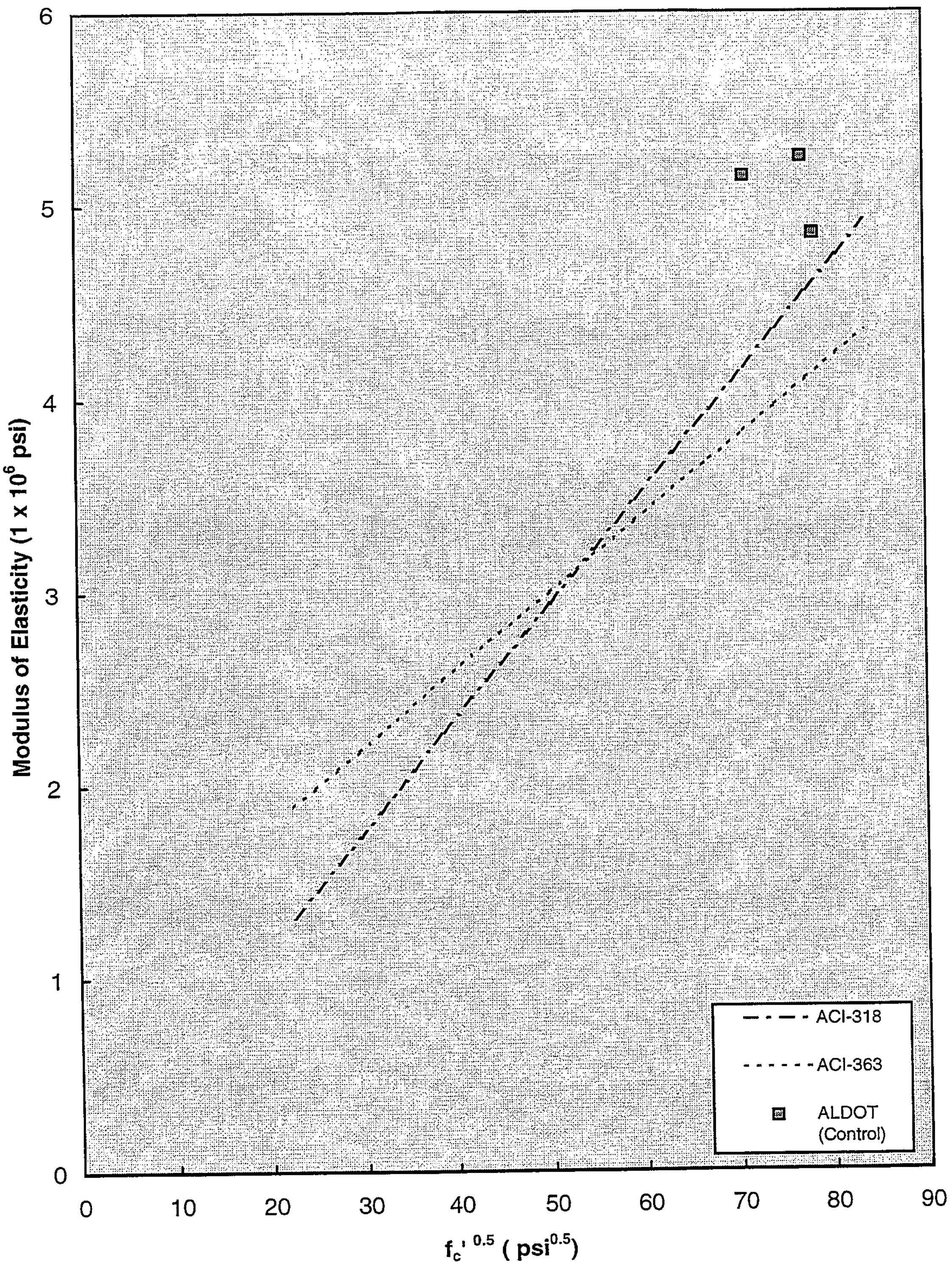


Figure 5.68 Comparison of Modulus of Elasticity Results of ALDOT (Control) Mixture with ACI-318 and ACI-363

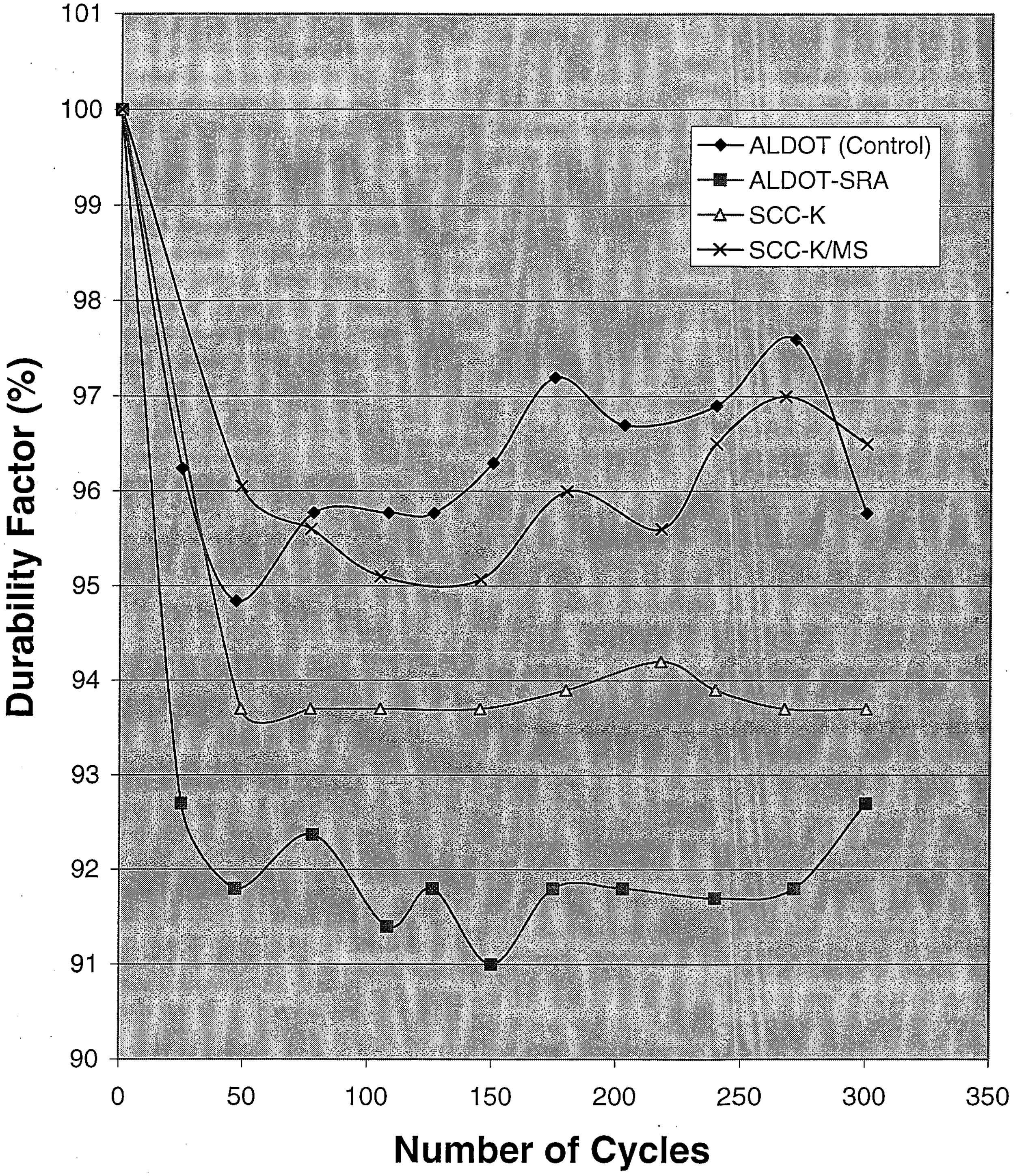


Figure 5.69 Freeze-Thaw Durability vs. Number of Freeze-Thaw Cycles.

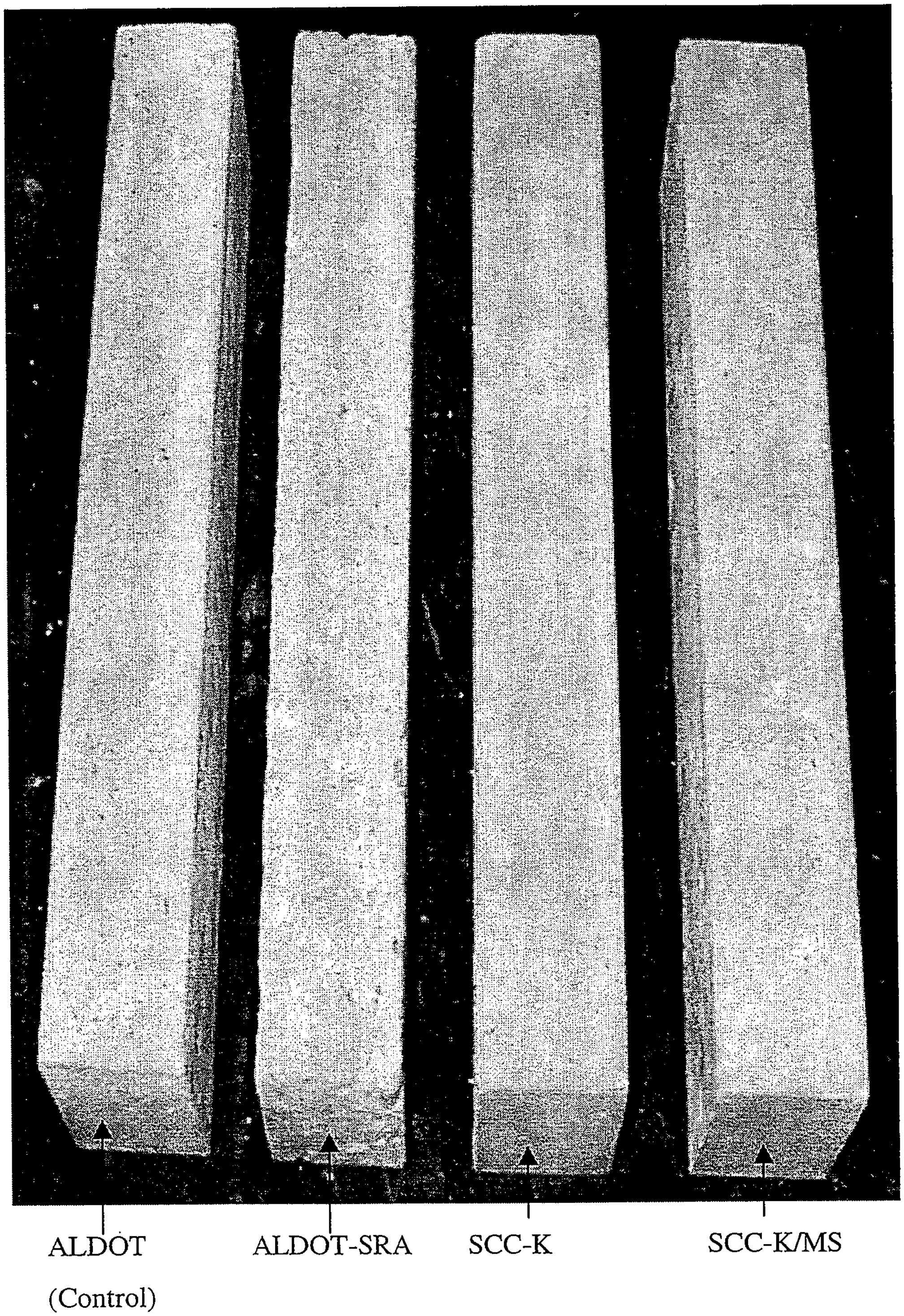


Figure 5.70 Scaling of Concrete due to Freeze-Thaw Test

Table 5.12 Rapid Chloride Ion Penetration Results for the Four Concrete Mixtures.

Concrete Mixture	Charged Passed[1] (Coulombs)	ASTM C1202 Rating
SCC-K	5192	High
SCC-K/MS	1418	Low
ALDOT-SRA	4954	High
ALDOT (Control)	5306	High

[1] Values shown are the averages for two specimens

*Values of the specimens incorporated in the averages above are shown in Table A.5 in the Appendix.

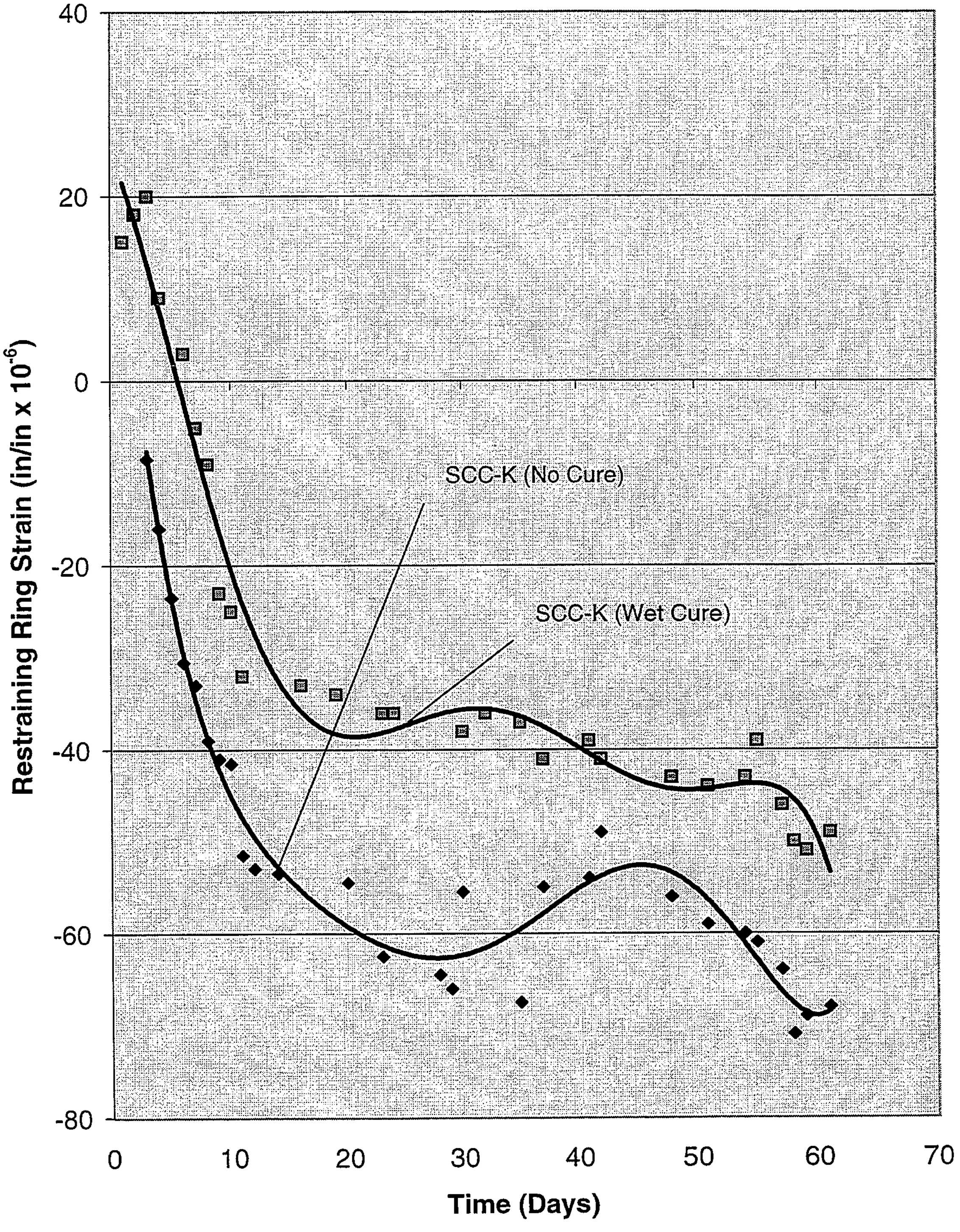


Figure 5.71 Ring Test Results for SCC-K Concrete Mixture

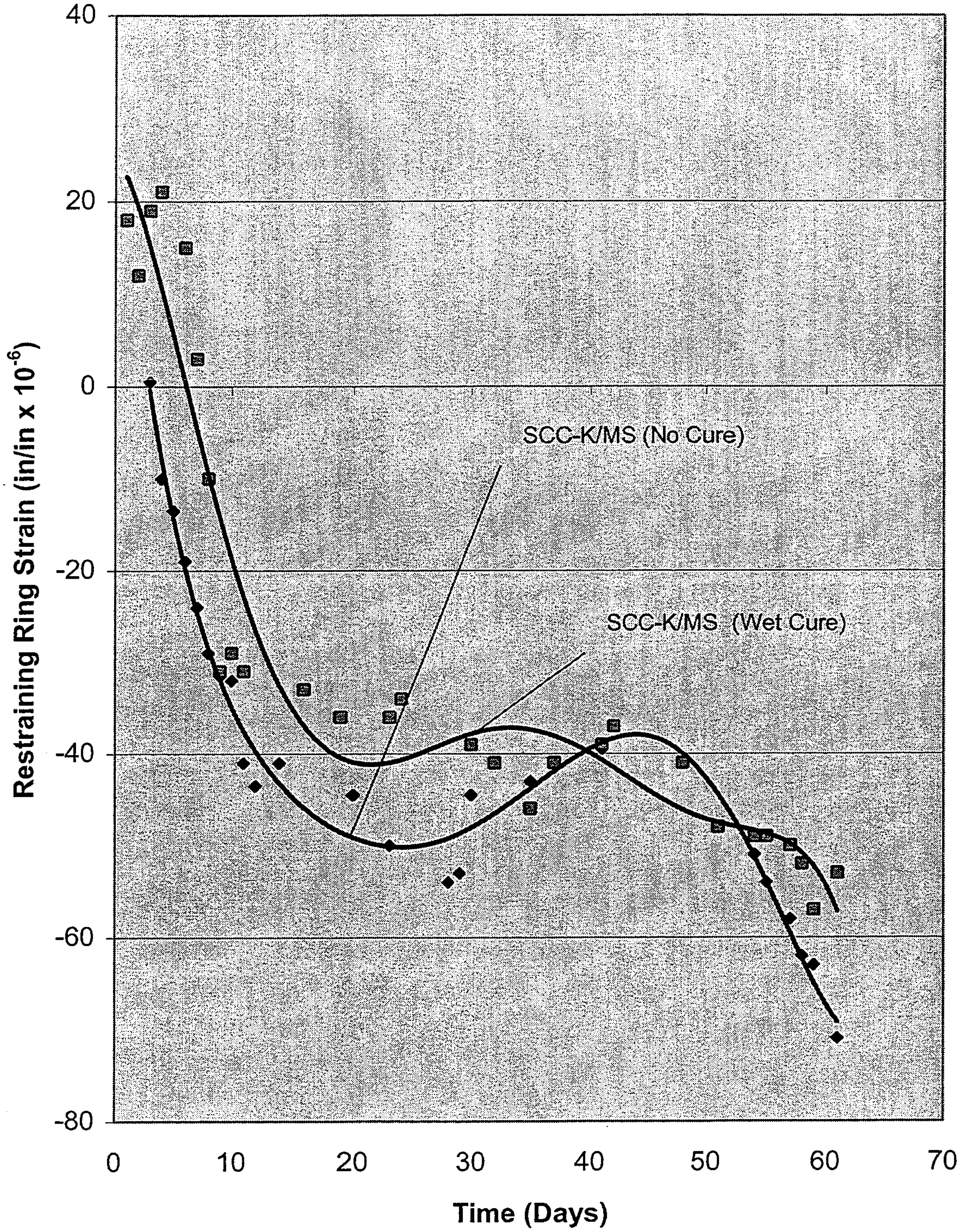


Figure 5.72 Ring Test Results for SCC-K/MS Concrete Mixture

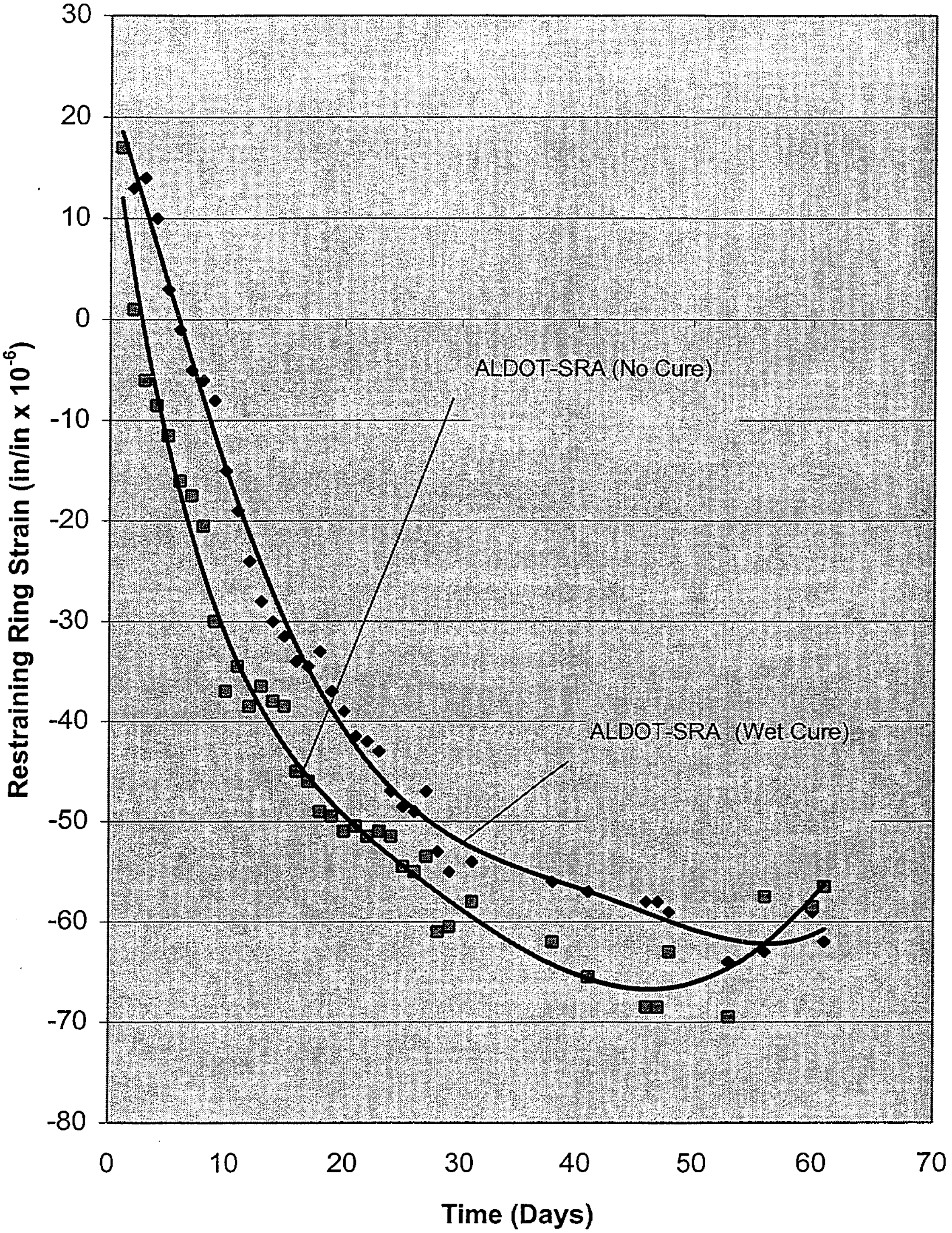


Figure 5.73 Ring Test Results for ALDOT-SRA Concrete Mixture

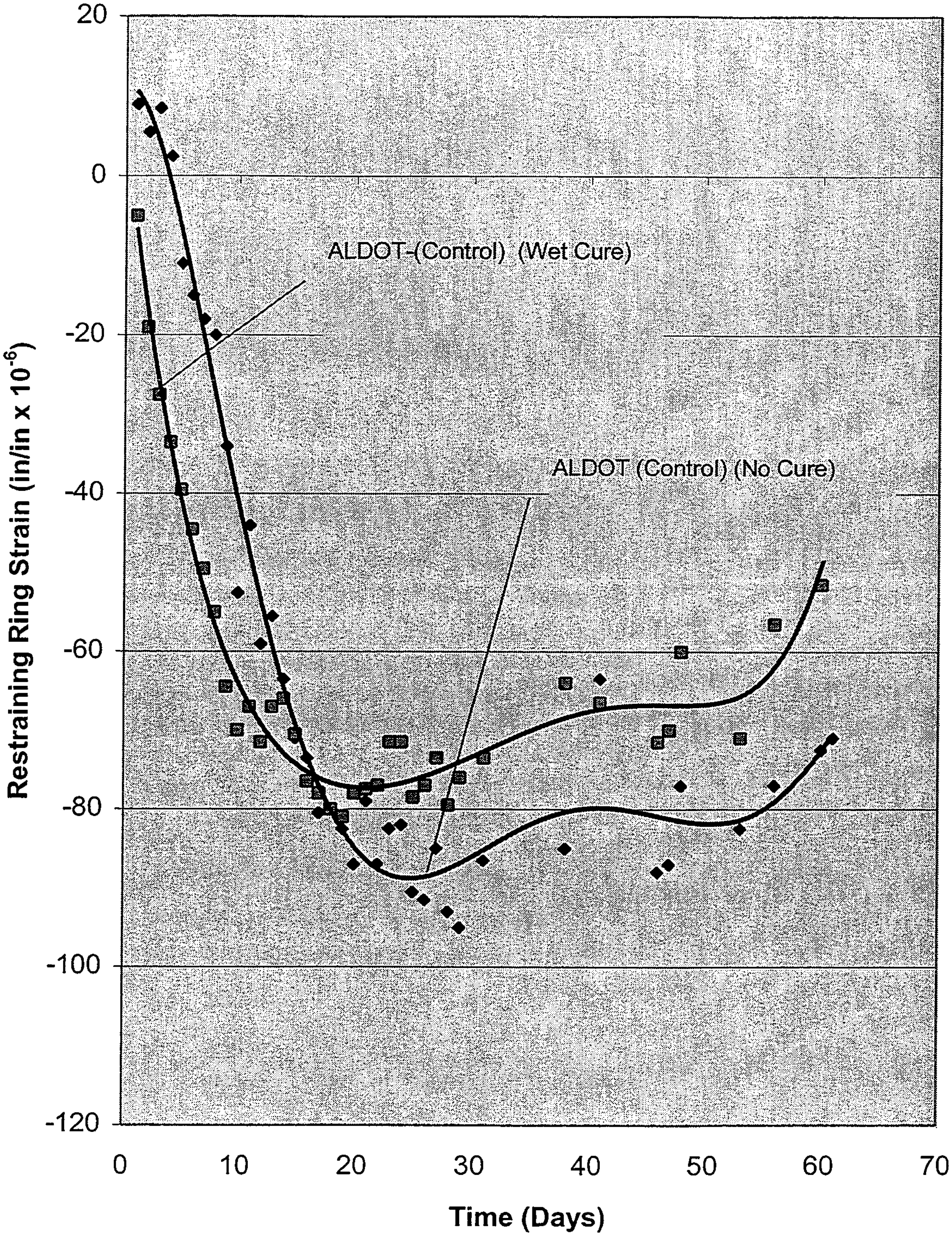


Figure 5.74 Ring Test Results for ALDOT (Control) Concrete Mixture

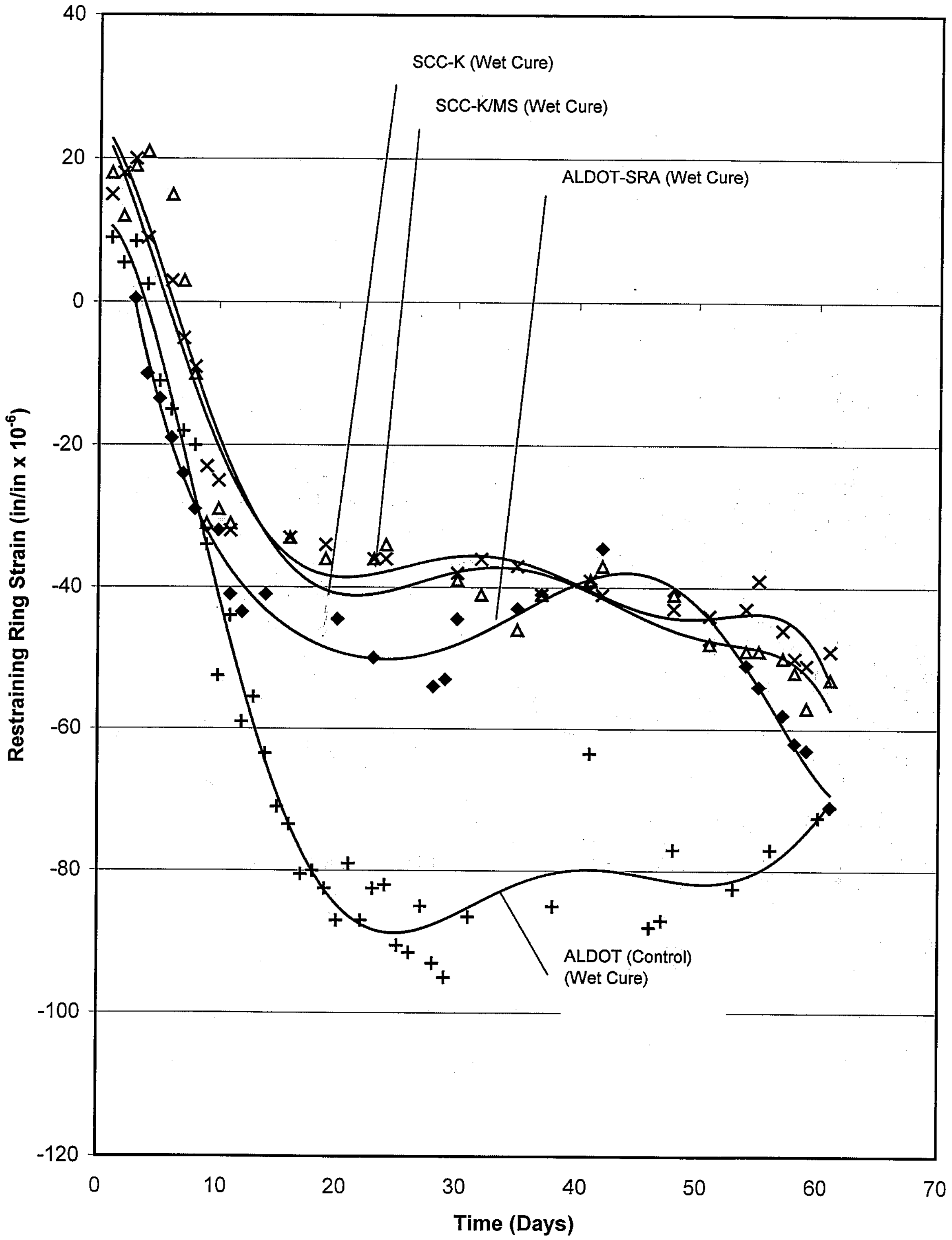


Figure 5.75 Ring Test Results for Concrete Mixtures Under Wet Curing Condition

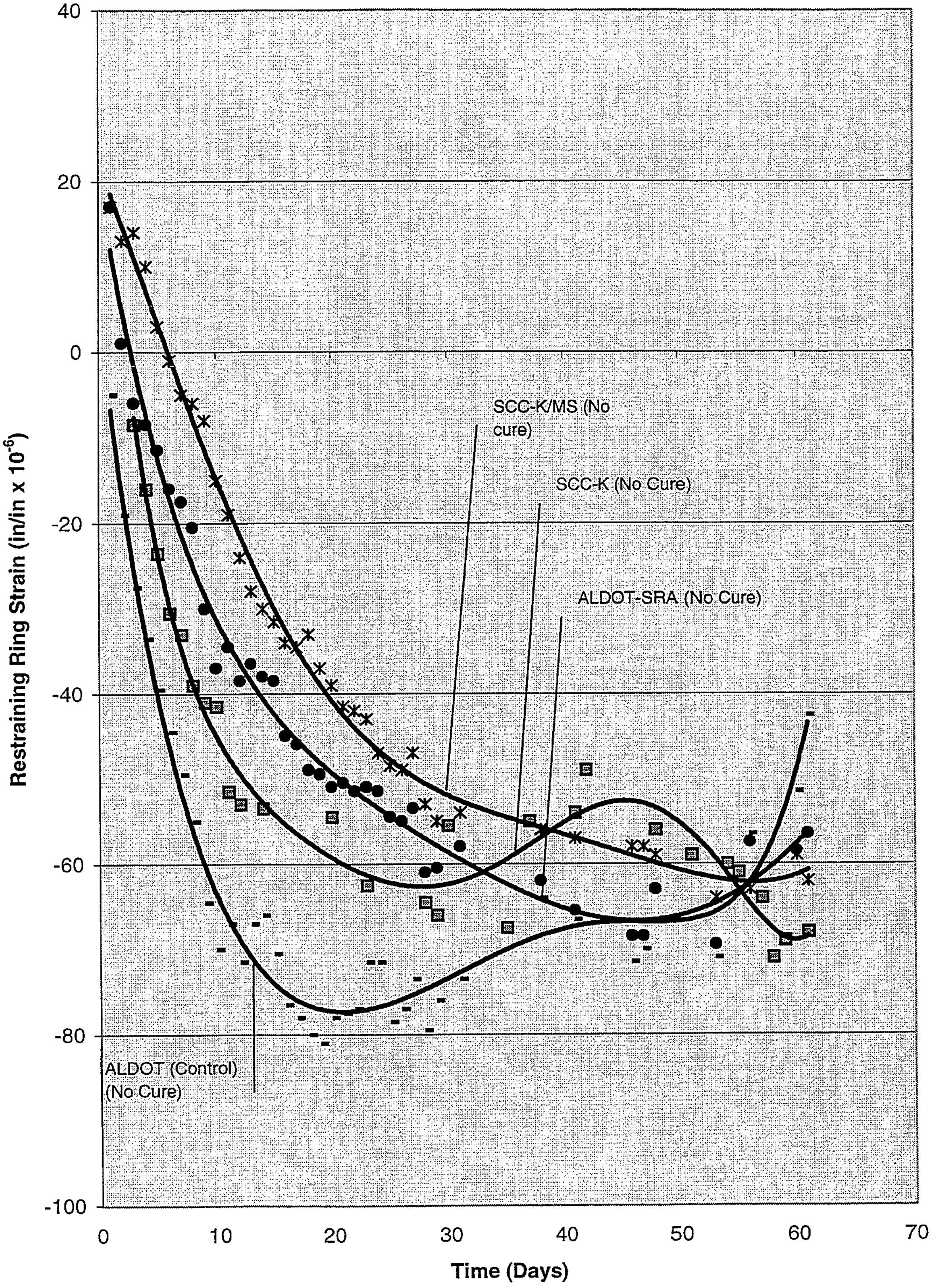


Figure 5.76 Ring Test Results for Concrete Mixtures Under No-Curing Condition

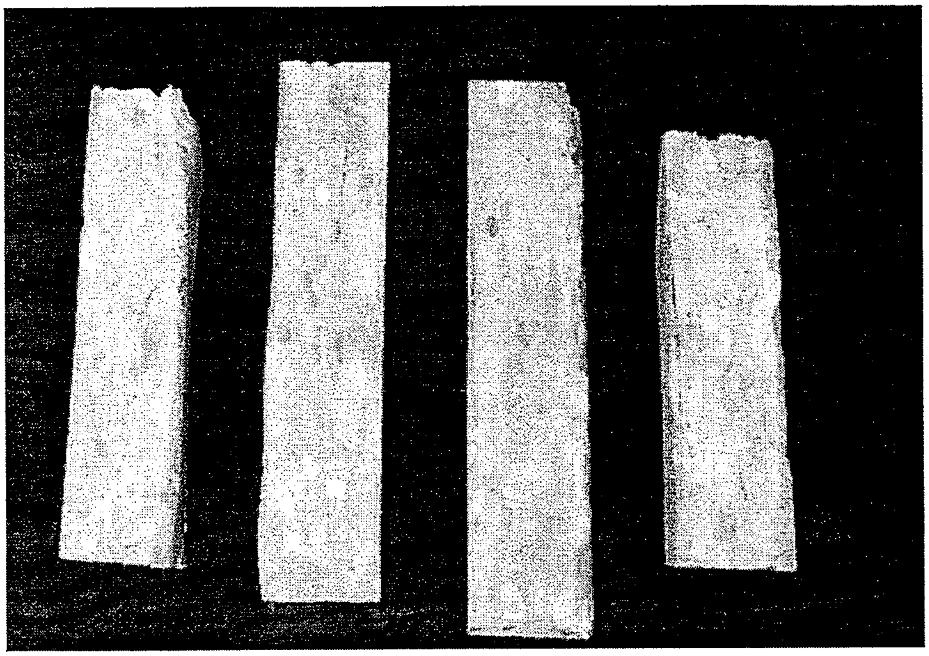


Figure 5.77 Cut-up Ring Specimens Under Wet Curing Conditions (Cut-Section Facing Up)

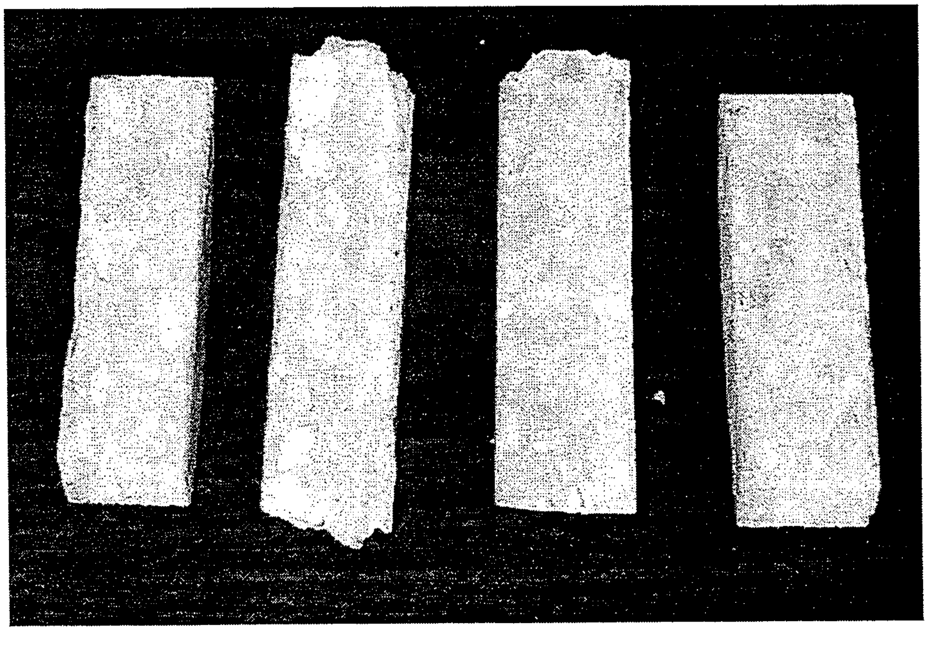


Figure 5.78 Cut-up Ring Specimens Under No-Curing Conditions (Cut-Section Facing Up)

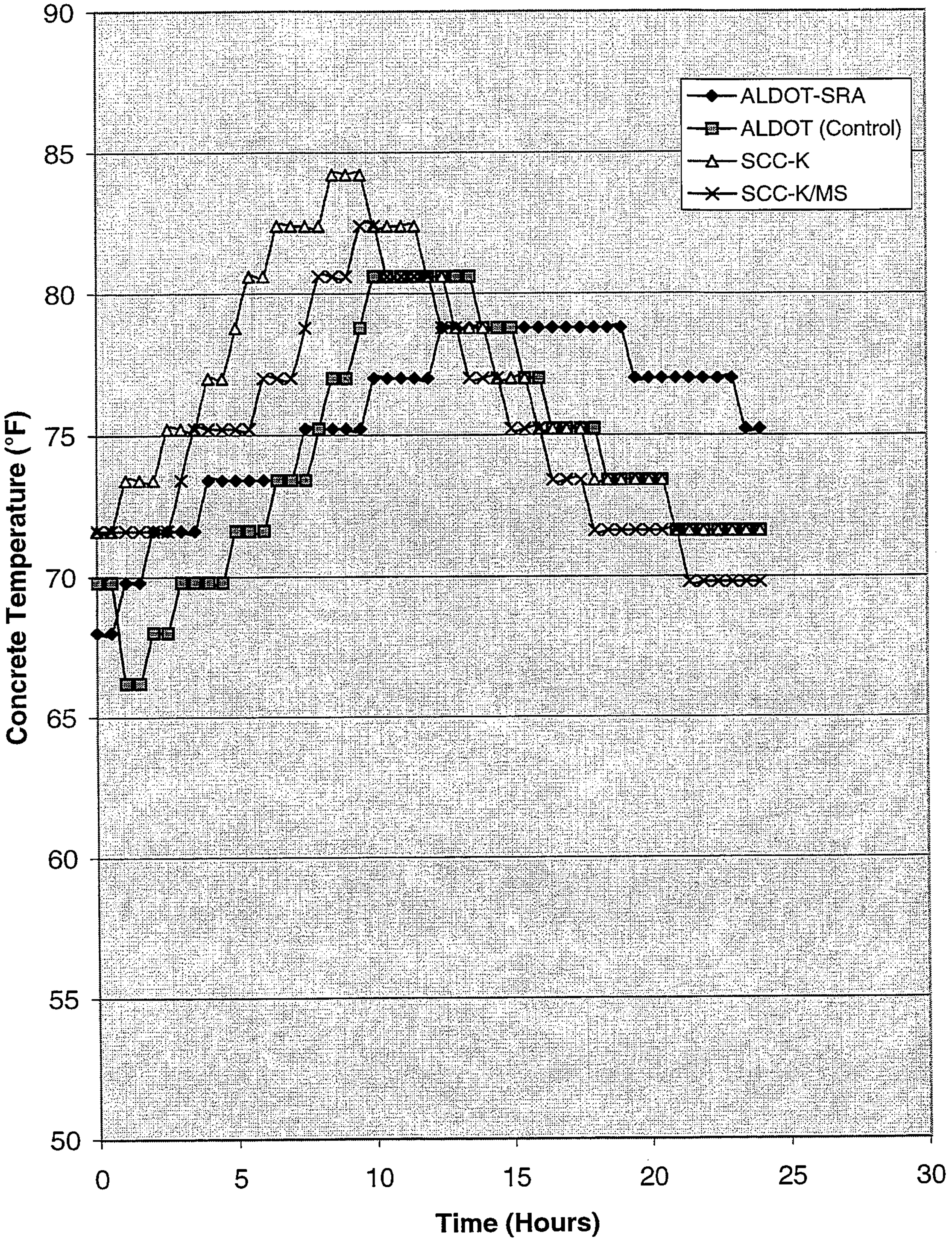


Figure 5.79 Heat of Hydration Results for Concrete Mixtures at 70° F Ambient Temperature

6. GUIDELINES FOR USE OF TYPE-K CEMENT/CONCRETE

6.1 General

As shown in Chapter 5, the Type-K cement/shrinkage compensating concrete (SCC-K) mixture is a viable potential replacement for ALDOT's current bridge deck concrete mixture. Since the SCC-K mixture reduces drying shrinkage and its other fresh and hardened concrete properties are comparable or superior to those of ALDOT's current mixture, it is important to identify the appropriate curing requirements, limitations on construction temperatures, and practical and effective concrete QC/QA monitoring/testing requirements to be employed when using the SCC-K mixture.

Construction guidelines and procedures were assembled from those used by the Ohio Turnpike Commission (OTC). The OTC's construction experiences with Type-K cement for bridge decks have been refined over a 14 year period. Upon completion of the initial draft of guidelines (based on OTC's work) for constructing with Type-K shrinkage compensating concrete, copies of the guidelines were sent to

- McInnis Corporation (Bridge Construction Contractor) Montgomery, Al.
- Blue Circle Cement Company (Cement Manufacturer) Atlanta, Ga.
- Williams Brothers (Ready Mix Concrete Company) Atlanta, Ga.

for their recommendations for improvements in the areas of

- material and deck performance

- construction and constructionability
- cost and holding cost increases to a minimum

Their suggestions and recommendations were studied and incorporated where appropriate into the final guidelines listed below.

6.2 Plant and In-Transit Guidelines

Presoak Sand and Coarse Aggregates: This is very important especially during hot weather. Less than saturated aggregates (especially gravels and lightweights) can severely increase mixture temperature, reduce slump, accelerate setting and cause plastic shrinkage cracks.

Admixtures: Only use admixtures which have been included and approved in the test mixture. Any proposed increases in dosages should be reviewed with the Engineer.

Truck: Wet the mixer drum and then expel all water. Make sure all wash water is expelled from return trucks before proportioning concrete ingredients in trucks. Proportion the concrete such that the volume placed in a truck is at least 2 cubic yards less than the rated capacity of the mix truck. This is necessary because Type-K mixtures are more cohesive than regular PC concrete and require additional space for proper mixing.

Batching Procedure: Charge mixer with approximately three-fourths of the mixing water with the air entrainment admixture if needed. With the mixer rotating at mixing speed start ribbon feeding of the coarse and fine aggregates. With approximately one-half of the aggregates in the truck, begin ribbon feeding of Type-K cement slowly to prevent balling. Proceed until all aggregates and cement are loaded. Add all remaining water and water reducers required.

Mixing Procedure: The truck should be pulled out from under the weigh batcher and washed down with the drum rotating at mixing speed. The shrinkage compensating concrete should be mixed for 70 revolutions or timed 5 minutes at mixing speed. A slump should be taken before the truck leaves the yard to assure a 7-inch slump.

Delivery Time: In accordance with ACI Standards, this should be limited to 90 minutes total elapsed time from batching to in-place.

Mixture Temperature: The site temperature for the mixture during placement is limited to 80° F. Therefore, steps should be taken to ensure that the plant mixture temperature is adjusted to compensate for ambient temperature, travel time and other variables. (Note that the maximum ambient temperature at placement is 80° F.) Like PC concrete, high temperatures and long mixing periods usually produce lower strength SC concrete. Additionally, they also reduce the amount of expansion and thus reduce the effectiveness of SC concrete in mitigating drying shrinkage cracking. Note also that like with PC concrete, chilled water or ice may be used with Type-K mixtures to help limit temperature.

Slump: The specifications limit slump at the site to 4" – 6". Since these mixtures need more water than most standard mixtures (to allow growth of the ettringite) and the w/c ratio may even be as high as 0.50, it is suggested that the plant slump be a minimum 7" for typical placements. Within reason, this higher slump and water content are needed and will not detract from the performance of the hardened concrete.

6.3 On-Site Guidelines

Ambient Temperature: Maximum ambient temperature at placement is 80° F.

Cool Off the Rebars and Forms: The mixture temperature at placement is limited to 90° F. Since the ambient temperature is limited to 80° F, take steps to cool off (via wetting with clean fresh water) any deck components which might increase the inform temperature of the mixture. If wooden forms are used, the wetting should be done to prevent the form from "sucking" water from the concrete mixture.

Slump: The slump range is 4" – 6". Target the high end. Slump loss due to pumping will be in the same order as that experienced with higher slump standard mixtures.

Air Entrainment: The ability of the mixture to entrain air should be normal. The higher slump and water content should help. Air losses due to pumping will not be unusual.

QC/QA of Concrete: Monitor slump, air content, concrete temperature, and concrete strength at point of placement of the concrete, i.e., at the rear of the truck if placing by bucket, or at the end of the pump line if placing by pump. This monitoring is continued for each truck load until an acceptable consistency is achieved, after which monitoring is cut back to every 50 yd^3.

Preplacement Meeting: Prior to making the first Type-K placement, a preplacement meeting should be held to discuss all aspects of bridge deck concrete placement. Parties at this meeting should be the contractor, concreting foreman, concrete supplier, test lab, inspector and project manager. Cement and admixture representatives should also attend this meeting. The meeting should conclude with a discussion of the "dry-run" (see below), which should be made within 1 or 2 days.

Dry Run: Conduct a complete and full size "dry run" prior to placing the first Type-K deck to familiarize supplier, contractor, finishers, tests lab, inspectors, etc., of what to expect with Type-K concrete. A 3-yard quantity should be batched, delivered, placed into a dummy form, finished, and initial curing applied as a dry run shortly before (1 or 2 days) making the first Type K deck placement. This same dry run can provide concrete for testing to assure the earlier accepted mixture design can be delivered to the site and properly emplaced. If construction personnel are familiar with, and have placed Type-K concrete before, the placement in a dummy form and finishing are not required. However, a dry run is required for batching and delivery to help assure the quality of the on-site concrete.

Placing Concrete: Delaying placing activities at the job site should be avoided since shrinkage compensating cement concrete loses slump faster than normal concrete. Delivery plus placement time of the concrete should be limited to 90 minutes. Type-K has more cohesiveness of "fat" than PC concrete, and thus has less tendency to segregate and is more easily pumped than PC concrete. Because of its higher slump, reduced tendency to segregate, and greater sensitivity to prolonged mixing time and time delays, it is highly recommended that Type-K deck concrete be placed by pumping. Placing of the concrete should be scheduled early in the day before temperature rise: the deck should not be placed if the ambient temperature is above 80° F. Also evening placement has advantages in that the greatest exothermic heat dissipation occurs during the cooler nighttime ambient temperatures.

Bleed Water: There will be a definite lack of surface bleed water. Typically only a sheen will appear. Therefore, spraying with Confilm (or equivalent) may be required in hot weather to limit rapid evaporation immediately behind the screed. This will reduce the tendency for plastic shrinkage cracking. Foggers and fog spraying maybe used inlieu of Confilm (or equivalent).

<u>Finishing:</u> The concrete will be creamy but may be sticky. Generally it finishes very well with 1 or 2 passes with a bull float. Do not over-finish with a float and do not use a steel trowel. Do not retouch the concrete after Confilm or other monofilm have been applied. It should be noted that concrete made with shrinkage-compensating cement will exhibit little or no bleed water; therefore, care must be taken to begin finishing operations at the proper time.

<u>Evaporation:</u> The use of Confilm or other acceptable monomolecular film is recommended for placement during hot weather for the purpose of reducing evaporation and thus prevention of drying of the deck surface prior to beginning the curing process. It acts to retard stiffening of the surface and thereby it tendency for plastic shrinkage cracking. This is particularly important for Type-K concrete because of little bleed water. Apply film as a spray immediately after finishing.

<u>Curing:</u> Two layers of pre-wet burlap sheets should be laid on the surface as soon after texturing as possible. These sheets should be maintained continuously wet for a period of 7 days after placement. The wetted burlap serves two purposes, (1) it provides water as needed for the concrete to properly hydrate and grow the ettringite, and (2) it keeps the deck cooled from heat of hydration and solar temperature build-ups. In turn, these greatly reduce drying shrinkage and thermal cracking, which are the dominant causes of nonstructural/early deck cracking. Care should be taken that greatly excessive water is not added that would cause run-off in the bridge gutters and damage the fresh concrete surfaces at those locations. Also, a polyethelene covering should not be used as it tends to create a "greenhouse" effect and increases the concrete temperature and later thermal stresses and cracking. After completion of the 7-day wet cure, a spray-on curing compound should be applied if the deck concrete was placed during the April–September period.

6.4 Closure

The guidelines for use of shrinkage compensating concrete (SCC) for bridge decks in Alabama presented above were primarily assembled from those used and refined by the Ohio Turnpike Commission (OTC) over a 14 year period. Thus, they have been field tested for a substantial period of time. Additionally, they have been refined based on recommendations from a local bridge construction contractor, cement manufacturer and ready-mix concrete producer for Alabama conditions. It is expected that in the process of placing some SCC bridge decks in Alabama, additional changes and refinements will be identified and made in the guidelines.

It was noted by the McInnis Corporation that from a bridge contractor perspective that they "saw nothing difficult or expensive as a result of the recommendations and that industry should not have a problem enforcing the guidelines." It was noted that since the volume of the concrete placed in a truck is to be at least 2 cubic yards less than the rated capacity of the mix truck that some increase in transportation costs may occur (approximately a 25% increase).

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 General

Based on results of reviewing the literature, talking with personnel from Blue Circle Cement Co., and performing laboratory testing on fresh and hardened concrete properties on the four concrete mixtures, it is the authors' opinion that the Type-K concrete mixture (SCC-K) is a suitable replacement of the ALDOT (Control) mixture. It is very effective in reducing drying shrinkage, is construction friendly, and its fresh and hardened concrete properties are either comparable to or exceeds those of the ALDOT (Control) mixture. Its somewhat higher initial cost could prove to be a lower life-cycle-cost due to reduced shrinkage cracking and potentially reduced deterioration and thus longer service life.

Shrinkage compensating cement, Type-K, has been used successfully to reduce drying shrinkage and to extend the service life of bridge decks. The Ohio Turnpike Commission, the nations leading user in Type-K cement, exclusively uses shrinkage compensating concrete for its 500+ bridge decks because they have found that it reduces shrinkage cracking and enhances the service life of bridge decks.

7.2 Conclusions

Based on performing laboratory testing on the fresh and hardened properties for four concrete mixture designs, the following conclusions were made:

SCC-K: The SCC-K mixture's fresh concrete properties showed a sensitivity to changes in ambient temperatures. The hotter temperatures proved to increase slump loss, unit weight and decrease the set-time while the lower temperatures showed the opposite. Therefore when using the SCC-K mixture in hot temperatures, a high range water reducer would prove to be beneficial to use to help make the concrete mixture more construction friendly. The hardened concrete properties produced comparable results or showed results exceeding those of the other mixtures. SCC-K proved to be an effective concrete mixture in reducing drying shrinkage when exposed to wet curing conditions. The best hardened concrete properties were observed when exposed to the excellent curing condition.

It was important to note that the SCC-K mixture's permeability was comparable to the ALDOT (Control) mixture. It has been a concern that Type-K cement may cause higher permeability but this testing has shown that the SCC-K mixture's permeability is comparable to the ALDOT (Control) mixtures.

SCC-K/MS: Micro-silica was added to the Type-K mixture to reduce permeability and to assess its effect on other pertinent properties. The mixture showed similar fresh and hardened concrete properties results to the SCC-K mixture. However, the permeability was much lower in this mixture, which is good, but the restrained shrinkage results where worse. Since the purpose of this research was to find a concrete mixture design to reduce drying shrinkage, and since concrete permeability is not a major issue in Alabama, the SCC-K mixture was preferred over the SCC-K/MS mixture.

ALDOT-SRA: The shrinkage reducing admixture, Eclipse, reduces drying shrinkage but the results of this research shows that the reduction in shrinkage is not as great as that of the SCC-K mixture. The ALDOT-SRA mixture does show significant shrinkage reduction, but the mixture's fresh and hardened concrete properties where much poorer than the ALDOT (Control) mixture. Eclipse caused the mixture to have a much longer set-time, increased the air entrainment admixture dosage requirement to reach the specified air content, produced the lowest compressive and tensile strengths and produced the lowest durability factor on the freeze-thaw test and scaled severely relative to the ALDOT (Control) mixture. For these reasons, the author believes that the SCC-K mixture is superior to the ALDOT-SRA mixture.

ALDOT (Control): The ALDOT (Control) mixture had comparable results with those of the Type-K mixture, except for the following tests: Freeze-Thaw Durability, Set-Time, and Shrinkage Bar Tests. The ALDOT (Control) mixture provided the worst freeze-thaw test results showing that it had a high tendency to scale (as shown in Figure 5.70). The set-time results showed that the ALDOT (Control) mixture had a initial set time of 8 hours and 30 minutes and a final set time of 9 hours and 39 minutes. This is unusually long for regular Portland Cement. The ALDOT (Control) mixture also provided the worst shrinkage bar results (restrained and unrestrained) concluding that the mixture is classified as High Shrinkage. This research shows that if drying shrinkage is the cause of the early deck deterioration and low durability, then the SCC-K mixture is a susceptible concrete mixture to replace the ALDOT (Control) mixture for bridge decks in Alabama.

7.3 Recommendations

Based on the results of this study, Type-K shrinkage compensating concrete appears to be a viable candidate for use in bridge decks to mitigate drying shrinkage cracking.

The SCC-K mixture exceeded or was comparable to all of the fresh and hardened concrete properties of the ALDOT (Control) mixture. This being the case, the following recommendations are made.

1. A "test deck" employing the SCC-K mixture should be placed by the ALDOT adjacent to one employing the ALDOT's standard deck concrete mixture for comparative evaluation purposes.
2. The "test deck" in (1) above should be monitored for 1-year to evaluate its performance and drying shrinkage cracking in particular.
3. Assess the appropriateness of the Guidelines for Constructing with SCC in Chapter 6 during placement of the "test deck" and make refinements and changes as necessary.
4. Continue to explore the development of a laboratory test method (similar to the ring test) which integrates the drying shrinkage, tensile strength, material stiffness modulus, and creep characteristics of a concrete mixture into a test to assess the mixtures drying shrinkage cracking susceptibility.

7. REFERENCES

1. AASHTO "AASHTO Manual for Bridge Maintenance," AASHTO, Washington, D.C., 1987.
2. ACI (S.L. Marusin-Editor), "In Place Performance of Polymer Concrete Overlays," ACI SP.-169, 1997.
3. ACI Committee 201, "Guide for Making a Condition Survey of Concrete Service," ACI Report, ACI 201. 1R-92, January 1993.
4. ACI Committee 223, "Expansive Cement Concretes-Present State of Knowledge." ACI Report, Title No. 67-35, August 1970.
5. ACI Committee 223 Report, "Standard Practice for the Use of Shrinkage Compensating Concrete (ACI 223-93)," ACI 223-93, June 1993.
6. ACI Committee 305, "Hot Weather Concreting." ACI 305R-9 1, American Concrete Institute, Detroit, MI, 1991.
7. ACI Committee 345, "Guide for Concrete Highway Bridge Deck Construction." ACI 345R91, Detroit Michigan, 1991.
8. Babaei, Khossrow and Fouladgar, Amir, M., "Solutions to Concrete Bridge Deck Cracking." Concrete International, July 1997, pp. 34-37.
9. Babaei, Khossrow and Purvis, Ronald L., Report on Laboratory Investigations of Concrete Shrinkage, PennDOT Research Project No. 89-01, Wilbur Smith and Associates, Falls Church, VA., January 1995.
10. Babaei, Khossrow and Purvis, Ronald, "Report on Surveys of Existing Bridges," Wilbur Smith Associates Report on PennDot Project No. 89-01, October 1994.
11. Berke N.S., Dellaire M.P., Hicks M.C. and Kerkar A. "New Developments in Shrinkage-Reducing Admixtures."
12. FHWA, Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects, Federal Highway Administration, FP-96, 1996.

13. Folliard, Kevin J. and Berke, Neal S., "Properties of High Performance Concrete Containing Shrinkage Reducing Agents," Vol. 27, No. 9, pp. 1357-1364. Elsevier Science Ltd. 1997.

14. Gebler, Steven, "Predict Evaporation Rate and Reduce Plastic Shrinkage Cracks." Concrete International, April 1993, pp. 19-22.

15. Grace Construction Products, "Eclipse, Product Information." W.R. Grace & Co.-Conn. 1996.

16. Gruner, P.W. and Plain, G.A., "Type K Shrinkage-Compensating Cement in Bridge Deck Concrete," Concrete International, October 1993, pp. 44-47.

17. Kosmatka, S.H. and Panarese, W.C. "Design and Control of Concrete Mixtures." PCA Engineering Bulletin. 13 1h Edition, Stokie, IL., pp. 153-156.

19. Lafuma, H., "Expansive Cements," Proceedings of Third International Symposium on the Chemistry of Cement (London, 1952), Cement and Concrete Association, London 1954, pp. 581-597.

20. Lerch, William, "Plastic Shrinkage." Journal of the American Concrete Institure, Vol.28, February 1957, pp. 797-802.

21. Mikhailov, V. V., "Stressing Cement and the Mechanism of Self-Stressing Concrete Regualtion," Fourth International Symposium on the Chemistry of Cement, Washington, D.C., V. 2, 1060, pp. 927-955.

22. Mindess, Sidney and Young, J. Francis, Concrete, Prentice-Hall, Englewood Cliffs, NJ, 1981.

23. National Cooperative Highway Research Program, "Transverse Cracking in Newly Constructed Bridge Decks," NCHRP Report 380. Transportation Research Board National Research Council.

24. Neville, A.M. Projects of Concrete, 3rd edition, Longman Scientific and Technical, London, England 198.1.

25. PCA,"Durability of Concrete Bridge Decks," Final Report of a Cooperative Study by PCA, Stokie, IL, 1970 (Revised 1995).

26. Powers, Trevel C. The Properties of Fresh Concrete, Wiley, New York, 1968.

27. Raina, V.K. Concrete Bridges, McGraw-Hill, New York, 1996.

28. Ramey, G.E., and Carden, Ashley, "An Assesment of Concrete Bridge Deck Evaporation Rates and Curing Requirements Categories for Alabama." Final Report on HRC Research Project 2-13746, February 1998.

29. Ramey, G.E., and Oliver, Russell, "Rapid Rehabilitation/Replacement of Bridge Decks." Final Report of HRC Research Project 930-376, November 1998.

30. Ramey, G.E, Pittman, D.W. and Webster, G.K., "Shrinkage Compensating Concrete for Bridge Decks," Concrete International, Vol. 21, No. 4, April 4, 1999, pp.29-34.

31. Ramey, G.E., Pittman., Webster, G. and Carden, A., "Use of Shrinkage Compensating Cement in Bridge Decks," Highway Research Center Report, Auburn, AL., October 1996.

32. Ravina, Dan and Shalon, Rahel, "Plastic Shrinkage Cracking." Journal of the American Concrete Institute Proceedings, Vol. 65, No. 4, April, 1968, pp. 282-291.

33. Russell, Ed, "Type-K, Expansive Cement." Blue Circle Data Sheet, 1993.

34. Samman, Tamim A., Mirza, Wajahai H., and Wafa, Faisal T., "Plastic Shrinkage Cracking fo Normal and High Strength Concrete: A Comparative Study." ACI Materials Journal, Vol. 93, No. 1, Jan-Feb. 1996, pp. 36-40.

35. Senbetta, Ephraim and Bury, Mark A., "Control of Plastic Shrinkage Cracking in Cold Weather." Secrets of Hot or Cold Weather Concreting, ACI, Detroit, MI, 1991, Rev. 1994, pp. 89-93.

36. Shaeles, Christos A. and Hover, Kenneth C., "Influence of Mix Proportions and Construction Operations on Plastic Shrinkage Cracking in Thin Slabs, Title No. 85-M48." ACI Materials Journal, Nov.-Dec. 1998, pp. 495-504.

37. Slate, F.O., and Matheus, R.E., "Volume Changes on Setting and Curing of Cement Paste and Concrete from Zero to Seven Days," ACI Journal, V. 64, No. 1, Jan. 1967, pp. 34-39.

38. Sprinkel, Michael M., "Predicting Plastic Shrinkage Cracking in LMC Overlays." Concrete Construction, 1998, 24-25.

39. Tonias, Demetrios E. Bridge Engineering, McGraw-Hill, 1995.

40. Wiss, Janey, Elstner Associates, Inc., "Transverse Cracking in Newly Constructed Bridge Decks." NCHRP Project 12-37, September 1995.

41. Zollinger, D.G., "Assesement of Durability Performance of "Early-Opening-To-Traffic" Portland Cement Concrete." Final Report, October 1998.

APPENDIX

CONCRETE TEST DATA

Table A.1 Compressive Strength Values for the Four Concrete Mixtures at the Four Different Curing Conditions.

Concrete Mixture	Curing Conditions															
	Lab Standard				Excellent				Fair				Poor			
	3-day	7-day	28-day	56-day	3-day	7-day	28-day	56-day	3-day	7-day	28-day	56-day	3-day	7-day	28-day	56-day
SCC-K																
Specimen #1	3790	4470	5350	5600	4000	4470	5900	6400	4500	5080	6100	6400	4290	4980	5285	5680
Specimen #2	3820	4510	5160	5690	3790	4560	6020	6320	4490	4620	5830	6520	4300	4900	5300	5750
Specimen #3	3873	4460	5300	5705	3565	4470	5930	6570	4353	4925	5920	6370	4265	5045	5150	5700
	3828	**4480**	**5270**	**5665**	**3785**	**4500**	**5950**	**6430**	**4448**	**4875**	**5950**	**6430**	**4285**	**4975**	**5245**	**5710**
SCC-K/MS																
Specimen #1	3150	3860	5860	5690	3000	3890	6580	6690	3560	4790	5160	5490	3290	4505	5180	5200
Specimen #2	3010	3850	5640	5775	3075	3830	6400	6610	3445	4860	5100	5350	3250	4620	5120	5460
Specimen #3	3020	4020	5570	5695	2985	3800	6385	6590	3435	4780	5100	5360	3225	4615	5000	5165
	3060	**3910**	**5690**	**5720**	**3020**	**3840**	**6455**	**6630**	**3480**	**4810**	**5120**	**5900**	**3255**	**4580**	**5100**	**5275**
ALDOT-SRA																
Specimen #1	3280	3720	4705	5020	3280	3960	5140	5560	3250	3790	4585	4820	3310	3790	4765	4775
Specimen #2	3235	3930	4685	5040	3170	3770	5240	5635	3220	3705	4520	4780	3200	3890	4710	4790
Specimen #3	3265	3960	4875	5240	3150	3775	4905	5605	3205	3755	4395	4740	3285	3795	4625	4700
	3260	**3870**	**4755**	**5100**	**3200**	**3835**	**5095**	**5600**	**3225**	**3750**	**4500**	**4780**	**3265**	**3825**	**4700**	**4755**
ALDOT (Control)																
Specimen #1	3800	5090	5830	6190	4175	4990	6470	6390	4190	5060	5490	5710	4210	4800	5150	5560
Specimen #2	3915	4980	6070	6110	4060	4960	6520	6670	4050	4950	5360	5560	4095	4845	5200	5530
Specimen #3	3865	5005	5905	6075	4095	4930	6465	6455	4090	4795	5350	5530	4010	4755	5070	5440
	3860	**5025**	**5935**	**6125**	**4110**	**4960**	**6485**	**6505**	**4110**	**4935**	**5400**	**5600**	**4105**	**4800**	**5140**	**5510**

* Values in bold are the average of the three specimens.

**Values are in pounds per square inch (psi)

Table A.2 Split Tensile Strength Values for the Four Concrete Mixtures at the Four Different Curing Conditions.

Concrete Mixture	Curing Conditions							
	Lab Standard		Excellent		Fair		Poor	
	7-day	28-day	7-day	28-day	7-day	28-day	7-day	28-day
SCC-K								
Specimen #1	270	373	327	520	345	531	459	455
Specimen #2	350	378	405	390	361	473	446	475
	310	**376**	**366**	**453**	**353**	**503**	**453**	**465**
SCC-K/MS								
Specimen #1	320	300	292	280	400	360	461	475
Specimen #2	334	390	299	326	336	418	514	509
	327	**345**	**296**	**303**	**368**	**389**	**488**	**492**
ALDOT-SRA								
Specimen #1	298	312	302	337	320	331	290	357
Specimen #2	304	312	346	341	336	327	316	335
	301	**312**	**324**	**339**	**328**	**329**	**303**	**346**
ALDOT (Control)								
Specimen #1	418	385	350	526	430	478	380	513
Specimen #2	386	445	360	472	520	526	510	531
	402	**415**	**355**	**499**	**475**	**502**	**445**	**522**

* Values in bold are the average of the two specimens.

**Values are in pounds per square inch (psi)

Table A.3 Elastic Modulus Results for the Four Concrete Mixtures.

Concrete Mixture	Days		
	7-day	28-day	56-day
SCC-K			
Specimen #1	3,800,000	3,900,000	3,950,000
Specimen #2	3,900,000	4,300,000	4,050,000
	3,850,000	**4,100,000**	**4,000,000**
SCC-K/MS			
Specimen #1	4,520,000	4,000,000	3,800,000
Specimen #2	4,580,000	4,200,000	4,200,000
	4,550,000	**4,100,000**	**4,000,000**
ALDOT-SRA			
Specimen #1	4,000,000	4,450,000	4,625,000
Specimen #2	4,800,000	4,950,000	5,275,000
	4,400,000	**4,700,000**	**4,950,000**
ALDOT (Control)			
Specimen #1	5,000,000	5,000,000	4,900,000
Specimen #2	5,300,000	5,500,000	4,800,000
	5,150,000	**5,250,000**	**4,850,000**

* Values in bold are the average of the two specimens.

**Values are in pounds per square inch (psi)

Table A.4 Freeze-Thaw Durability Results for the Four Concrete Mixtures.

Concrete Mixture	Initial Frequency (Hz)	Final Frequency (Hz)
SCC-K		
Specimen #1	2023	1961
Specimen #2	2027	1959
	2025	**1960**
SCC-K/MS		
Specimen #1	2007	1968
Specimen #2	2003	1972
	2005	**1970**
ALDOT-SRA		
Specimen #1	2150	2072
Specimen #2	2160	2078
	2155	**2075**
ALDOT (Control)		
Specimen #1	2101	2058
Specimen #2	2109	2062
	2105	**2060**

* Values in bold are the average of the two specimens.

Table A.5 Rapid Chloride Ion Penetration Results for the Four Concrete Mixtures.

Concrete Mixture	Charged Passed (Coulombs)
SCC-K	
Specimen #1	5582
Specimen #2	4802
	5192
SCC-K/MS	
Specimen #1	1622
Specimen #2	1214
	1418
ALDOT-SRA	
Specimen #1	5200
Specimen #2	4708
	4954
ALDOT (Control)	
Specimen #1	5110
Specimen #2	5502
	5306

* Values in bold are the average of the two specimens.