TENSILE STRENGTH OF SHRINKAGE-COMPENSATING CONCRETE WITH FLY ASH

By

Julissa Rosario Peña Báez

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Approved by:

________________________________ _________________
Arsenio Cáceres, Ph.D. Date
President, Graduate Committee

________________________________ _________________
Felipe J. Acosta, Ph.D. Date
Member, Graduate Committee

________________________________ _________________
Ricardo R. López, Ph.D. Date
Member, Graduate Committee

________________________________ _________________
Ismael Pagán Trinidad, M.Sc. Date
Chairperson of the Department

________________________________ _________________
Anand D. Sharma, Ph.D. Date
Representative of Graduate Studies

ABSTRACT

In order to evaluate the tensile strength of concrete made with a shrinkage-reducing admixture (SRA) along with fly ash, nine mix designs were prepared and tested at ages of 3, 5, 7, 14, 28, and 56 days under different curing times (3, 7, and 28 days). The compressive strength and the effectiveness of SRA for reducing drying shrinkage of concrete under prevailing conditions in Puerto Rico were also evaluated. The results indicated that the use of partial substitution of Portland cement by Class F fly ash without changing the water or aggregate content reduced the splitting tensile strength and compressive strength of the mixes. Also, the use of shrinkage-reducing admixture and fly ash was effective in reducing the free shrinkage strains for all the concrete mixes tested. It was found that the difference between 3 and 7 days of moist curing was not significant in terms of strength gain of concrete mixes, but it helped to reduce the shrinkage of concrete made with SRA and fly ash.

RESUMEN

Con el objetivo de evaluar la resistencia en tensión de mezclas de concreto hechas con un aditivo reductor de encogimiento (SRA, por sus siglas en inglés) y con ceniza volante, se prepararon nueve diseños de mezcla los cuales fueron probados a los 3, 5, 7, 14, 28 y 56 días en diferentes tiempos de curado (3, 7 y 28 días). También se evalúo la resistencia a compresión y el encogimiento del concreto bajo las condiciones imperantes en Puerto Rico. Los resultados indicaron que el uso de la ceniza volante Clase F en sustitución parcial del cemento Pórtland, sin cambiar el agua o el contenido de agregado de las mezclas, redujo la resistencia a la tensión y a la compresión. Además, el uso del aditivo reductor de encogimiento y ceniza volante fue eficaz en la reducción del encogimiento libre de todas las mezclas de hormigón probadas. Se encontró también que la diferencia entre 3 y 7 días de curado húmedo, no fue significativa en términos de ganancia de resistencia de las mezclas de concreto, pero sí contribuyó a reducir el encogimiento del mismo con el aditivo y ceniza volante.

For the people that love me
and care about me…
Specially to my family, and my
friends from Dominican Republic….

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Thanks to God for being my guide and giving me health and the necessary strength to carry out all my goals. All my gratitude to my family, because without their support and trust this experience would not have been possible. Mom and dad, thanks for being the best parents in the world.

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CHAPTER 1
INTRODUCTION

1.1 GENERAL

Concrete is one of the most used construction materials in the world. Its widespread use stems from its many advantageous properties such as durability, relative low cost, the facility to be molded into a variety of shapes and sizes, and the availability of its basic components. Even though it has many advantages, it also has weaknesses; some of them may be serious if unattended. Among its weaknesses, cracking is one of the most prominent disadvantages of concrete because it adversely affects its durability, functionality, and appearance. There are many factors that can cause cracks on concrete, but no matter the reason, the problem is that if some forces impose tensile stresses on the concrete exceeding its tensile strength, cracking will occur.

One of the phenomena causing cracking in concrete is shrinkage. It can be attributed to loss of moisture, chemical reactions of the cement with water, variations in temperature, or chemical reactions of the cement with atmospheric carbon dioxide. The two most common types of shrinkage are plastic and drying. Plastic shrinkage develops in fresh concrete as a result of moisture loss. Drying shrinkage is the result of evaporation when hardened concrete is exposed to air with a relative humidity less than 100%. Shrinkage is probably one of the least desirable properties of concrete. When it is restrained it may lead to shrinkage cracking. This spoils the appearance of concrete and makes it more vulnerable to attack by external agents, thus adversely affecting its durability. Of all the different types of shrinkage, drying shrinkage usually results in the largest volume change and thereby cracking. Thus, this is a phenomenon that merits careful consideration in concrete design and construction.

It is not surprising, therefore, that many attempts have been made to develop a concrete which would counteract the deformation induced by shrinkage. The result of this development is the concrete known as shrinkage-compensating concrete (SCC). According to ACI Committee 223 [1] SCC is an expansive concrete which is used to minimize cracking caused by drying shrinkage in concrete slabs, pavements and structures. SCC is made with special expansive cement (typically Type K) or an additive component plus Type I or II cement. They cause the concrete volume to increase after it sets.

The use of expansive cements has advanced mainly in the USA, where the main manufacturer in the world is located. On 1982 revolutionary admixtures that reduce drying shrinkage called shrinkage-reducing admixtures (SRA) were introduced into the concrete industry in Japan. In some countries such as Puerto Rico it is more economical to import the expansive admixture than to import expansive cement because of freight costs.

On a different aspect, some actions have been taken in the world to reduce the amount of clinker in the cement, and thus reduce pollution associated with their production. One of them is the use of *supplementary cementitious materials* (SCM) such as fly ash, silica fume, blast furnace slag, and limestone powder, which are recycled by-products. The Department of Consumer Affairs (Departamento de Asuntos del Consumidor, DACO) in Puerto Rico has recently approved the use of SCM for sale and consumption in the island. Therefore it is important to continue developing and analyzing the characteristics of the concrete made with SCM and to explore new possibilities in the use of these materials to produce sustainable concrete.

SCC has not been used commercially on a large scale in Puerto Rico, which leads us to investigate about the subject. However, nowadays the use of supplementary cementitious materials must be a key point in any investigation, due to the environmental benefits it brings. Therefore, this research focuses in the use of fly ash for the production of SCC. As mentioned before, the tensile strength of concrete is considered the basis for cracking resistance. That is why this thesis investigates the tensile strength of SCC.

1.2 JUSTIFICATION

Cracking due to drying shrinkage is caused by tensile stresses that are created by differential strains that occur under drying or restraint on concrete. Therefore, the tensile strength is a good indicator of the resistance of the concrete to cracking. That is why it could be considered as the threshold of cracking. There are conflicting results in the tensile strength of concrete made with fly ash, and the effect of SRA in the strength. Then, an investigation focused in the behavior of different percentages of fly ash in tensile strength of concrete is necessary.

While there is no specific reference in the commercially production of SCC on a large scale in Puerto Rico, nor previous investigations focused in the use of SCC with fly ash in the island, this research can encourage the use of shrinkage-reducing admixtures to prevent shrinkage cracking of concrete in Puerto Rico. That is why it is necessary to identify the benefits that SCC can accomplish and create a source for future investigations in the island. In addition to that, due to the great interest in the use of SCM in concrete, especially fly ash, which is currently available for sale on the island, this thesis focused on the use of fly ash in SCC.

1.3 OBJECTIVES

The primary objective of this research was to determine the tensile strength of concrete mixes made with shrinkage-reducing admixture (SRA) and fly ash at different curing times. The research was also conducted to evaluate the effectiveness of SRA for reducing drying shrinkage of concrete in the prevailing conditions of Puerto Rico.

To achieve this objective, the following specific tasks in the project were identified:

- Perform a comprehensive literature review on drying shrinkage, shrinkage-compensating concrete (SCC) and the use of shrinkage-reducing admixture (SRA) and fly ash on SCC.

- Plan and conduct a laboratory testing program on SCC made with shrinkage-reducing admixture and different dosages of fly ash.

- Test the tensile strength at different ages on SCC and compare the results with control mixes.

- Study the effect of SRA and fly ash in other properties of concrete including slump, drying shrinkage, and compressive strength.

- Determine the sensitivity of different concrete mix designs to curing conditions.

1.4 SCOPE OF WORK

In this research an expansive admixtures were used to produce shrinkage-compensating concrete: a shrinkage-reducing admixture (SRA), Tetraguard AS 20. Two dosage rates of SRA were used: 1) zero (as control) and 2) the maximum dosage rate recommended by the manufacturer. Fly ash was used as supplementary cementitious material. A serie of nine mixes were tested, all of them with a water-cementitious materials (*w/cm*) ratio of 0.5. The properties of the concrete tested were slump on fresh concrete, drying shrinkage, compressive strength and splitting tensile strength in the hardened concrete. Environmental conditions prevailing in Puerto Rico were considered in the work.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

2.1 INTRODUCTION

This chapter presents background information on the basics concepts of concrete shrinkage, free shrinkage, the tensile strength, tension and cracking, shrinkage-compensating concrete, and sustainable high-performance concrete. Then, a literature review on previous work related to the use of shrinkage-reducing admixtures and fly ash in concrete is presented.

2.2 BACKGROUND INFORMATION

2.2.1 SHRINKAGE: DEFINITION AND CLASSIFICATION

Shrinkage is a reduction in volume. In concrete it can be attributed to loss of moisture, but also can be generated by chemical reactions of cement with water, variations in temperature, and chemical reactions of cement with atmospheric carbon dioxide [2]. In most cases, shrinkage is measured by monitoring longitudinal strain. When tensile stresses due to restrained volume contraction exceed the tensile strength of concrete, the shrinkage leads to cracking, which is called shrinkage cracking. Shrinkage is classified based on the causes of volume change and the state of the concrete. They are classified as plastic shrinkage, drying shrinkage, autogenous shrinkage, and carbonation shrinkage.

Plastic shrinkage

Plastic shrinkage is the shrinkage that occurs due to loss of moisture of fresh concrete. This loss can be in the form of surface evaporation or for slabs on ground in moisture loss to the subgrade. Differential volume changes produce tensile stresses in concrete, which may result in the formation of cracks in the plastic concrete. Environmental considerations including solar effects, wind speed, high temperature and low relative humidity, drastically influence the potential for plastic shrinkage cracking [3]. Generally, plastic shrinkage cracking can be prevented by limiting early age evaporation with the use of mono-molecular film, water fogging or wind breaks in conjunction with properly designed concrete mixes. This type of cracking generally appears in random patterns and is shallow.

Drying shrinkage

Drying shrinkage occurs due to the loss of moisture from hardened concrete, when is exposed to air with a relative humidity less than 100 percent [2]. Among the different types of shrinkage, drying shrinkage usually results in the largest volume change. Moisture loss causes volume changes based on three mechanisms that result in changes in capillary stress, disjoining pressure, and surface free energy [4].

Capillary stress occurs between relative humidity of 45 and 95 percent, when a meniscus forms in the pore water within pores in cement paste. The meniscus is under hydrostatic tension, and adopts a curved surface. The water exerts the corresponding compression on the solid skeleton, reducing the size of the pores. The capillary stress is given by the Equation 2-1.

$$P_{cap} = \frac{2\gamma}{r} = \frac{\ln(RH)}{K} \qquad \text{2-1}$$

where:

P_{cap} = capillary stress,

r = pore radius,

γ = surface tension of the water,

RH = relative humidity, and

K = constant.

Disjoining pressure is the pressure caused by adsorbed water confined within the small spaces of capillary pores. In this narrow space, water exerts pressure on the adjacent cement surfaces. When the adsorbed water is lost, the disjoining pressure is reduced and the cement particles are drawn closer together, which results in shrinkage. As with capillary stress, disjoining pressure is significant down to about 45 percent relative humidity. Below 45 percent *RH*, shrinkage is explained by changes in surface energy. As the most strongly adsorbed water surrounding the cement particles is removed, the free surface energy of the solid increases significantly. This water has high surface tension and exerts a compressive pressure on cement particle, causing a reduction in volume [4].

Autogenous shrinkage

Also known as chemical shrinkage, autogenous shrinkage is a volume change that occurs without moisture loss to the surrounding environment. It occurs when water in cement paste is consumed by the hydration reactions. This phenomenon is known as self-desiccation of the concrete. Self-desiccation occurs in all concrete irrespectively of the water/cementitious materials (*w/cm*) ratio [5]. But this type of shrinkage is higher in mixes with low *w/cm* ratios and may increase by the use of reactive pozzolans. For concretes with *w/cm* ratios of 0.42 and greater, autogenous shrinkage is normally small and can be considered as part of drying shrinkage.

Carbonation shrinkage

Carbonation shrinkage occurs as the result of chemical reactions between hardened cement paste and carbon dioxide. It is believed that CO_2 reacts with calcium silicate hydrate (C-S-H) inducing a decrease in its calcium-silica (C/S) ratio with a concomitant water loss. Carbonation shrinkage is a function of relative humidity ***(RH)*** and is greatest around 50 percent *RH*. Carbonation shrinkage, although is not very significant itself, can be added to the effect of drying shrinkage and thereby lead to cracking.

2.2.2 FREE SHRINKAGE

"*Free shrinkage*" is the term associated with the method of test used to evaluate the shrinkage of concrete. In this method, unrestrained concrete specimens are allowed to shrink in a controlled environment. The shrinkage strain, normally the longitudinal strain, is measured at regular intervals. There are different ways in which the free shrinkage of concrete can be measured. Several test configurations, with different types of specimens, have been employed to evaluate the unrestrained shrinkage of concrete [6]. This study employs ASTM C 157, "Standard Test Method for Length Change of Hardened Hydraulic Cement Mortar and Concrete" [7] to measure the free shrinkage of concrete. This method uses rectangular concrete prisms with gage studs at each end. A mechanical dial gage length comparator is used to measure length change over time (see Figure 2-1).

The ultimate laboratory shrinkage of unrestrained concrete is typically on an order of magnitude of 0.08% (800 microstrain), with 0.04% (400 microstrain) considered low [8]. The free shrinkage test does not, by itself, evaluate the cracking tendency of concrete. There is, however, a correlation between free shrinkage and the cracking tendency of concrete. Mokaren [9] reported that the potential for cracking could be minimized by limiting the unrestrained shrinkage of concrete. They stated that, length change should be limited to 0.04% (400 microstrain) at 28 days and 0.05% (500 microstrain) at 90 days to reduce the probability of cracking due to drying shrinkage. Although free shrinkage measurements are useful in comparing different mix proportions, they do not provide sufficient information to determine if concrete will crack in service [10].

(a) (b)

Figure 2-1 Free shrinkage test set up: (a) view with the length comparator, (b) view with the test specimen.

2.2.3 TENSILE STRENGTH

The tensile strength (f'_t) of concrete is much lower than the compressive strength (f'_c) because of the ease with which cracks can propagate under tensile loads. The value of tensile strength of concrete is usually considered zero in flexural design. However it is an important property since cracking in concrete is most generally due to the tensile stresses that occur under load, or due to environmental changes [4].

No standard tests have yet been adopted by ASTM to provide a direct measurement of the tensile strength of concrete. It is most often evaluated using a flexure test, in which plain concrete is loaded in bending [11]; the ASTM and AASHTO have standard specifications for tests with center-point and third-point loadings. The

Figure 2-2, indicates that the mid-point loading results in a moment diagram that is a triangle whereas the third-point loading results in a diagram that is a trapezoid. To equal maximum moments, the third-point loading would have to be 50 percent greater than the mid-point loading. Not surprisingly, the two test yield different results. Higher strengths are obtained from the mid-point loading. The theoretical maximum tensile strength or modulus of rupture *(R or* f'_r*)* for the third-point loading is calculated from a simple formula:

$$R = \frac{Pl}{bd^2} \qquad \text{2-2}$$

where:

P = maximum load,

L = span length,

b = specimen width, and

d = specimen depth.

The results from the modulus of rupture test tend to overestimate the tensile strength of concrete by 50 to 100 percent, mainly because the flexure formula assumes a linear stress-strain relationship in concrete throughout the cross section of the beam. Nevertheless, the flexure test is usually preferred for quality control of concrete for highway and airport pavements, where the concrete is loading in bending rather than in axial tension [12].

There are really three types of test to measure the tensile strength, the two flexural tests in Figure 2-2 and the *splitting tensile test*. This test is standardized by the ASTM C 496 [13] and is a common method for estimating the tensile strength of concrete through an indirect tension test (see Figure 2-3). This method was developed in Brazil and Japan [11], and is used in some states of the United States, in part of Canada and Puerto Rico.

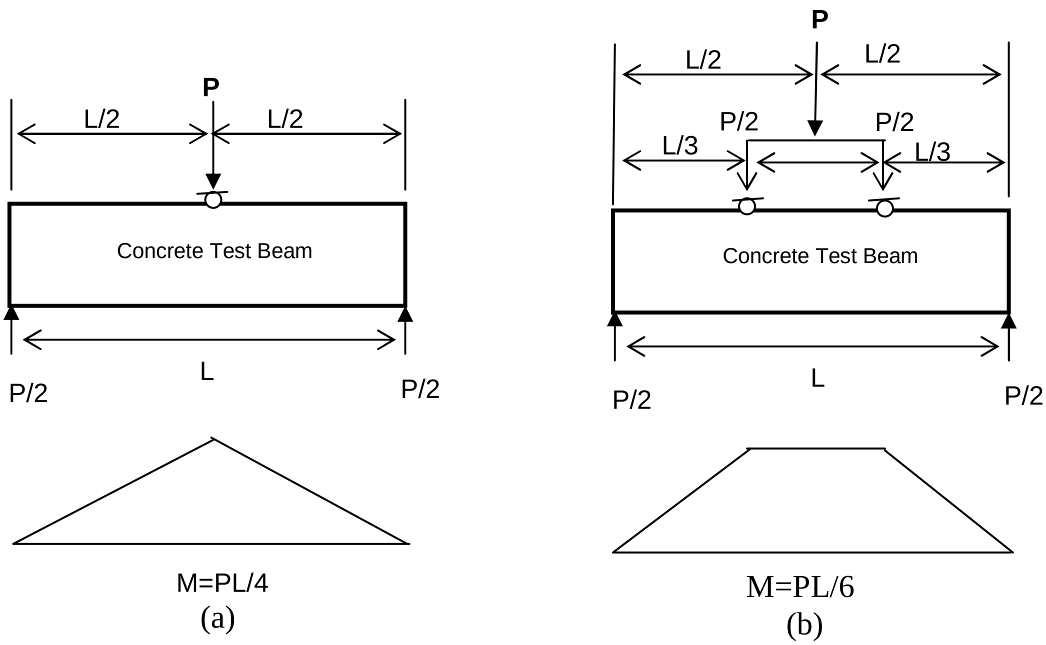


Figure 2-2 Flexure test and moment diagrams: (a) center-point loading, (b) third-point loading flexural tests.

It has the peculiarity that it uses an ordinary compression test cylinder turned on its side. This test will be used in this research to determine the tensile strength of the mixes. The cylinder is then subjected to the following horizontal stress in tension (Equation 2-3):

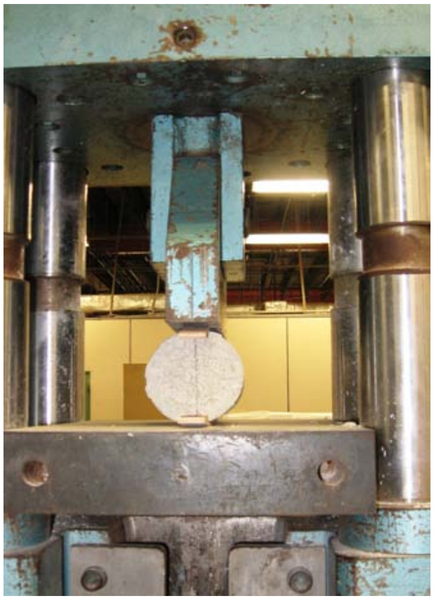
$$f'_{sp} = \frac{2P}{\pi LD} \qquad 2\text{-}3$$

where:

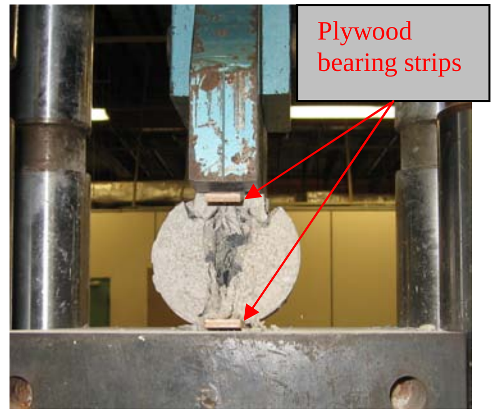
P = applied compressive load,

L = cylinder length, and

D = cylinder diameter.



(a)



(b)

Figure 2-3 Splitting tensile test set up: (a) cylinder ready for being tested (b) close up of cylinder in failure.

The compressive and tensile strength are closely related; however, there is no direct proportionality. In general, as age and strength increase, the ratio of tensile to compressive strength (f'_t/f'_c) decreases. The relationship (f'_t/f'_c) seems to be determined by the effect of various factors on properties of both the matrix and the transition zone in concrete. It is observed that not only the curing age but also the characteristics of the concrete mixture such as *w/c* ratio , type of aggregates and admixtures affects the (f'_t/f'_c) ratio to varying degrees [12]. It has been found that compared to moist curing; air curing reduces the tensile strength more than it does compressive strength, probably because of the effect of drying shrinkage cracks. Thus the (f'_t/f'_c) ratio is lower for air-cured than it is for moist-cured concrete [4]. In concrete containing calcareous aggregate or mineral admixtures, it is possible to obtain after adequate curing a relative high (f'_t/f'_c) ratio even at high levels of compressive strength. The ratio is considerably higher when fly ash is present in the concrete mix [12].

A number of expressions have been developed to represent the relationship between flexural and compressive strengths. Equation 2-4 shows the relationship used by ACI 318 [14]:

$$f'_r = 7.5\sqrt{f'_c} \qquad (\text{lb/in}^2) \qquad \text{2-4}$$

According to a study made Ahmad and Sha [15], the relationship between the splitting tensile strength and compressive strength vary widely and exhibit significant scatter (Figure 2-4).

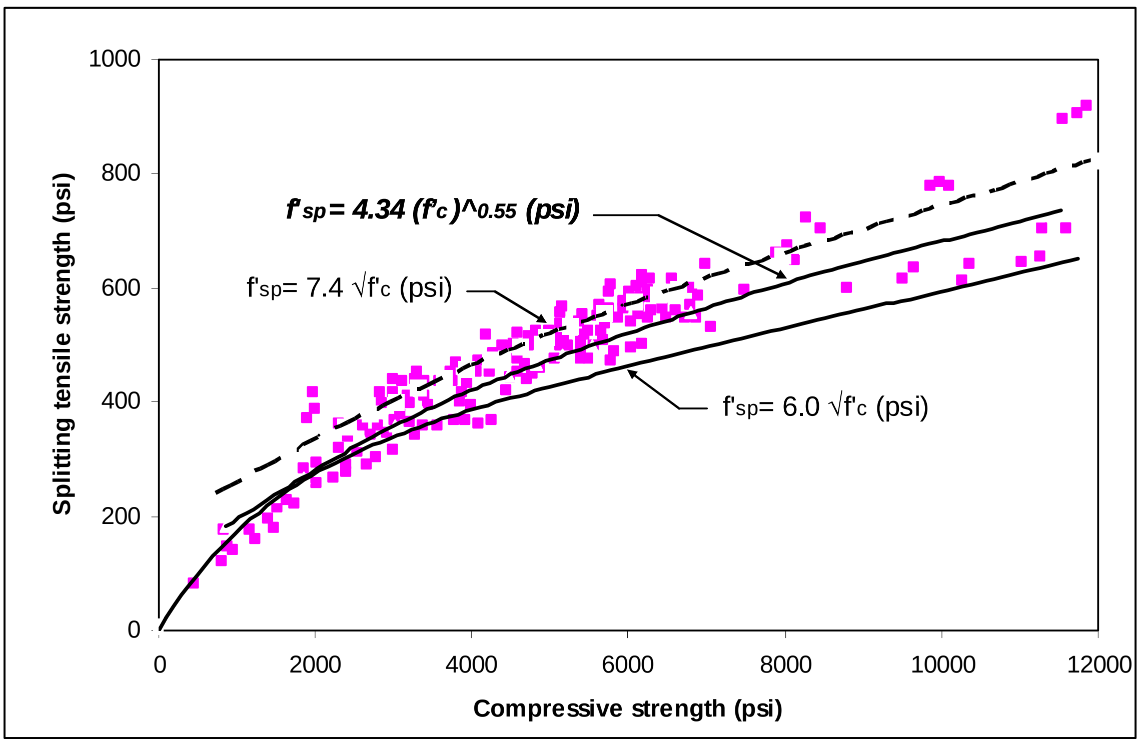


Figure 2-4 Relationship between the splitting tensile strength (f'_{sp}) and compressive strength (f'_c) of normal-weight concrete. (Adapted from Ahmad and Shah [15].)

2.2.4 TENSION AND CRACKING

Cracking in concrete occurs because it is weak in tension and has very low ductility [16]. Some of the factors that cause cracks in concrete are:

- High water content in the concrete mix which creates more drying shrinkage.
- High cement content, which in turn requires more water and results in the same problem with drying shrinkage.
- High cement content generates an extra heat through the hydration process of the cement. It produces thermal stresses that exceed the tensile strength of the concrete, particularly at early ages.
- Cycles of drying and wetting due to rain and sun cause dimensional expansion and contraction and bring out stresses in excess of the tensile strength of the concrete.
- Temperature changes cause expansion in hot weather and contraction in cold weather. That again creates tensile stresses beyond the capability of the concrete to resist it.
- Cycles of freezing and thawing generate temperature changes and ensuing dimensional changes that introduce tension beyond the capability of the concrete to withstand. Also, when the concrete is wet the forces due to freezing of the water create additional tensile stresses.
- The effect of the chloride ions on the reinforcing steel which causes rusting and expansion of the steel will in turn bring about tensile stresses in the concrete.
- Dry hot winds during placing remove the surface water fast and cause surface shrinkage and thereby cracking.

- Structural adjustments due to foundation movements by settlement or due to expansive soils bring about cracking due to the stresses exceeding the tensile strength of the concrete.

- The reaction between the alkalies in the cement and certain types of silica in aggregates causes the formation of a gel that brings out internal pressures that cause the concrete to break up in tension due to these pressures.

- Sulfate attack of the concrete that produces calcium sulfoaluminate (ettringite), which occupies larger space than the chemicals that formed it in the reaction. This again places internal pressure of crystallization that breaks up the concrete in tension.

There must be many other reasons for concrete to crack, and perhaps some variations from these basic documented reasons, but in the end, all these situations result in creating tensile stresses in the concrete that may exceed the concrete tensile strength [16]. Shrinkage cracking, which occurs as concrete losses moisture and shrinks as it dries, is one of the common types of cracking [17]. When concrete shrink freely, it will usually not crack. However in most cases concrete is not allowed to shrink freely, but it is restrained due to various components, such as reinforcing bars, fixed supports, girders, and others, which tend to restrain volume change and eventually lead to cracking [10].

Shrinkage cracking can reduce the performance life of structures, for example, leaking cracks in water retaining structures; or can cause general durability problems, for example, cracks in bridge decks that allows harmful and potentially corrosive substances to enter the concrete, causing poor durability and shorter service life [18], [19]. One solution to shrinkage cracking is the use of shrinkage-compensating concrete (SCC) made with expansive cement or expansive additives.

2.2.5 SHRINKAGE-COMPENSATING CONCRETE

According to the ACI Committee 223 [1] shrinkage-compensating concrete (SCC) is an expansive concrete which is used to minimize cracking cause by shrinkage. It is normally produced using an expansive cement call Type K cement or Type I, II, or V cement in combination with an additive that causes the volume to increase after setting. SCC made with expansive cement typically expands during the first 1 to 7 days after placement. If this expansion is properly and elastically restrained by reinforcing steel, compressive stresses are induced in the concrete. After approximately 7 days, SCC shrinks like normal concrete and the tensioned reinforcing steel acts like stretched rubber band to keep the SCC in compression while it shrinks. If everything functions as it should, the concrete decreases approximately to its original volume, and the concrete is left in a practically crack-free state. The result is a concrete that can minimize drying shrinkage cracks and offer advantages in design and construction over conventional Portland cement [20], [21].

ASTM C 845 [22] recognized three shrinkage compensating cements: Type K, Type S and Type M. The expansion of each of these cements when mixed with sufficient water is due principally to the formation of ettringite, an expansive gel created by a reaction between tricalcium aluminates and gypsum in the paste. One of the most common types of cement used in SCC is Type K Portland cement [19]. On the other hand, the expansive additive can be a shrinkage-reducing admixture (SRA) or expansive agents in form of mineral admixtures based on CaO or calcium sulfoaluminate; they also can be applied topically to concrete surfaces. Most of then function by reducing the capillary tension and the attraction forces that develop within the pore spaces of concrete as it dries [23].

Expansive cements

Early development of expansive cements took place in Russia and in France where Lossier [24] used a mix of Portland cement, an expanding agent and a stabilizer. The expanding agent was obtained by burning a mix of gypsum, bauxite and chalk, which form calcium sulfate and calcium aluminates. In the presence of water, these compounds react to form calcium sulfoaluminate hydrate (ettringite), with an accompanying expansion of the cement paste. The stabilizer, which is blast furnace slag, slowly takes up the excess calcium sulfate and brings expansion to an end [25]. Table 2-1 shows the different types of shrinkage-compensating cements and their constituents. Nowadays, only Type K is commercially available in the United States. Figure 2-5 shows the dimensional changes of SCC made with Type K cement and conventional concrete made with Type I cement.

Shrinkage-reducing admixture (SRA)

To meet the demands of the concrete construction industry to further reduce drying shrinkage, particular manufacturers of specialty construction chemicals have developed and introduced specialty shrinkage-reducing admixtures (SRAs) which have shown to provide significant reductions in concrete drying shrinkage and improved durability. The potential benefits that SRAs can provide have resulted in increased use of these products.

SRAs were first developed in Japan in 1982 in a partnership between Nihon Cement Co. and Sanyo Chemical Industries [27]. Since this invention, interest in the technology has grown and a patent number was taken out in the USA in 1985 and since this time many projects have been successfully completed using SRA [2]. Its composition varies depending on the manufacturer, but it generally consists of a surface-active organic polymer solution. It functions by reducing the capillary tension and the attraction forces that develop within the pore spaces of concrete as it dries. SRAs are predominantly low viscosity water-soluble liquids and primarily used as integral admixtures [28].

It can be applied in two ways. One is to simply spray it on top of concrete surface, called the *impregnation method* or *topical application*. The second method is to integrate it in the mix during the mixing of concrete separately from any other admixture. It has been found that the integration method provide much better results in reducing drying shrinkage [29].

Table 2-1 Shrinkage-compensating cements and their constituents [1].

Expansive cement	Principal constituents	Reactive aluminates available for ettringite formation
Type K	(A) Portland cement (B) Calcium sulfate (C) Portland-like cement containing C_4A_3S	C_4A_3S
Type M	(A) Portland cement (B)Calcium sulfate (C) Calcium-aluminates cement (CA and $C_{12}A_7$)	CA and $C_{12}A_7$
Type S	(A) Portland cement high in C_3A (B) Calcium sulfate	C_3A

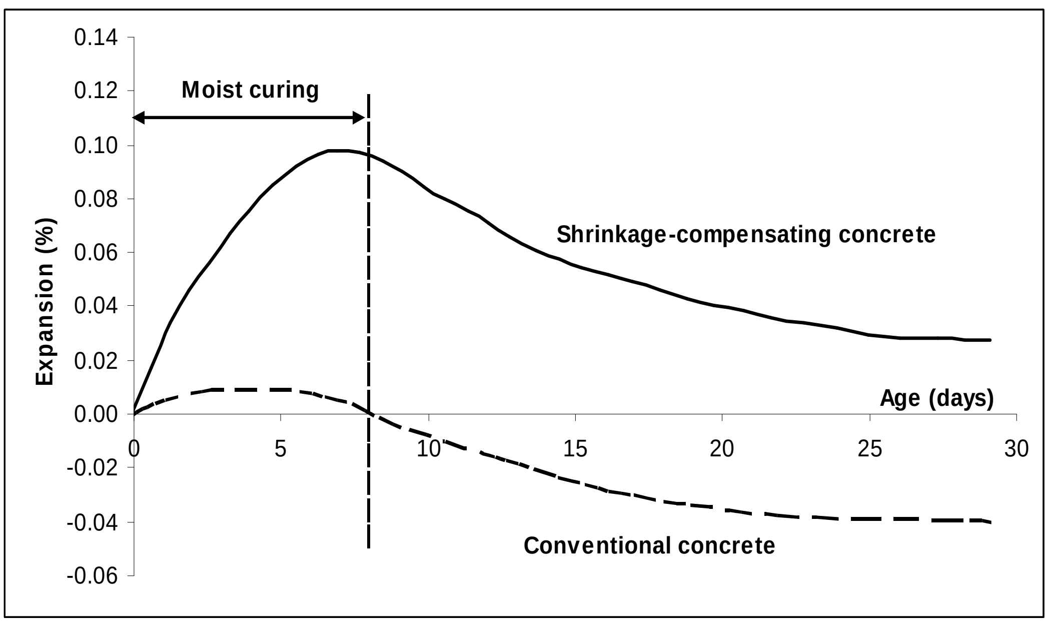


Figure 2-5 Dimensional changes of shrinkage-compensating Type K and Type I Portland cement concrete (Adapted from Bayasi and Abifaher [26]).

For the ***integral application***, the typical dosage of SRA range is 1.2 to 2.0 gal/yd^3 of concrete or it can be dosed by mass of cementitious materials in ranges from 1% to 10% [30]. However, for most applications, the recommended dosage is 1.5 gal/yd^3. The SRA can be introduced into the concrete mix either during initial batching or as a delayed addition. To maintain consistency, the mix water content is reduced by the amount of SRA used. With the exception of the adjustment in mix water content, no other changes are required when SRA is added to a concrete mix. In the topical application the SRA is brushed onto the surface or spray-applied at rates between 0.03 to 0.09 gal/ft^3. The topical application can commence any time after bleeding stops and at early concrete ages. If the SRA is used prior to final set, surface hardening may be retarded slightly [27]. Data obtained by D'Souza [28] indicated that the topical application effectively reduced drying shrinkage at 28 days, and especially at *w/c* ratios greater than 0.45.

In conclusion, the use of SRA can bring about the following benefits to concrete structures such as bridge decks, concrete pavements, tanks and others [27], [28].

- Reduce drying shrinkage cracking.
- Reduce autogenous shrinkage cracking.
- Reduce permeability.
- Less corrosion of steel reinforcing bars and steel beams, and less spalling of concrete by reducing penetration of moisture and chloride ions through micro and macro-cracks.
- Reduce curling.
- Longer joint spacing.
- Less deterioration from cracking, soaking, and spalling along joints.

- A smoother surface for pavements

- Fewer repairs, traffic congestions, accidents, and detouring.

- Lower life-cycle costs.

- Minimize or eliminates leakage of containment structures.

- Minimize or eliminates ground water contamination.

2.2.6 SUSTAINABLE HIGH-PERFORMANCE CONCRETE

The concept of sustainability for human life includes the use of energy and natural resources in a way that assumes long-term viability. What is threatening this viability is a potential shortage of energy and raw materials in the near future and unacceptable levels of environmental pollution from the solid, liquid, and gaseous waste products. For example, the threat of climate change due to global warming and greenhouse effect mostly resulting from high volumes of carbon dioxide emission increased public awareness of the environmental impact of all human activity [31]. As a major part of the world economy, the concrete industry must play an active role in sustainable development. There are few new technologies on the horizon that can reduce CO_2 emissions from the manufacturing of Portland cement, however, the answer to reducing CO_2 emissions lies in minimizing the output of cement clinker. Reduction in clinker production can be balanced by the use of fly ash and other supplementary cementitious materials such as blast furnace slag, limestone powder and silica fume [32].

Fly Ash

Fly ash is a by-product of burning ground or powdered coal in power plants. It primarily comprises very small, condensed glass spheres that are collected by electrostatic precipitators from the furnace exhaust gases. Used in concrete, fly ash acts as a pozzolan, a material that has little or no cementitious value itself, but can chemically react with calcium hydroxide (CaOH) in the presence of moisture to create calcium silicate hydrate (C-S-H), a durable cementitious compound. The calcium hydroxide needed for this pozzolanic reaction is a product of the hydration reaction of Portland cement [33]. ASTM C 618 [34] defines two classes of fly ash suitable for use in concrete, Class F and Class C fly ash.

While the two classes have identical physical characteristics, they are distinguished by their chemical compositions. For Class F fly ash, which normally results from the burning of anthracite or bituminous coal (and is the more readily available of the two), the sum of silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3) must constitute at least 70% of the ash total weight. Class F fly ash is low (typically less than 10%) in calcium oxide (CaO). For Class C fly ash, which normally results from the burning of lignite or subbituminous coal, the sum of silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3) must constitute at least 50% of the total weight. Class C fly ash has a high calcium oxide content (between 10% and 30%), and almost all of its mineral constituents are reactive, giving it both pozzolanic and cementitious properties [33].

In typical concrete mixes containing fly ash, between 15% and 35% of the total cementitious material (Portland cement, pozzolans, and reactive minerals) is fly ash. High volume fly ash (HVFA) concrete, containing a larger percentage of fly ash, can also be produced.

On the other hand, the use of fly ash in concrete can provide environmental benefits and at the same time it enhances many properties of concrete. It has been reported that the current annual production of fly ash is on the order of 900 millions tons worldwide, with major production occurring in China, India and the USA. Puerto Rico produces approximately 4 millions of cubic yards of concrete by year, which in turns generates the use of 990,000 tons of cement. Only 2 percent from the total of cement used in Puerto Rico have been replaced by supplementary cementitious materials and have achieved successful projects [35].

In addition, there are millions of tons of fly ash that has been stockpiles over the years. That is why, short-term and long-term strategies are needed to reduce the environmental impact of the concrete industry as the use of recycled products in concrete. Due to large quantities of fly ash available throughout the world, the use of high volume fly ash (HVFA) concrete, with at least 50% cement replacement by fly ash, seems to offer the best short-term solution of meeting escalating cement demands without increasing the production of Portland cement clinker. Studies by Mehta [31] have shown that HVFA concrete can be used to build crack-free and highly durable concrete structures. However, the use of fly ash requires a good understanding of the effect of substituting fly ash for a portion of the Portland cement in a given concrete mix.

The addition of fly ash may produce changes in some of the properties of the mixes. In general, fly ash has a lower density than Portland cement and the substitution of fly ash for an equal weight of Portland cement therefore increase the paste volume in the concrete and thereby enhances the plasticity of the mix. The spherical shape of the fly ash particles also contributes to the workability of concrete. Then, the use of fly ash as a partial cement replacement will usually reduce the water content of concrete at equal consistency. When a portion of cement is replaced by a Class F fly ash the concrete generally exhibits lower heat of hydration, and is therefore suitable for hot weather applications and massive concrete. Also it can prolong the setting time as well as reduce bleeding and segregation of concrete [33], [36], [37].

In the hardened properties of fly ash concrete, it should be noted that it shows slower early age compressive strength gain than regular concrete. At later ages, however, concrete containing fly ash exhibits higher compressive strength and faster strength gain due to its continued pozzolanic activity. Moreover, due to its higher calcium oxide content and reactive components, Class C fly ash produces significantly higher early compressive strength than Class F fly ash, then it can be suitable for applications where high early strength is required. Also it reduces creep and shrinkage, and its reduction in permeability is one of its primary benefits [33]. Due to the lower early strength gain of fly ash concrete, the use of HVFA with proportions of 50% or more, are not feasible to use in all situations, that is why the average dosage is relatively low, about 20% by weight of total cementitious content. Obla *et al*. [38] in search of implementing the use of HVFA concrete gave several options of how to achieve higher early strength in HVFA, and recommended fly ash content related to the type of concrete structure.

However some authors like Simons [39] declared that there is no possibility that a mix with some of the cement removed and replaced with fly ash could perform the same as a control mix with all of its cement. They proposed another method for proportioning with fly ash, including it in addition of cement and deleting the equivalent volume from the coarse and fine aggregates.

2.3 PREVIOUS WORK

As mentioned before, SRA was developed in Japan in 1982. Then on 1985 Goto *et al.* patented the product in USA, the main component of which is polyoxiyalkylene alkyl ether, a lower alcohol alkyleneoxide adduct. Since then, interest in this technology has grown and on 1997, Berke et al. patented a SRA with a similar base composition in the USA [27]. SRA has proved to be very effective by reducing the drying shrinkage on concrete and consequently, cracking due to drying shrinkage. SRA_s work by reducing the capillary tension of water and the tensile forces that develops within the pores as the water dries [2]. It has been used in a lot of projects in the Far East, particularly in Japan, since 1983. Applications include slabs, pavements, bridges, guide walls, reservoirs, filtration plants and many others structures [27].

As early as 1989, Shah *et al*. [40] studied the effect of different types and amounts of SRA in free shrinkage and other hardened properties of concrete such as compressive strength and splitting tensile strength in mixes leaving the same materials proportions. In general, they found that the addition of SRA significantly reduces the free shrinkage of concrete, and that reduction is higher when the amount of admixture is increased. It reduced slightly the compressive and splitting tensile strength, and those variations in strength were attributed to the length of curing and the amount and types of admixtures used. They also found that SRA reduced crack widths, and increase the workability. Other study made by D'Souza [28] also found similar results, indicating that reductions in drying shrinkage of up to 50% can be obtained with the use of SRA and that the percent reduction is linear with the dosage used. Also they found that SRA is compatible with traditional water reducing and accelerating admixtures, the setting times were increased by between 10% and 15% and it did not affect the slump.

Ramey *et al*. [41] evaluated fresh and hardened properties of SCC mixes made with Type K cement and SRA in five different curing conditions, varying from a good curing condition submerged in water for 7 days to a poor curing condition, exposed to ambient temperature. They found that SRA reduced drying shrinkage but not to the extent of Type K mix. Also the fresh and hardened properties of SRA were much poorer. According to the other authors mentioned before, SRA reduced the compressive strength by approximately 10% and the splitting tensile strength was reduced between 8% to 34% compared with that of the other mixes. Nevertheless the SRA postponed the shrinkage up to 30 days, so the shrinkage stresses occurred at a time when the concrete had attained higher tensile strength. They also found that the curing condition did not have significant effect in the splitting tensile strength; in fact, the 7 and 28 days strengths for the poor curing condition were higher than the strengths for the best curing condition.

In 2003, Ribeiro *et al.* [42] have reported similar results in the effectiveness of shrinkage-reducing admixtures on different concrete mixes using two SRA products at different dosage rates. All the mixes were prepared with 25% replacement of cement by Class F fly ash. Their study showed a maximum reduction in drying shrinkage of about 30% with the use of SRA and fly ash. The reduction in shrinkage was related to admixture dosage, where the maximum reduction in drying shrinkage was obtained with the maximum dosage of SRA. It was also observed that there was a reduction in compressive strength due to incorporation of SRA and fly ash. That reduction in compressive strength was more pronounced at early ages.

Then in 2006, Naik *et al.* [43] investigated and compared the effectiveness of SRAs for reducing drying and autogenous shrinkage in concrete mixes made with and without Class C fly ash. They also studied the effects on other properties of concrete, including the slump, compressive strength, splitting tensile strength and chloride ion penetration. Three different brands of shrinkage-reducing admixtures were used: 1) SRA-1: Eucon SRA from Euclid Chemical Company; 2) SRA-2: Eclipse Plus from Grace Construction Products; and 3) SRA-3: Tetraguard AS20 from Degussa (formerly Master Builders). This third product was used in this research as SRA. The researchers tested the admixtures using three based concrete mixes: A mix with 35% of the cement replaced by Class C fly ash, other without fly ash and the last one a high cementitious concrete. After 2 years of investigation they found the next conclusions:

- All three SRAs reduced the drying shrinkage and autogenous shrinkage of concrete.
- That reduction was in approximately direct proportion to the amount of SRA used.
- If the SRA was used in excess of the amount recommended dosage, the drying shrinkage was not reduced any further.
- Concrete with class C fly ash showed a slightly higher drying shrinkage.
- Concrete mixes made with SRA-1 and SRA-3 did not affect or increased the compressive strength.
- SRA-2 showed a relatively low compressive strength.
- SRA-1 and SRA-3 generally did not affect the splitting-tensile strength.
- SRA affected or improved the resistance of concrete to chloride-ion penetration.

In 2007, other study made by Suresh [44], evaluated the effects of paste volume, water-cement ratio, aggregate type, cement type, curing period, and the use of mineral admixtures and superplasticizers on the free shrinkage of concrete. Three concrete prisms were cast and tested in accordance with ASTM C 157 [7] for each mix up to an age of 365 days under controlled conditions of 73 ± 3 °F and 50 ± 4 percent relative humidity. The specimens were cured in lime saturated water for 3, 7, 14, and 28 days. The results indicated that concrete shrinkage decreases with an increase in the aggregate content and a decrease in the paste content of the mix. For a given aggregate content, no clear effect of water-cement ratio on the shrinkage was observed. In general, granite coarse aggregates resulted in lower shrinkage than limestone coarse aggregates. The used of partial volume replacement of Portland cement by Class C fly ash without changing the water or aggregate content generally leads to increased shrinkage. An increase in the curing period helped to reduce shrinkage. In the study, a significant reduction in shrinkage was observed when the curing period is increased from 7 to 14 or 28 days. The difference in shrinkage for concrete cured for three days and concrete cured for seven days was not large in many cases.

In another study using fly ash, Atis [45] reported a decrease in drying shrinkage with the use of fly ash. In his work, drying shrinkage and other properties of concrete containing high volumes of fly ash were tested. Fifty and 70 percent replacements of Portland cement using Class F fly ash were used in the mixes. A total of six mixes were made, two each with 100 percent of Portland cement (control mixes), 70 percent fly ash replacement and 50 percent fly ash replacement. The actual *w/cm* ratios ranged from 0.28 to 0.34. The optimum water content and actual *w/cm* ratios for the fly ash mixes were less than those for the control mixes. Due to the differences in specific gravities, however, the paste volume in fly ash mixes was higher. Changes in length due to drying shrinkage were measured with a mechanical dial gage. The specimens were demolded one day after casting and stored at 68 ºF and 65 percent relative humidity until the final measurement was taken at an age of six months. Two prisms were cast for each concrete mix, and the average concrete shrinkage was reported. It should be noted that with one day of curing, the reaction of fly ash with calcium hydroxide should be limited.

Significantly lower shrinkage was observed for the high volume fly ash concrete than for the control concrete. The reduction was greater with the 70 percent fly ash replacement than with the 50 percent replacement. The shrinkage at an age of six months was lowest with 70 percent fly ash concrete, medium for the 50 percent fly ash concrete, and highest for the concrete made with ordinary Portland cement. The compressive strengths of the mixes containing 70 percent fly ash were lower than the compressive strengths of the corresponding control mixes at all ages in about a 50%. The compressive strengths of mixes containing 50 percent fly ash, however, were comparable or higher than the strengths of the corresponding control mixes at 7 days of age and beyond. The author claimed that the low shrinkage properties and high strength of the high volume (up to 50 percent) fly ash concrete make this type of material a possible alternative to the ordinary Portland cement concrete used on concrete pavements and bridge decks, where shrinkage cracking is a critical consideration.

To evaluate the early age shrinkage and cracking in Nevada bridge decks, an investigation made by As-Sha [46] was conducted. Some different mix designs were prepared using SRA, shrinkage compensating cement, fly ash and various combinations of these admixtures. The test program consisted of compressive strength, drying shrinkage, modulus of rupture, chloride ion penetration, cracking tendency and other tests that considerate the weather effects in Nevada. Two different curing conditions were evaluated, both using a curing compound. In the poor curing it was used for 1 day and in the moist curing for 3 days, and then exposed to the ambient temperature and humidity of the laboratory. Class F fly ash replaced 25% of cement weight in this study. In conclusions, in agreement with the researchers above, the results suggested that SRA was very effective to reduce drying shrinkage, regardless the curing applied, but a moist cured further reduced the drying shrinkage by 15%. The reduction, was even more pronounced when fly ash was added, especially in the first days. The compressive strength was reduced with the use of SRA and fly ash but the tensile strength measured by the modulus of rupture, yielded satisfactory results compared with the ACI equations. The moist curing, improved all properties.

According to the statistical results of an investigation about concrete shrinkage cracking made in Florida in 2005 [47], the SRA did not affect the compressive strength, splitting tensile strength and modulus of elasticity. These results differ with previous studies related to the same topic. In the same study they found that the mixes containing 20 and 35 percent of Class F fly ash showed the lower free shrinkage and appeared to improve the resistance to shrinkage cracking of concrete. However, the use of SRA has been widely accepted, especially in Japan and many states of the USA, where many successfully projects have been developed using SRA [48]. Even in countries like Argentina [49] have been conducted successful projects, due to the ease of exporting chemicals admixtures that are used in low proportion, than having to import an entire batch of expansive cement.

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

This chapter describes the experimental work performed in the study. It includes the materials, mix proportions, equipments, method of preparation of the concrete mixes, and testing procedures. For the design of the mixes, available materials in Puerto Rico were used: Type I Portland cement, Class F fly ash, coarse and fine aggregate from a local source and Tetraguard AS20 as shrinkage-reducing admixture (SRA), supplied by BASF Chemical Company. No other chemical admixture was used for the mix proportions.

The laboratory testing program in this research focused mainly on drying shrinkage, splitting tensile strength and compressive strength of concrete made with SRA and different dosages of fly ash in two different curing conditions: submerged in lime-saturated water for 3 days and the same mix submerged for 7 days. After that they were exposed to an average ambient temperature of 82 ^{o}F and approximately 70 to 80 percent relative humidity ***(RH)*** until tested for strength. ACI 308 [50] suggests seven days of moist curing for most structural concrete. Thus, in this research, 7 days curing represents a good cured and 3 days curing a poor cured. These curing conditions were performed at the facilities of the Civil Engineering Materials Laboratory at the University of Puerto Rico, Mayaguez campus.

To fulfill the objectives, the laboratory materials testing program consisted in the development of SCC made with SRA and fly ash in these proportions: 0%, 10%, 20%, 30%, and 50% of weight of cement replaced by fly ash, and a control mix. The primary target was to determine early-age splitting tensile strength and drying shrinkage of the mixes under the two different curing conditions. Another two concrete mix designs were prepared using Type I Portland cement, SRA and 30% of fly ash as cement replacement and a control one. Those mixes were evaluated under three curing conditions, 3, 7 and 28 days submerged in water, and then tested in tension and compression at 28 and 56 days. The objective was to identify the influence of the water curing days in the development of strength of SCC with fly ash.

As explained in the literature review, the use of fly ash in concrete tends to reduce the early strengths up to 28 days but improves the ultimate strength. That is why the mixes were tested up to 56 days. To facilitate the execution of a parametric study on the properties of the concrete mixes, the plan required that the quantities of the coarse aggregate, fine aggregate, SRA and the water/cementitious materials (*w/cm*) ratio stay constant.

3.2 FACILITIES

Preparation of the specimens for this work was performed at the materials laboratory of CEMEX (Cementos Mexicanos) located in Carolina, Puerto Rico. CEMEX Puerto Rico supplied the Portland cement and aggregates needed for the mixes. At 24 hours after mixing procedure, mixes were moved to the facilities of the Civil Engineering Materials Laboratory at the University of Puerto Rico, Mayagüez campus (UPRM) to perform the various curing conditions and to perform the different tests on the hardened concrete.

3.3 MATERIALS

The materials that were used to prepare the mixes and their specifications are reported in this section:

3.3.1 CEMENT

CEMEX Puerto Rico provided the Type I Portland cement used in the concrete mixes that were prepared for the project. The physical characteristics and the chemical composition of the cement are present in Table 3-1 and Table 3-2, respectively. The cement met the chemical and physical requirements of ASTM C 150 "Standard Specification for Portland Cement" [51].

Table 3-1 Physical characteristics of Type I Portland cement.

ASTM	Item	Test Result	Standard requirement of ASTM C 150 for Type I cement
C 185	Air content of mortar (volume %)	6	12 maximum
C 204	Fineness (specific surface) by Blaine air-permeability apparatus (m^2/kg)	346	280 minimum
C 151	Autoclave expansion (%)	0.07	0.80 maximum
C 109	Compressive strength of cement mortars (psi):		
	1 day	2080	--
	3 days	3590	1740 minimum
	7 days	4400	2760 minimum
	28 days	5620	--
C 191	Initial time of setting by Vicat needle (minutes)	105	Between 45 to 375
C 188	Density (lb/ft^3)	94	--
C 150	Specific gravity	3.15	3.15
	Physical appearance	Gray	

Table 3-2 Chemical composition of Type I Portland cement.

Item	Test result (% by mass)	Standard requirement of ASTM C 150 for Type I cement
Silicon Dioxide, SiO_2	20.55	--
Aluminum Oxide, Al_2O_3	5.35	--
Ferric Oxide, Fe_2O_3	2.60	--
Calcium Oxide, CaO	65.50	--
Magnesium Oxide, MgO	1.45	6.0 maximum
Sulfur Trioxide, SO_3	2.42	3.0 maximum, when $C_3A \leq 8\%$ 3.5 maximum, when $C_3A > 8\%$
Loss of ignition	1.28	3 maximum
Insoluble residue	0.15	0.75 maximum
Potassium Oxide K_2O	0.20	--
Sodium Monoxide Na_2O	0.40	--

3.3.2 FLY ASH

Class F fly ash, derived from naturally occurring coal was provided by The Company Bloques Carmelo in Puerto Rico. It met the requirements of ASTM C 618 “Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete” [34]. The chemical composition and physical characteristics are shown in Table 3-3 and Table 3-4, respectively.

Table 3-3 Chemical composition of Class F fly ash.

Ingredients	Formula	%
Aluminosilicate Glass	Contains Al, Si, Fe, Ca, Mg, Ti	85 - 95
Crystalline Silica (total)	SiO_2	5 - 10
Crystalline Silica (respirable)	SiO_2	ND
Iron Mineral Dusts	Fe_2O_3, Fe_3O_4	0 - 5

Table 3-4 Physical characteristics of Class F fly ash.

Property	Value
Appearance	Gray to tan color
Odor	No odor
Average particle size	10 - 20 microns
Specific Gravity (H_2O=1)	2.2 - 2.8
Melting point	> 2000 ^oF
Water reactive	No reactive

3.3.3 FINE AGGREGATE

Manufactured sand from Carmelo Quarry at Vega Baja, Puerto Rico, was used as fine aggregate for the concrete mixes. The sand had oven dry bulk specific gravity of 2.52 and 2.774% of absorption.

Figure 3-1 and Figure 3-2 show the sieves and fine aggregate used in the laboratory, respectively. Sieve analysis results are reported in Table 3-5 along with the grading requirements of ASTM C 33 [52]. The gradation plot of the sand is displayed in Table 3-5.

Figure 3-1 Sieves used for sand gradation.

Figure 3-2 Fine aggregate used.

Table 3-5 Sieve analysis of fine aggregate (manufactured sand).

Sieve Analysis					
Initial weight = 500 gr.					
Sieve number	Weight retained	Percent retained	Cumulative percent retained	Percent passing	ASTM C 33 specification (%)
3/8 in	0.00	0.00%	0.00%	100.00%	100
No.4	1.80	0.36%	0.36%	99.64%	95 to 100
No.8	72.83	14.58%	14.94%	85.06%	80 to 100
No.16	136.55	27.34%	42.29%	57.71%	50 to 85
No.30	92.85	18.59%	60.88%	39.12%	25 to 60
No.50	61.98	12.41%	73.29%	26.71%	5 to 30
No.100	39.73	7.96%	81.25%	18.75%	0 to 10
No.200	25.22	5.05%	86.30%	13.70%	
Pan	68.43	13.70%	100.00%	0.00%	
Total	499.39				
% loss	0.12	Fineness modulus		2.73	2.3 - 3.1

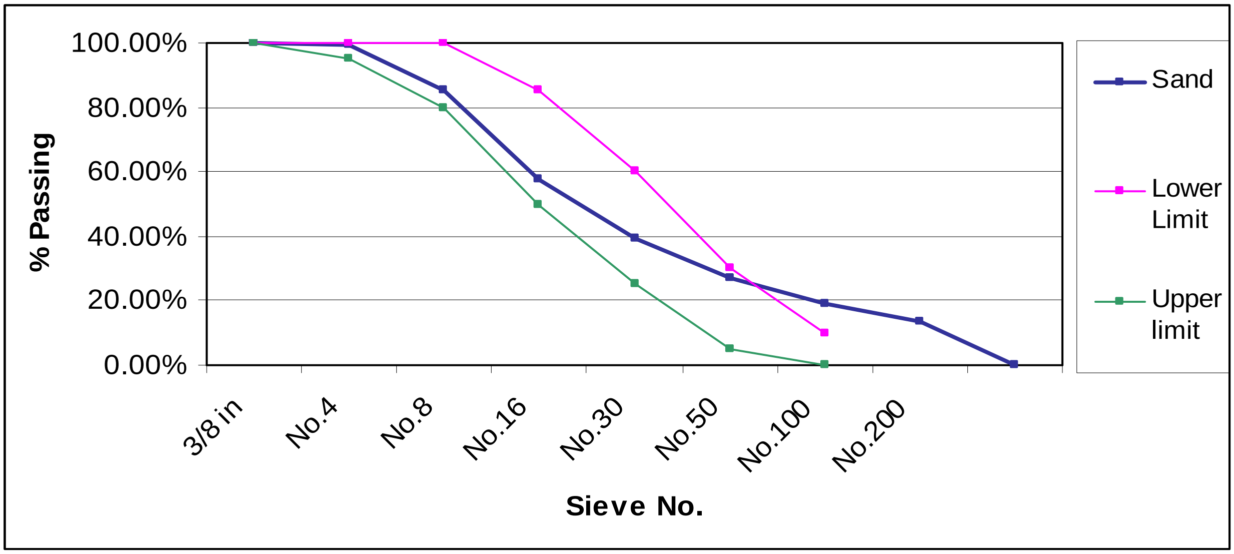


Figure 3-3 Gradation plot for fine aggregate.

3.3.4 COARSE AGGREGATE

The coarse aggregate used was # 56 stone from Carraizo Quarry at Guaynabo, Puerto Rico. The coarse aggregate had a nominal maximum size of ¾ in, an oven dry bulk specific gravity of 2.7 and absorption of 1.69%. It met the requirements of ASTM C 33. Figure 3-4 shows the coarse aggregate used in the mixes. Sieve analysis results for coarse aggregate are presented in Table 3-6 and the gradation plot is displayed in Figure 3-5.

Figure 3-4 Coarse aggregate used.

Table 3-6 Sieve analysis of coarse aggregate

Sieve Analysis					
Initial weight = 25 pounds					
Sieve number	Weight retained	Percent retained	Cumulative percent retained	Percent passing	ASTM C 33 specification
1 1/2"	0.00	0.00%	0.00%	100.00%	100
1"	0.00	0.00%	0.00%	100.00%	90 to 100
3/4"	3.10	12.40%	12.40%	87.60%	40 to 85
1/2"	18.50	74.00%	86.40%	13.60%	10 to 40
3/8"	2.70	10.80%	97.20%	2.80%	0 to 15
No.4	0.55	2.20%	99.40%	0.60%	0 to 5
Pan	0.15	0.60%	100.00%	0.00%	
Total	25.00				
% loss	0.00			Grading	# 56

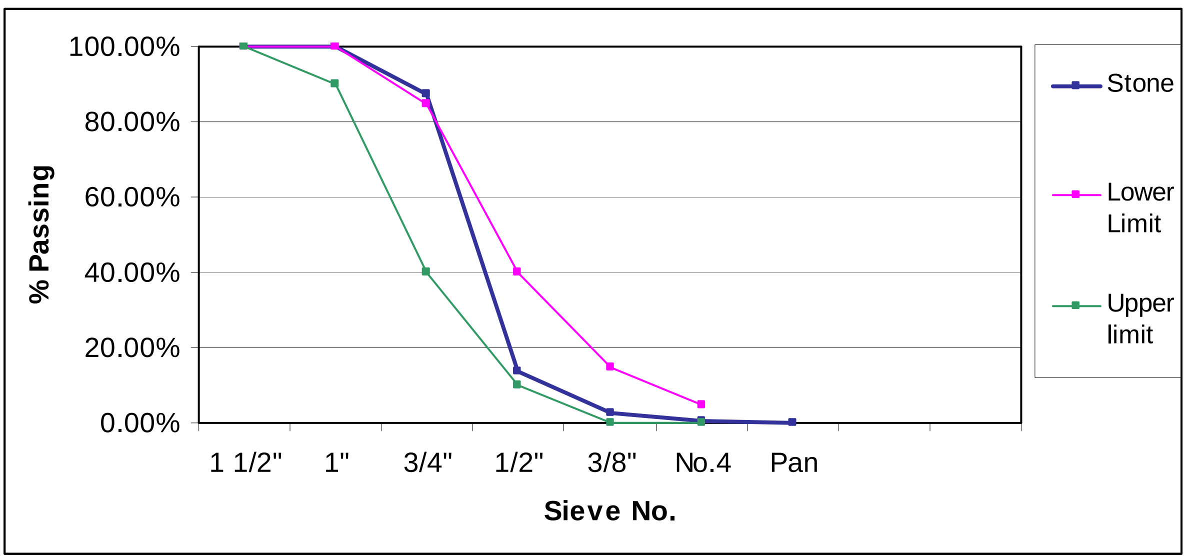


Figure 3-5 Gradation plot for coarse aggregate.

3.3.5 SHRINKAGE-REDUCING ADMIXTURE (SRA)

Tetraguard AS20 based on Polyoxyalkylene alkyl ether supplied by BASF Chemical Company was used to create shrinkage-compensating concrete (SCC) mixes. Tetraguard is the first commercially available chemical admixture developed specifically to reduce drying shrinkage of concrete and mortar, and the potential for subsequent cracking. It has been used in the Far East and North American constructions since its introduction in 1985. It is a clear liquid admixture that functions by reducing capillary tension of pore water. Significantly reduces drying shrinkage by as much as 80% at 28 days and up to 50% at one year and beyond. The typical dosage range of Tetraguard AS20 is 0.5 to 1.5 gal/yd^3 [53]. In this study 1.5 gal/yd^3 of the admixture was used in SCC mixes. The focus was not to observe the effect of variation in SRA dosages, rather to observe if the SRA was efficient in reducing drying shrinkage.

3.3.6 MATERIALS STORAGE

The cementitious materials: cement and fly ash, and SRA, were stored in the laboratory, protected from weather conditions. The cement and fly ash were in its sealed bucket until used. The admixture containers were opened only before each trial mix batching. The fine and coarse aggregates were stored in a large plastic box and kept outdoors.

3.4 MIX DESIGNATIONS

The designation of a concrete mix was based on whether it was a conventional Portland cement concrete (PCC) or a shrinkage-compensating concrete (SCC) made with SRA. It also was based on the percentage of fly ash used as cement replacement and curing time.

PCC = control mix, SCC = Mix with SRA

XXX-XX-XX (X) → Indicates the curing time

Indicate the % of fly ash (FA) as cement replacement

For example: SCC-30-FA(3) = Concrete mix with a fix dosage of SRA and 30% of fly ash as cement replacement, cured for 3 days.

3.5 MIX PROPORTIONS

Five mixes were prepared with SRA and (0%, 10%, 20%, 30% and 50%) of Type I cement replaced with class F fly ash. Two control mixes: 1) without SRA and fly ash and 2) without SRA but 30% of cement replacement by fly ash. These mixes were used to evaluate the effect of different dosages of fly ash in different curing periods (3 and 7 days submerged in water) on the mechanical properties of concrete such as slump, drying shrinkage, splitting tensile strength and compressive strength.

Two additional concrete mixes were made: 1) mix with SRA and 30% of fly ash and 2) a control mix. Both of them were cured for 3, 7 and 28 days in water and tested in tension and compression at 28 and 56 days. The objective was to evaluate the relationship of curing time on the strength gain on these concrete mixes.

Table 3-7 shows the materials proportions of each mix used in the research. The aggregates moisture content was taken immediately before each trial mix batching with an electrical humidifier, Ohaus MB35, shown in Figure 3-6.

Table 3-7 Mix proportions.

Mix designation	Cement (lb/yd^3)	Coarse aggregate (lb/yd^3)	Fine aggregate (lb/yd^3)	Fly ash (lb/yd^3)	Design water (lb/yd^3)	SRA (onz/yd^3)	*w/cm* ratio
PCC-00-FA	578	1600	1525	0	292	0	0.5
SCC-00-FA	578	1600	1512	0	292	192	0.5
SCC-10-FA	520	1600	1521	58	292	192	0.5
SCC-20-FA	462	1600	1506	116	292	192	0.5
SCC-30-FA	414	1600	1489	169	292	192	0.5
SCC-50-FA	291	1600	1459	291	292	192	0.5
PCC-30-FA	414	1600	1489	169	292	0	0.5

(a) (b)

Figure 3-6 Electrical humidifier: (a) open with a sand sample and (b) closed and working

3.6 PREPARATION OF CONCRETE MIXES

A total of nine concrete mixes, based on seven mix designs, were produced and tested in this research. The concrete mixer used was an electrical rotary Gilson mixer with capacity of 3 ft^3, as shown in Figure 3-7.and. Test specimens of concrete were made and cured according to the ASTM C 192 [54].

(a)

(b)

Figure 3-7 Rotary mixer used: (a) lateral view and (b) mixer in motion.

3.6.1 MIXING OF CONCRETE

The next procedure of mixing concrete was followed in the preparation of each concrete mix:

- The materials were weight into 25 liters (5 gallons) buckets before each trial mix batching.

- The surface of the interior portion of the drum was rinsed with water to avoid absorption.

- Prior to starting rotation of the mixer, the coarse aggregate and part of the mixing water were added. The drum was started and running for about 2 minutes.

- After that, the drum was stopped and part of the fine aggregate, the cementitious materials and finally the remaining fine aggregate were added in that order, to avoid loss of cementitious materials. The mixing was continued for an additional 3 minutes.

- The remaining water was mixed with the SRA and added slowly into the drum in motion.

- After all ingredients were in the mixer, the concrete was mixed for about 5 minutes. The mixer was stopped if necessary, to remove any material that sticked to the drum.

- It was followed by 3 minutes rest and then 2 minutes of final mixing.

- The trial batch was discharged into a wheelbarrow (Figure 3-8) and tested for slump as shown in Figure 3-9. Immediately after that, the drum was cleaned with water.

Figure 3-8 Wheelbarrow with concrete mix.

Figure 3-9. Slump test.

3.6.2 PREPARATION OF CONCRETE SPECIMENS AND CASTING

The next procedures were followed in the preparation of each concrete specimen:

- The 36 (4 x 8 in) cylindrical molds and 4 (3 x 3 x 11.25 in) square prism specimens, of each mix were covered with oil before placing the concrete.
- Each mold was filled with fresh concrete to one half of its height and vibrated for 20 seconds on a vibrating (see Figure 3-10).
- The second layer of concrete was then placed and vibrated similarly to the first layer.
- The excess concrete was then removed and the surface of the concrete was finished with a hand trowel and cover with a plastic cap to prevent water evaporation.
- Specimens were moved from the vibrating table to the casting room floor for initial curing, as shown in Figure 3-11.
- After 24 hours, the concrete specimens were demolded and relocated to the laboratory at UPRM for proper curing until the specific test (compressive strength, splitting tensile strength and free shrinkage test) were performed at the specified curing times (such as 3, 5, 7, and 28 days).

3.6.3 CURING

After all cylindrical specimens were stripped from their molds they were placed in lime-saturated water in a curing tank at approximately (77 ± 5 ^{o}F) for additional 2 days, giving a total curing period of 3 days for each specimen. Curing periods of 3, 5, 7, and 28 days were used in this project. After curing in lime-saturated water, the specimens were allowed to dry in laboratory conditions with an average temperature of 82 ^{o}F and 75 RH, approximately. Figure 3-12 shows the curing tank in the laboratory.

Figure 3-10 Vibrating table used.

Figure 3-11 Specimens after filled.

In accordance with ASTM C 157, the square specimens for free shrinkage measurement were demolded at 23½ ± ½ hours after casting. The initial reading was immediately taken on the specimens using the length comparator. The specimens were placed in a plastic container with lime-saturated water for additional two days at 77 ± 5 °F (see Figure 3-13) giving a total curing period of three days for each specimen. Curing periods of 3 and 7 days were used for the beams in the free shrinkage test. After curing in lime-saturated water, the specimens were allowed to dry in laboratory conditions as described before.

Figure 3-12 Curing tank with concrete specimens.

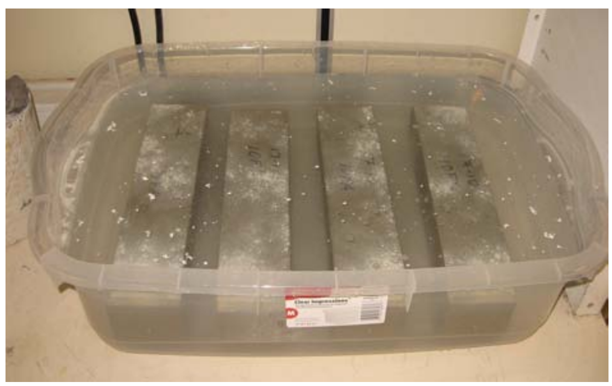


Figure 3-13 Beams for free shrinkage cured in lime-saturated water.

3.7 LABORATORY TESTING PROGRAM

This section describes the laboratory testing program conducted to evaluate the mechanical properties of the concrete mixes on fresh and hardened concrete such as slump, splitting tensile strength, compressive strength and free shrinkage test. It includes the description of the test and the appropriated instrumentation.

3.7.1 TEST ON FRESH CONCRETE

The following test was performed on fresh concrete:

- Slump test (ASTM C 143 [55]) (see Figure 3-14)

Figure 3-14 Slump test in fresh concrete.

3.7.2 TEST ON HARDENED CONCRETE

The following tests were performed in the hardened concrete:

- Compressive strength (ASTM C 39). Using 4 x 8 in. cylindrical specimens, tested at 7, 28, and 56 days under different curing conditions. (2 replicates per condition).

- Splitting tensile strength (ASTM C 496). Using 4 x 8 in. cylindrical specimens, tested at 3, 5, 7, 28, and 56 days under different curing conditions. (2 replicates per condition).

- Free shrinkage test (ASTM C 157). Using 3 x 3 x 11.25 in. square specimens (beams), tested at 3, 5, 7 days and then every week up to 56 days, under different curing conditions. (2 replicates per condition).

Compressive strength test

The compressive strength test was made in accordance of ASTM C 39 [56] using 4 x 8 in. specimens. The testing machine used was a FORNEY model LT-900-2 with a capacity of 600000 pounds. The entire test was run with a loading rate between 250 and 650 pounds per second. Figure 3-15 shows a specimen ready to be tested in the FORNEY machine. Figure 3-16 shows the instrumentation panel of the testing machine. Two or three 4 x 8 in. cylindrical specimens per batch per curing condition were tested to gather the data.

For each trial mix design, 12 cylinders (4 x 8 in) were cast. After 24 hours, all of them were cured as described in section 3.6.3. Six cylinders were left to cure until 3 days and the other six cylinders for 7 days. The specimens for the first 7 mixes were tested in the laboratory for compressive strength when they reached the age of 7, 28 and 56 days. Then, for the two other mixes, 18 cylinders (4 x 8 in) were prepared, six of them were cured for 3 days, other six for 7 days and the last six for 28 days. Then, the specimens were tested when they reached the 28 and 56 days. The results of this test are presented in Chapter 4.

The compressive strength was calculated using the following Equation 3-1:

$$f'_c = \frac{P}{A} \qquad \text{3-1}$$

where:

f'_c = ultimate compressive strength in lb/in^2 (psi),

P = ultimate load attained during the test in pounds (lb), and

A = loading area in square inches (in^2).

Figure 3-15 Compressive strength test of concrete.

Figure 3-16 Load indicator of the compressive machine.

Splitting tensile strength test

The splitting tensile strength test was made in accordance of ASTM C 496 [13] using 4 x 8 in. specimens and the same testing machine used for compressive strength test. The entire test was run with a loading rate between 250 and 650 pounds per second. Figure 3-17 shows a specimen ready to be tested in the FORNEY machine. Figure 3-18 shows a close up of the specimen after failure. Two or three 4 x 8 in cylindrical specimens per batch per curing condition were tested for the analysis.

The specimens were tested for splitting tensile strength when they reached the age of 3, 5, 7, 14, 28 and 56 days. Seven mixes were cured for 3 and 7 days. Two other mixes were cured for 3, 7 and 28 days, those mixes were tested when they reached the 28 and 56 days. The results of this test are presented in Chapter 4.

Figure 3-17 Splitting tensile strength test of concrete.

The splitting tensile strength was calculated using the following Equation 3-2, as was mentioned in the literature review:

$$f'_t = \frac{2P}{\pi LD} \qquad \text{3-2}$$

where:

f'_t = ultimate splitting tensile strength in lb/in^2 (psi),

P = ultimate load attained during the test in pounds (lb),

L = length of the cylindrical specimen (in), and

D = diameter of the cylindrical specimen (in).

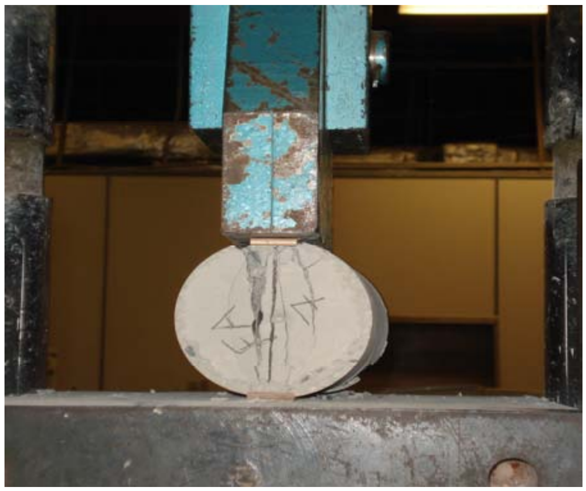


Figure 3-18 Specimen in failure.

Free shrinkage test

The free shrinkage test was made according to the ASTM C 157 [7]. Square prism specimens (3 x 3 x 11.25 in) were used in the test. Figure 3-19 shows the mold used and concrete beam. In Figure 3-20 a diagram of the molds used is presented. Figure 3-21 show the cross-section of the concrete beam with the specified measures.

(a) (b)

Figure 3-19 Free shrinkage test: (a) Molds used and (b) concrete beam sample.

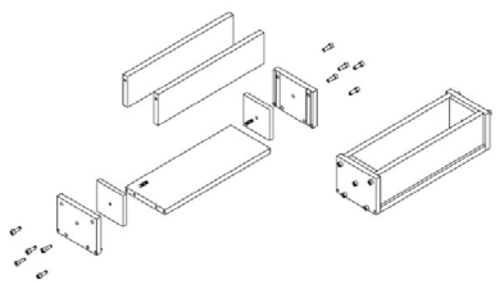


Figure 3-20 Diagram of free shrinkage specimen mold.

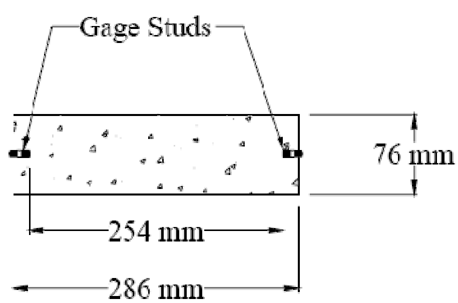


Figure 3-21 Cross-section of the free shrinkage specimen.

Figure 3-22 shows a length comparator. It measures the relative length, compared to a reference bar in accordance with ASTM C 157. A reference bar was used to establish a reference reading before the specimens in each batch were read. The dial gage was read with the reference bar in the comparator for each batch of specimens and then the comparator dial was read with the specimens in the comparator. Care was taken to position the specimen in such a way that the same side of the specimen was at top during the measurement every time. The initial Comparator Reading Difference (CDR) that is the difference between the comparator reading of a specimen and that of the bar was recorded immediately after demolding (see Figure 3-23). The length change at a given age was calculated as the difference between the CRD at that age and the initial CRD.

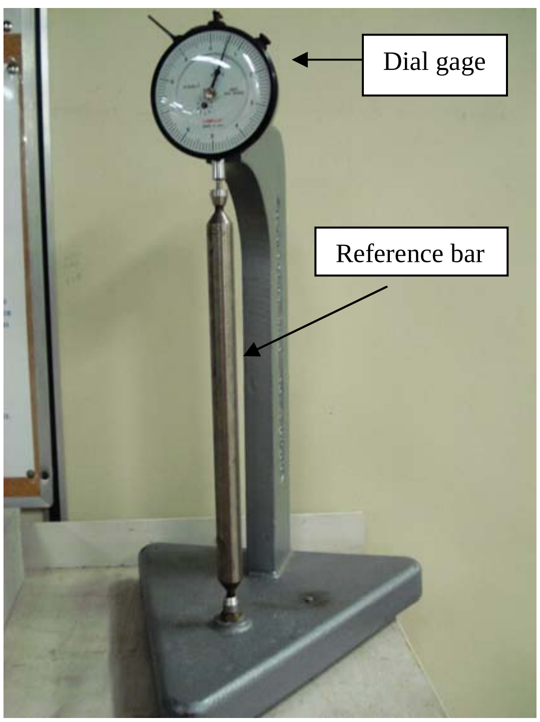


Figure 3-22 Length comparator.

Figure 3-23 Free shrinkage test set up.

The strain was calculated as the length change divided by the gage length of 10 in. The shrinkage or expansion, in microstrain, for any batch is reported as the average strain of two specimens at a given age. Frequent measurements were made in this study to obtain a better comparison between the shrinkage behavior of the batches. Readings were recorded in alternate days for a period of 7 days and then every week up to 56 days in every specimen for all trial mix designs. The tests results are presented in Chapter 4.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 INTRODUCTION

This chapter presents the results of the laboratory testing program described in Chapter 3. As indicated in that chapter, the investigation was focused in the tensile strength of concrete mixes made with SRA and fly ash (FA). Other properties such as slump, free shrinkage and compressive strength were also evaluated. The influence of SRA, fly ash and curing time in the fresh and hardened properties of concrete were analyzed. Finally the discussions of the results are presented.

4.2 TEST RESULTS

This research included tests for slump, free shrinkage, splitting tensile strength and compressive strength on 9 different mixes. The effects of SRA, percent of fly ash and curing time in each of the test are evaluated and discussed in this section. The mixes were designated as follows:

PCC-00-FA	Control mix, no SRA, no FA
PCC-30-FA	Control mix for fly ash, no SRA, 30% of cement replaced by FA
SCC-00-FA	Concrete with SRA and 0% of cement replaced by FA
SCC-10-FA	Concrete with SRA and 10% of cement replaced by FA
SCC-20-FA	Concrete with SRA and 20% of cement replaced by FA
SCC-30-FA	Concrete with SRA and 30% of cement replaced by FA

SCC-50-FA	Concrete with SRA and 50% of cement replaced by FA

The mix designs for these concrete mixes are described in Table 3-7 in Chapter 3. As explained in that chapter, all mixes had the same *w/cm* ratio of 0.5 and SRA used was 1.5 gallon per cubic yard of concrete. The fly ash substituted the specified percent by weight of cement used. Mixes were subjected to 3 and 7 days of curing.

4.2.1 SLUMP TEST (ASTM C 143)

Table 4-1 shows the slump in inches and the percentage difference with respect to the control mix. As shown in Table 4-1, the use of SRA in concrete increased the slump in 17% compared with that of the control mix. Using 30% of fly ash in concrete the slump was increased in a 50% compared to the no-fly ash concrete. Figure 4-1 shows the influence of fly ahs content in concrete slump. The use of fly ash and SRA significantly affected the workability of the concrete. Figure 4-1 shows the influence of fly ash content of SCC mixes in the slump.

Table 4-1 Slump in concrete mixes with fly ash and SRA.

Mix Designation	Slump (in)	% Increase
PCC-00-FA *	3.0	0
PCC-30-FA	4.5	50
SCC-00-FA	3.5	17
SCC-10-FA	4.0	33
SCC-20-FA	4.5	50
SCC-30-FA	5.5	83
SCC-50-FA	8.5	183

* Control mix.

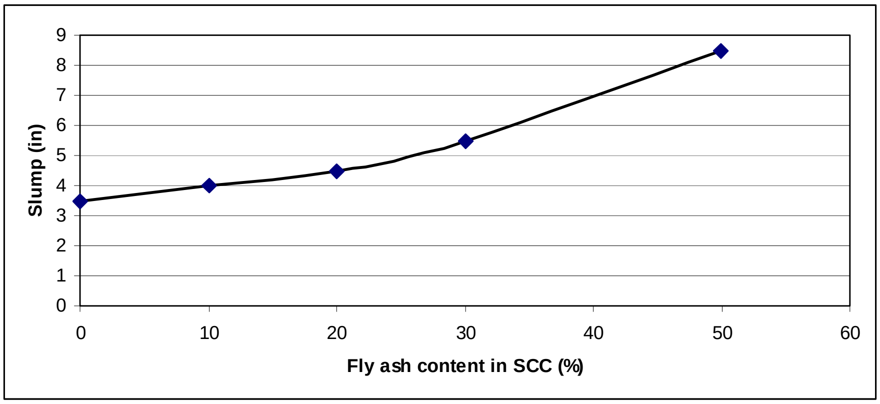


Figure 4-1 Influence of fly ash content in slump.

4.2.2 FREE SHRINKAGE TEST (ASTM C 157)

The tests results of the free shrinkage of concrete mixes cured for 3 days and 7 days are presented in Table 4-2 and Table 4-3, respectively. The values of free shrinkage strain measurement in units of microstrain (10^{-6}) represent the average of two specimens for each curing condition. The relation of the free shrinkage strains and the time of measurement for all mixes cured for 3 and 7 days are plotted in Figure 4-2 and Figure 4-3, respectively. It can be seen that the largest shrinkage strain for both curing conditions occurred in the control mix, followed by the mix containing fly ash with no SRA and finally mixes with SRA and fly ash.

The percentage reduction in free shrinkage strains of the mixes containing SRA and fly ash compared with the control mixes were computed and presented in Table 4-4 and Table 4-5 at 3-days and 7-days curing, respectively. Percentage reduction was calculated at 14 days up to 56 days. That was because most of the concrete mixes had begun to shrink from that day.

Table 4-2 Free shrinkage strains of the concrete mixes cured for 3 days.

Time[1] (days)[2]	Free Shrinkage						
	Average Length Change (microstrains) of Mixes Cured for 3 Days						
	PCC-00-FA	**PCC-30-FA**	**SCC-00-FA**	**SCC-10-FA**	**SCC-20-FA**	**SCC-30-FA**	**SCC-50-FA**
3	-1	10	22	-45	138	63	183
5	-193	-12	22	53	45	75	172
7	-185	-7	-20	-8	10	-75	115
14	-283	-164	-78	-53	26	-90	-26
21	-441	-245	-148	-225	-49	-105	-108
28	-448	-309	-187	-121	-128	-35	-200
35	-557	-367	-215	-189	-168	-67	-260
42	-600	-410	-220	-190	-130	-100	-290
49	-614	-425	-268	-225	-183	-199	-338
56	-463	-440	-282	-230	-130	-282	-337

[1] Time of measurement. [2] Denotes days after casting.

Negative sign means shrinkage, positive sign means expansion.

Table 4-3 Free shrinkage strains of the concrete mixes cured for 7 days.

Time[1] (days)[2]	Free Shrinkage						
	Average Length Change (microstrains) of Mixes Cured for 7 Days						
	PCC-00-FA	**PCC-30-FA**	**SCC-00-FA**	**SCC-10-FA**	**SCC-20-FA**	**SCC-30-FA**	**SCC-50-FA**
3	-1	10	22	-45	138	63	183
5	18	55	-20	20	200	165	60
7	-30	100	-18	5	240	35	103
14	-167	-70	-123	-65	141	21	3
21	-268	-143	-173	-135	82	5	-145
28	-335	-207	-196	-163	3	40	-195
35	-400	-253	-247	-219	-43	14	-241
42	-433	-293	-279	-255	-8	-12	-262
49	-536	-324	-298	-252	-70	-115	-307
56	-540	-355	-325	-250	-13	-185	-311

[1] Time of measurement. [2] Denotes days after casting.

Negative sign means shrinkage, positive sign means expansion.

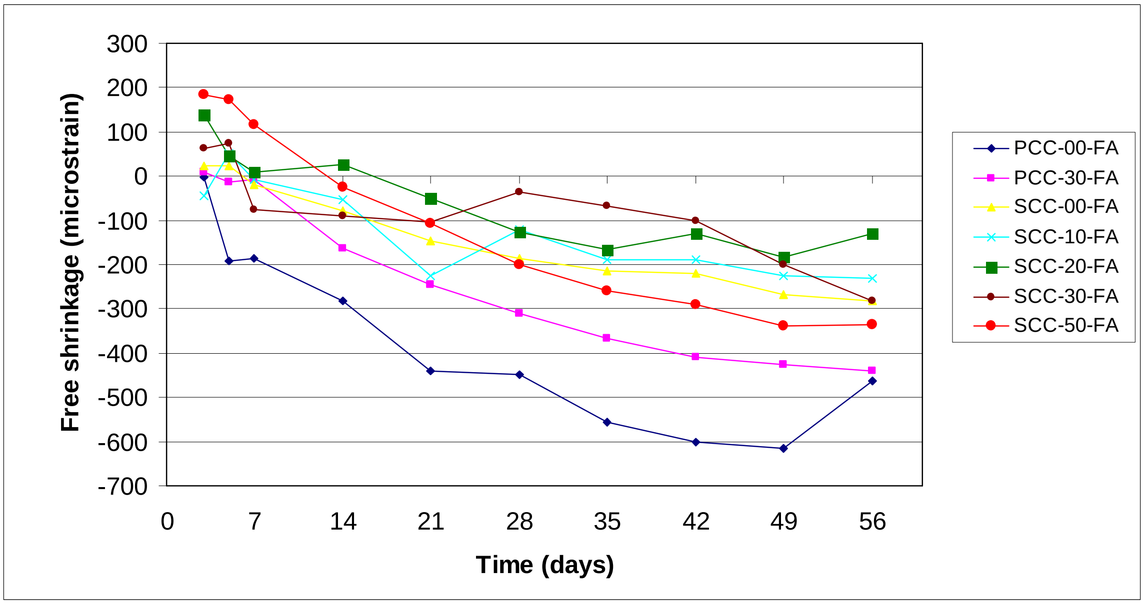


Figure 4-2 Free shrinkage strains vs. time of concrete mixes cured for 3 days.

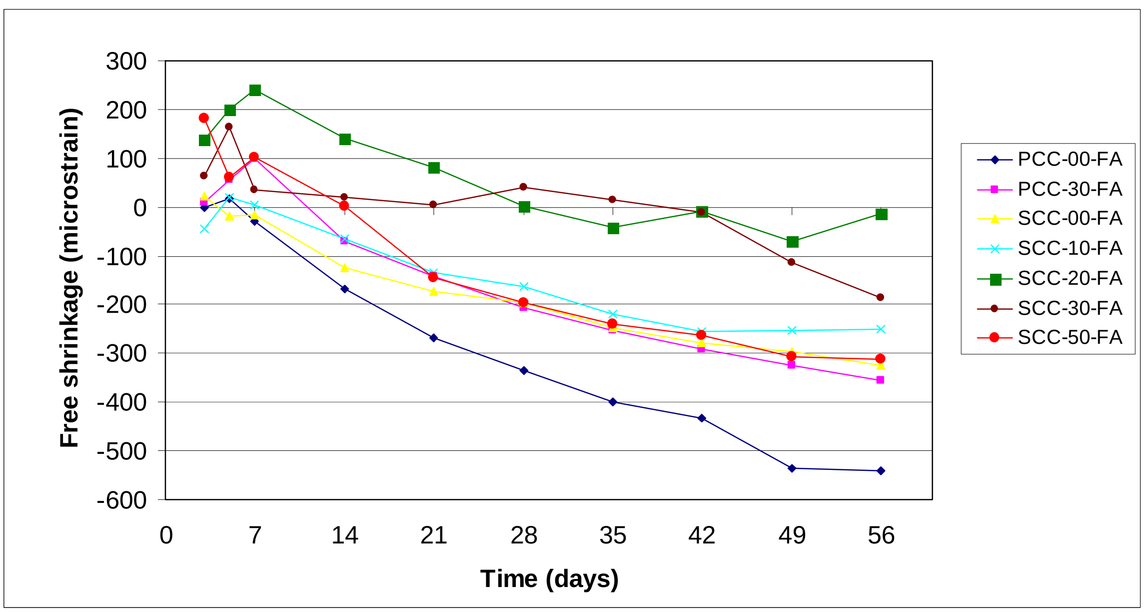


Figure 4-3 Free shrinkage strains vs. time of concrete mixes cured for 7 days.

Table 4-4 Percentage reduction in free shrinkage strains of the SRA and fly ash mixes as compared with the control mixes cured for 3 days.

Time of measurement (days)	% Reduction in Free Shrinkage of SRA and FA Mixes over Control (3-day curing)						
	Compared with PCC-00-FA						PCC-30-FA
	PCC-30-FA	SCC-00-FA	SCC-10-FA	SCC-20-FA	SCC-30-FA	SCC-50-FA	SCC-30-FA
14	42	72	81	109	68	91	45
21	44	67	49	89	76	76	57
28	31	58	73	72	92	55	89
35	34	61	66	70	88	53	82
42	32	63	68	78	83	52	76
49	31	56	63	70	68	45	53
56	5	39	50	72	39	27	36
Average	37	64	67	85	78	71	66

Table 4-5 Percentage reduction in free shrinkage strains of the SRA and fly ash mixes as compared with the control mixes cured for 7 days.

Time of measurement (days)	% Reduction in Free Shrinkage of SRA and FA Mixes over Control (7-day curing)						
	Compared with PCC-00-FA						PCC-30-FA
	PCC-30-FA	SCC-00-FA	SCC-10-FA	SCC-20-FA	SCC-30-FA	SCC-50-FA	SCC-30-FA
14	58	27	61	184	113	102	130
21	47	36	50	131	102	46	103
28	38	41	51	101	112	42	119
35	37	38	45	89	104	40	106
42	32	35	41	98	97	39	96
49	40	44	53	87	79	43	65
56	34	40	54	98	66	42	48
Average	45	38	50	125	101	59	102

Effect of shrinkage-reducing admixture in free shrinkage

The effect of SRA in free shrinkage is shown in Figure 4-4. The figure describes the free shrinkage behavior in the SCC mixes subjected to 3 days and 7 days of moist curing. The figure suggests that the SRA was very effective in reducing the free shrinkage of concrete. Table 4-4 and Table 4-5 indicated that the average reduction in free shrinkage was 64% in SCC mixes cured for 3 days and 38% in mixes cured for 7 days. That difference in reduction indicated that the curing time affected very strongly the control mix, as can be appreciated in Figure 4-4. As shown in Figure 4-5, the influence of SRA was higher in fly ash mixes, with an average reduction of 66% and 102% for 3-day and 7-day curing time, respectively. Thus the SRA added in the specified dosage (1.5 gal/yd^3) reduced the free shrinkage of concrete mixes tested by at least 38% and its effect was improved with the curing days. It is worth noting that the effect of SRA was more significant in the mix with 30% of fly ash.

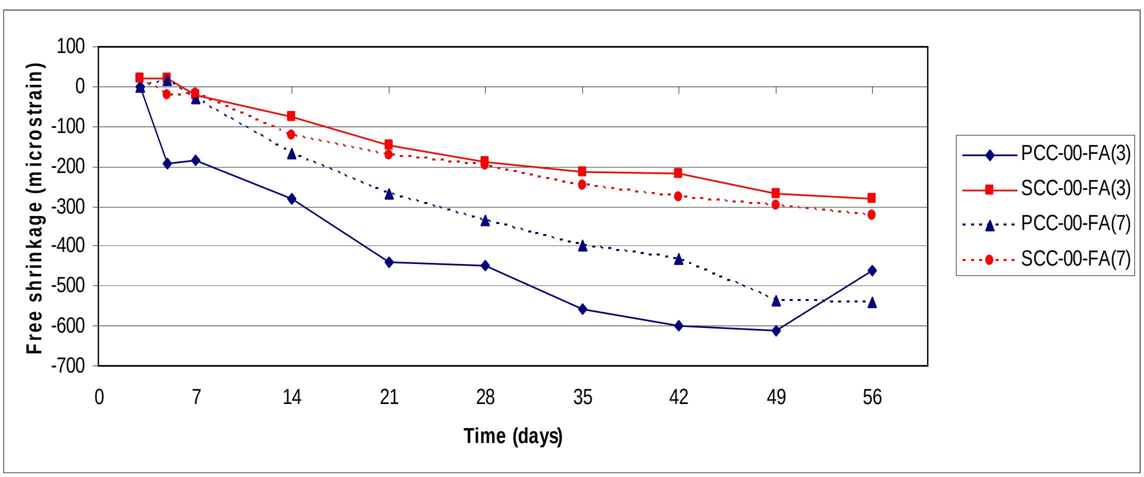


Figure 4-4 Influence of SRA in PCC mixes cured for 3 and 7 days.

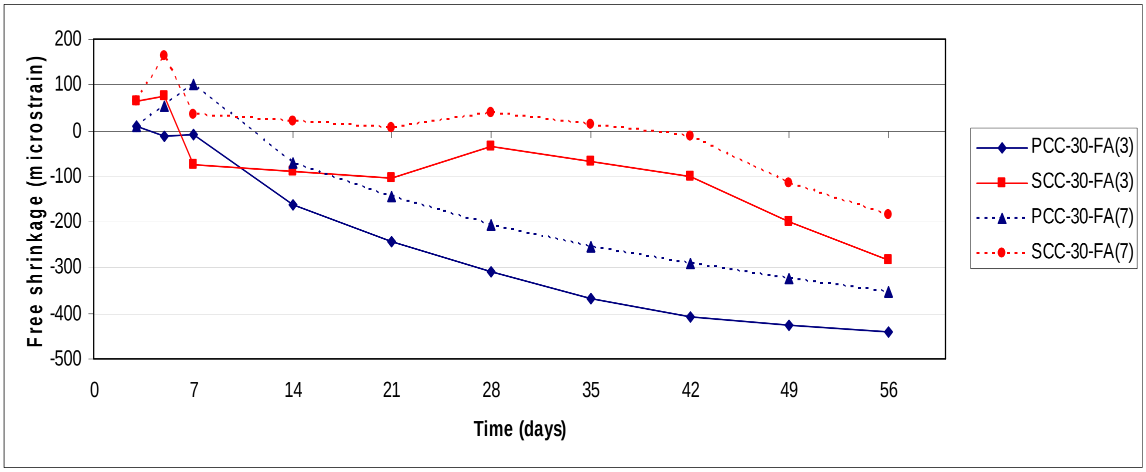


Figure 4-5 Influence of SRA in fly ash concrete mixes cured for 3 and 7 days.

Effect of fly ash in free shrinkage

The free shrinkage was also reduced with the effect of fly ash. As seen in Table 4-4 and Table 4-5, mixes with 30% of fly ash reduced the drying shrinkage an average of 37% in 3-day cured concrete and 45% in 7-day cured concrete. These results reflected an expansive effect of fly ash in concrete.

Effect of shrinkage-reducing admixture and fly ash content in free shrinkage

It can be seen in Table 4-4 and Table 4-5 that the use of SRA and fly ash reduced the drying shrinkage substantially for all mixes, and that reduction in drying shrinkage was greater for early ages. The percentage of reduction for all mixes varies from 55 % to 92% at 28 days and from 27% to 72% at 56 days for 3-day cured specimens. At 7 days curing of concrete, the reduction was from 41% to 112% at 28 days and from 40% to 98% at 56 days.

As indicated above, the use of fly ash by itself reduced the drying shrinkage and when it was mixed with the SRA, it produced a better effect. Figure 4-6 and Figure 4-7 show the influence of fly ash content in free shrinkage strains measured at 28 and 56 days for SCC mixes cured for 3 and 7 days respectively. The decrease in shrinkage was not proportional to the content of fly ash, rather it can be appreciated that the lowest drying shrinkage occurs in the mix containing 20% of fly ash and SRA. That mix also represents the largest expansion of concrete up to 21 days at 3-day curing and up to 28 days at 7-day curing. It is important to mention that the mix with a higher content of fly ash is the one that produced the largest shrinkage in relation to the other percentages of fly ash.

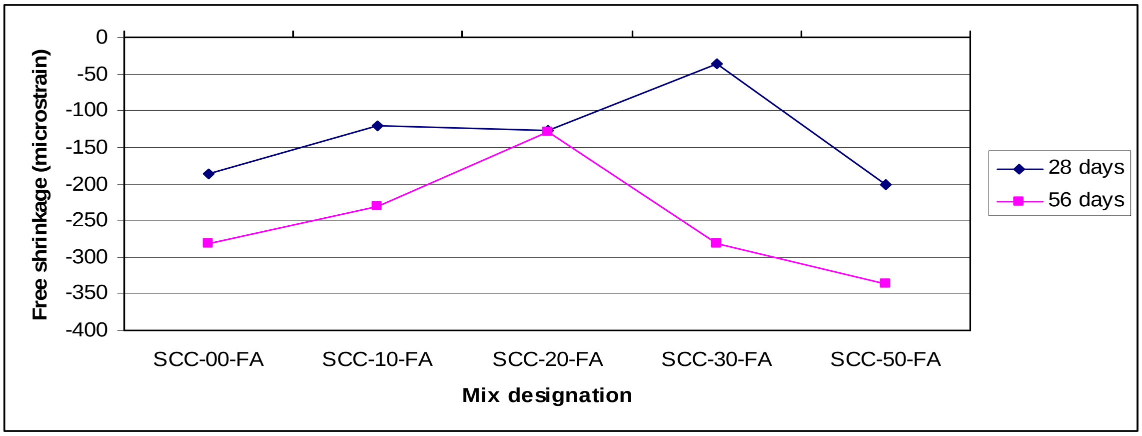


Figure 4-6 Influence of fly ash content in free shrinkage strains measured at 28 and 56 days in SCC mixes cured for 3 days.

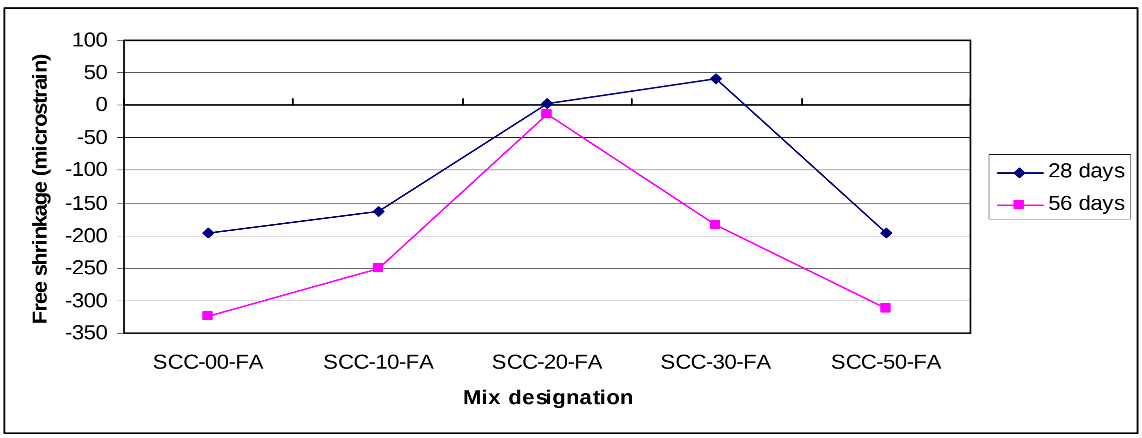


Figure 4-7 Influence of fly ash content in free shrinkage strains measured at 28 and 56 days in SCC mixes cured for 7 days.

Effect of curing time in free shrinkage

Figure 4-8 to Figure 4-13 show the influence of the two curing conditions (3 and 7 days submerged in water) in the expansion or shrinkage of each mix over time. As can be appreciated in Figure 4-8 in the control the mix, the drying shrinkage was reduced enough with 7-day curing, but only up to 56 days. While the influence of 4 more days of curing had the major impact in mixes with 20% and 30% of fly ash (see Figure 4-11 and Figure 4-12). In mixes with SRA, 10% and 50% of fly ash, the curing time seems not to affect the shrinkage (see Figure 4-9, Figure 4-10 and Figure 4-13).

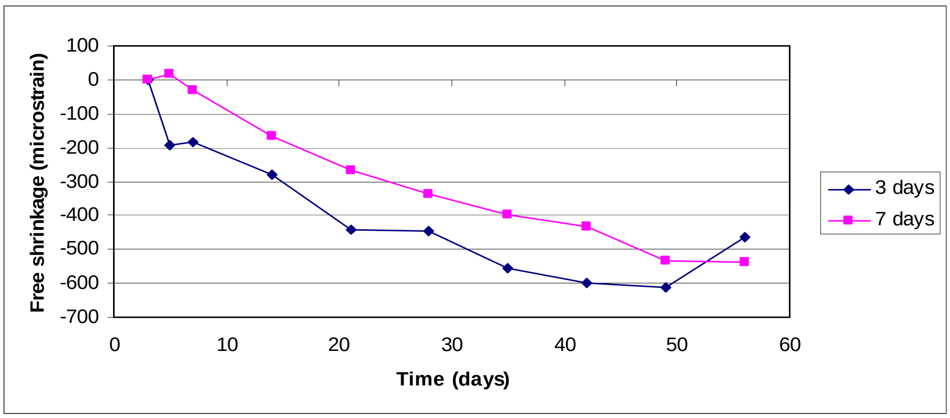


Figure 4-8 Effect of curing time in control mix.

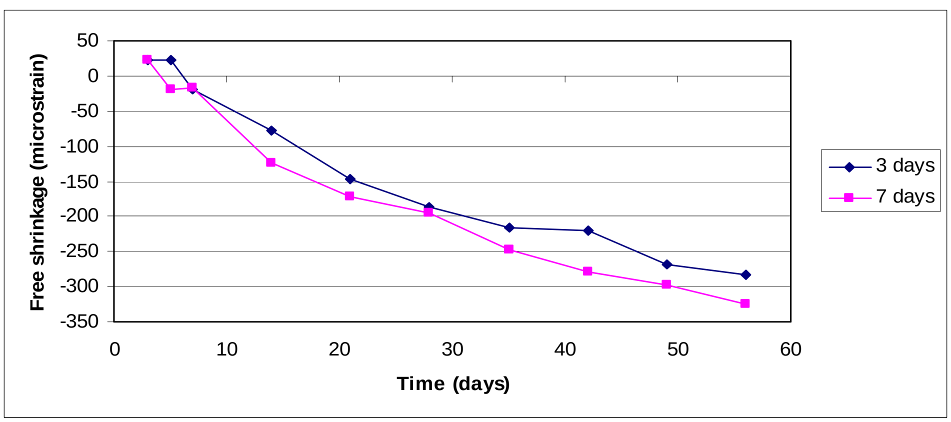


Figure 4-9 Effect of curing time in SCC-00-FA.

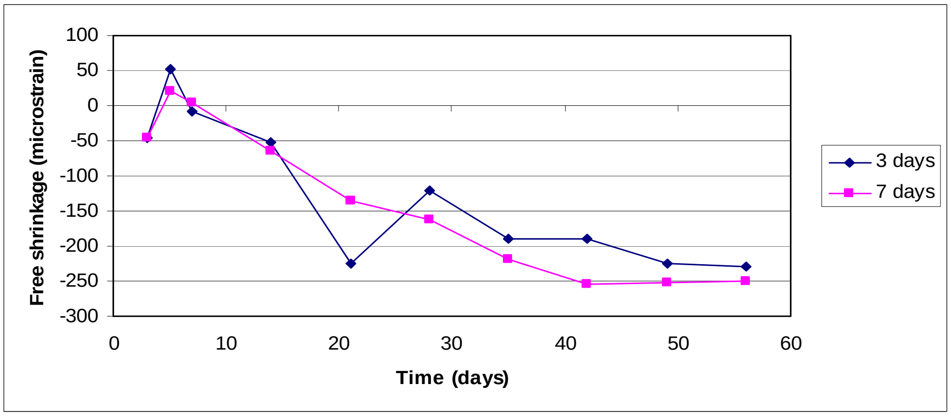


Figure 4-10 Effect of curing time in SCC-10-FA.

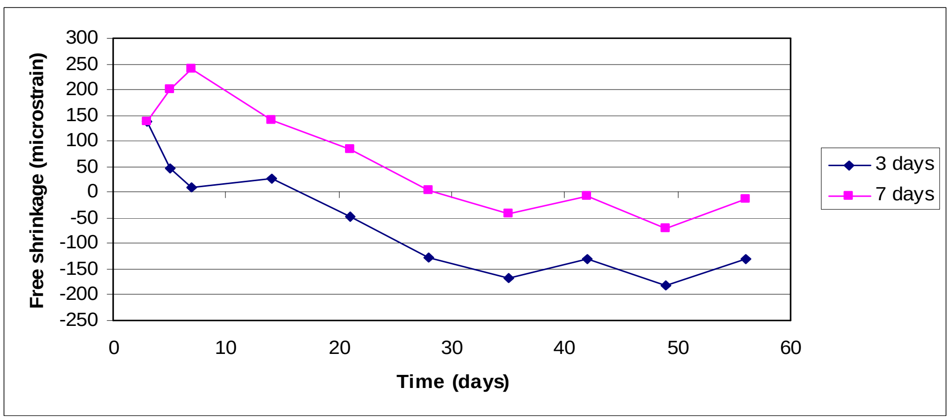


Figure 4-11 Effect of curing time in SCC-20-FA.

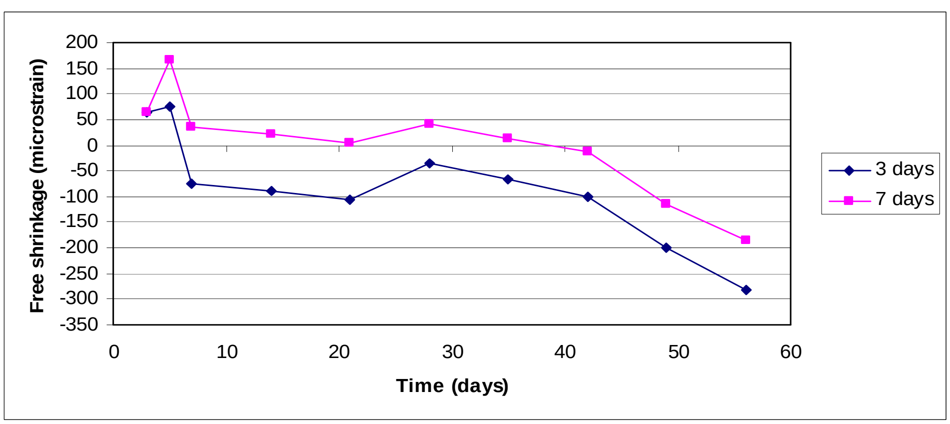


Figure 4-12 Effect of curing time in SCC-30-FA.

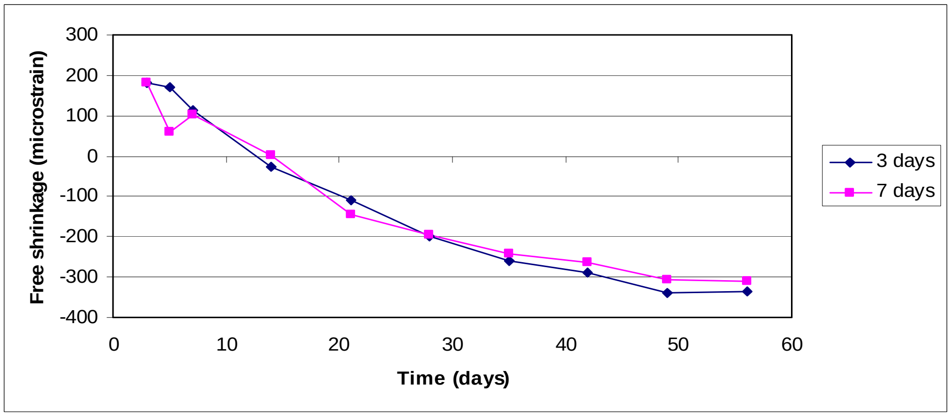


Figure 4-13 Effect of curing time in SCC-50-FA.

4.2.3 SPLITTING TENSILE STRENGTH (ASTM C 496)

The test results for splitting tensile strength of concrete mixes cured for 3, 5 and 7 days are reported in Table 4-6. The values of tensile strength represent the average of two specimens for each curing condition. The data in Table 4-6 shows that the control mix exhibited the greatest splitting tensile strength at each age of testing and at each curing condition. The reduction percentages in splitting tensile strength between SCC mixes and the controls mixes are reported in Table 4-7 and Table 4-8, for 3, 5 and 7 days curing. In the following sections the percentages reduction in strength will be discussed in detail.

Effect of shrinkage-reducing admixture in splitting tensile strength

Figure 4-14 shows the results for splitting tensile strength of SCC mix compared with the results of the control mix at different curing conditions. It can be seen from Figure 4-14 that the SRA had lower tensile strength than the control mix tested at 5 and 56 days. In Table 4-7 and Table 4-8, the reduction percentage between the SCC and control mix cured for 3 and 7 days is reported. The tensile strength was reduced an average of 12% at 5 days and 17% at 56 days. Nevertheless, in some testing days, the SCC mix appeared to slightly increase the tensile strength while at other ages it appeared to have lower strength.

Table 4-6 Splitting tensile strength of concrete mixes.

Mixes	Testing Age (days)	Splitting Tensile Strength (psi)								
		Curing time								
		3 days			5 days			7 days		
		1	2	Average	1	2	Average	1	2	Average
PCC-00-FA C-100%	3	508	468	488						
	5	622	626	624	569	643	606			
	7	605	635	620				607	584	595
	14	601	725	663				674	742	708
	28	666	797	732				672	691	682
	56	739	764	752				721	816	768
PCC-30-FA C-70%, FA-30%	3	441	427	434						
	5	478	493	486	488	478	483			
	7	558	505	532				456	466	461
	14	563	566	565				549	524	537
	28	632	555	594				634	703	669
	56	576	651	613				667	657	662
SCC-00-FA SRA C-100%	3	479	483	481						
	5	547	546	547	556	522	539			
	7	628	593	610				581	562	572
	14	675	660	668				675	713	694
	28	666	711	688				766	670	718
	56	646	631	639				643	604	623
SCC-10-FA SRA C-90%, FA-10%	3	454	444	449						
	5	518	467	492	466	483	475			
	7	528	507	517				524	507	516
	14	593	602	597				597	613	605
	28	636	582	609				604	642	623
	56	575	668	622				684	724	704
SCC-20-FA SRA C-80%, FA-20%	3	421	415	418						
	5	412	467	440	460	467	463			
	7	492	423	457				491	483	487
	14	420	509	465				554	580	567
	28	603	599	601				611	620	616
	56	662	625	644				651	664	657
SCC-30-FA SRA C-70%, FA-30%	3	349	362	355						
	5	421	426	423	419	362	390			
	7	473	402	437				446	429	438
	14	587	510	549				496	585	540
	28	532	561	546				542	562	552
	56	618	695	657				622	646	634
SCC-50-FA SRA C-50%, FA-50%	3	291	280	286						
	5	341	357	349	320	317	319			
	7	320	317	319				342	372	357
	14	453	478	466				520	376	448
	28	517	529	523				551	523	537
	56	559	543	551				518	568	543

Table 4-7 Reduction percentage in splitting tensile strength of the SRA and fly ash mixes as compared with the control mixes at 3-days curing.

Testing Age (days)	% Reduction in Splitting Tensile Strength of SRA and FA Mixes over Control					
	Compared to PCC-00-FA					PCC-30-FA
	PCC-30-FA	SCC-00-FA	SCC-10-FA	SCC-20-FA	SCC-30-FA	SCC-50-FA	SCC-30-FA
3	11	1	8	14	27	41	18
5	22	12	21	30	32	44	13
7	14	2	17	26	29	49	18
14	15	-1	10	30	17	30	3
28	19	6	17	18	25	29	8
56	18	15	17	14	13	27	-7
Average	17	6	15	22	24	37	9

Table 4-8. Reduction percentage in splitting tensile strength of the SRA and fly ash mixes as compared with the control mixes at 7-days curing.

Testing Age (days)	% Reduction in Splitting Tensile Strength of SRA and FA Mixes over Control						
	Compared to PCC-00-FA						PCC-30-FA
	PCC-30-FA	SCC-00-FA	SCC-10-FA	SCC-20-FA	SCC-30-FA	SCC-50-FA	SCC-30-FA
5	20	11	22	24	36	47	19
7	23	4	13	18	26	40	5
14	24	2	15	20	24	37	-1
28	2	-5	9	10	19	21	17
56	14	19	8	14	17	29	4
Average	17	6	13	17	24	35	9

These observed differences could be due to the inherent variability of the material, because concrete is not a homogeneous material. Also, it should be considered that the test is not a completely accurate test; it has limitations, as the eccentricity with the applied load, the type of the bearing strips, and others.

In addition, the influence of SRA in a fly ash mix was verified. The average reduction in tensile strength was slightly higher in fly ash mixes compared with the mixes without fly ash. The data indicated that the use of SRA in fly ash mixes substantially affected the tensile strength of concrete. As shown in Table 4-7 and Table 4-8 an average reduction of 9% was observed in fly ash mixes when the SRA was added. In conclusion, the use of SRA in a PCC mix reduced the tensile strength about 6% up to 56 days and 9% in fly ash mixes.

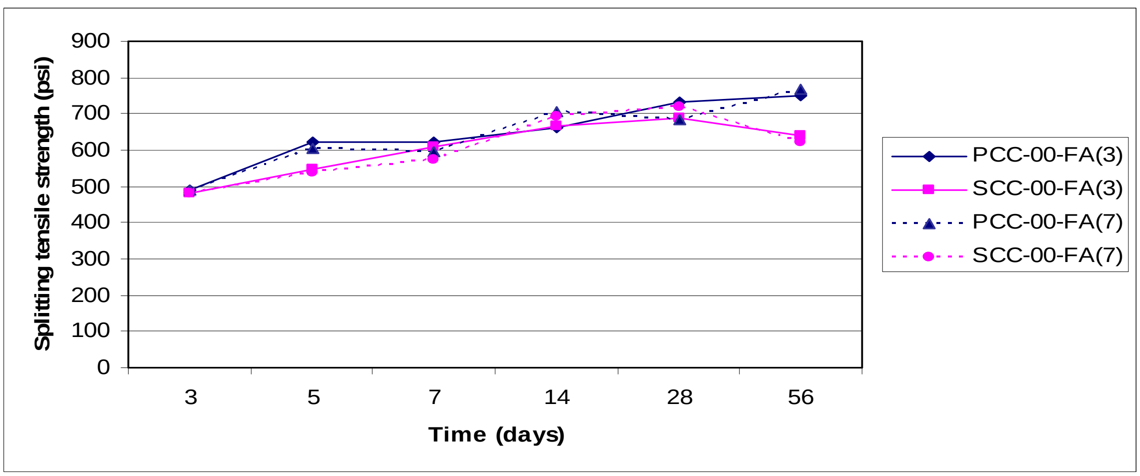


Figure 4-14 Influence of SRA in splitting tensile strength.

Effect of fly ash in splitting tensile strength of PCC

As it is shown in Figure 4-15, the use of fly ash as cement replacement significantly reduced the splitting tensile strength of concrete. That reduction was higher at early ages. Table 4-7 and Table 4-8, showed that the tensile strength in 30% fly ash mixes was reduced an average of 17% for both curing times.

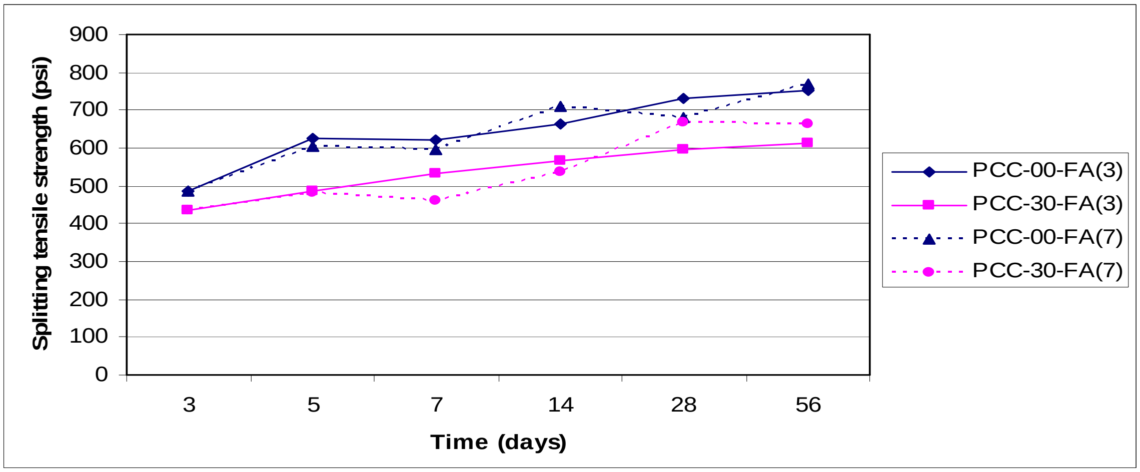


Figure 4-15 Influence of fly ash in splitting tensile strength.

Effect of fly ash content and SRA in splitting tensile strength of SCC

Five different contents of fly ash (0, 10, 20, 30, and 50% substitution) in mixes with the same percentage of SRA were evaluated to compare the influence of fly ash content in concrete properties. It can be seen in Figure 4-16 and Figure 4-17 that the use of fly ash reduced the tensile strength of all mixes. The reduction was higher at early ages, and it was strongly influenced by the fly ash content. At 56 days the tensile strength in mixes with 10%, 20%, and 30% of fly ash were very similar, but the mix with 50% did not reach that strength. As shown in Table 4-7 and Table 4-8, the fly ash mixes compared with the control mix reduced the splitting tensile strength in an average of 15%, 22%, 24% and 37% for mixes with 10, 20, 30 and 50% of fly ash, respectively, when they were cured for 3 days. Mixes cured for 7 days presented similar reduction to that of 3 days curing. It should be noted that the gain strength in the first 7 days was much lower for fly ash mixes.

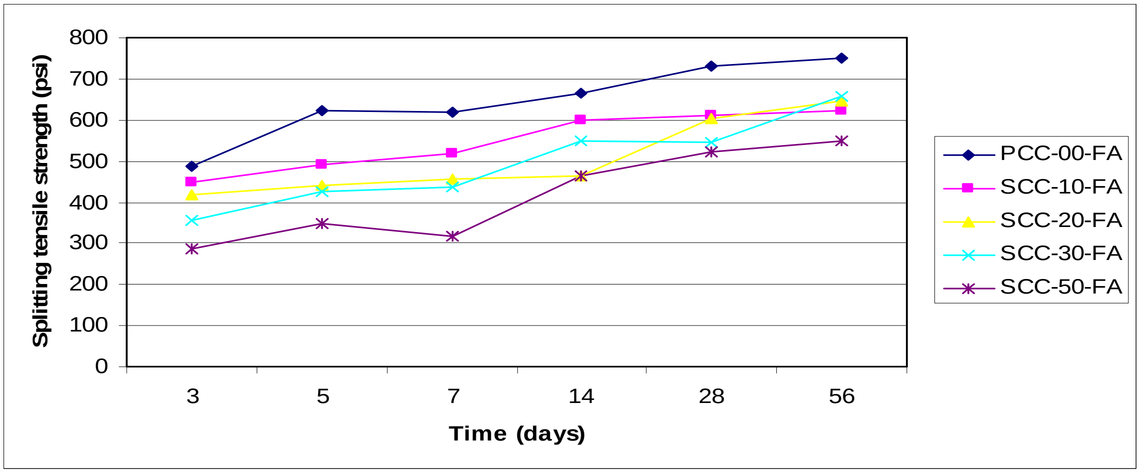


Figure 4-16 Influence of SRA and fly ash content in splitting tensile strength of concrete mixes cured for 3 days.

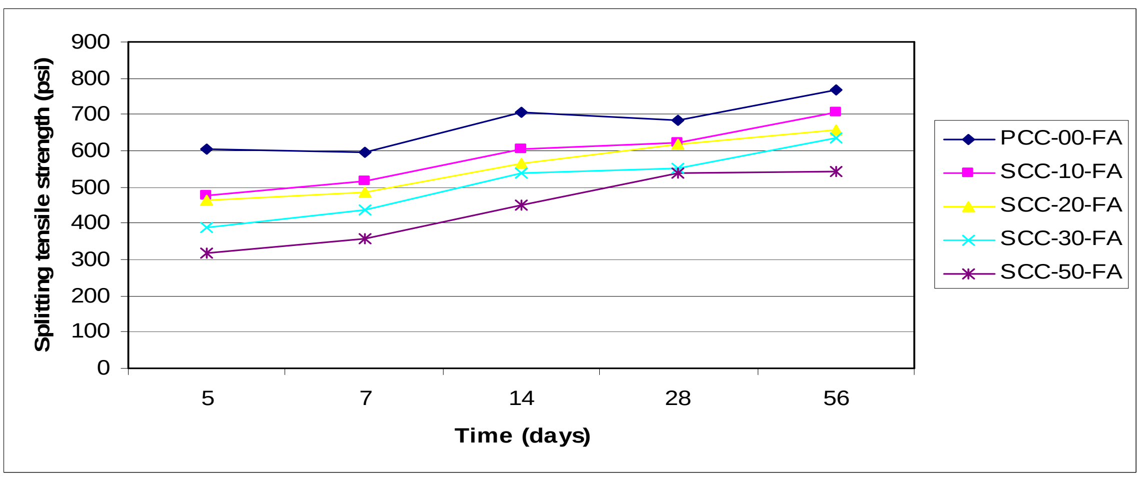


Figure 4-17 Influence of SRA and fly ash content in splitting tensile strength of concrete mixes cured for 7 days.

Effect of curing time in splitting tensile strength

The difference between three and seven days of moist curing in the concrete mixes did not significantly improve the splitting tensile strength in PCC or concrete containing SRA and fly ash. Figure A1- 1 to Figure A1- 6 in the Appendix A show the effect of curing time in the splitting tensile strength of mixes. Figure 4-18 shows the effect of 3 and 7 days of moist curing in the mix with 30% of fly ash. This behavior was very similar in most of the mixes. Cure for 3 or 7 days had no or very little effect in the tensile strength of SCC mixes with fly ash and the control mix.

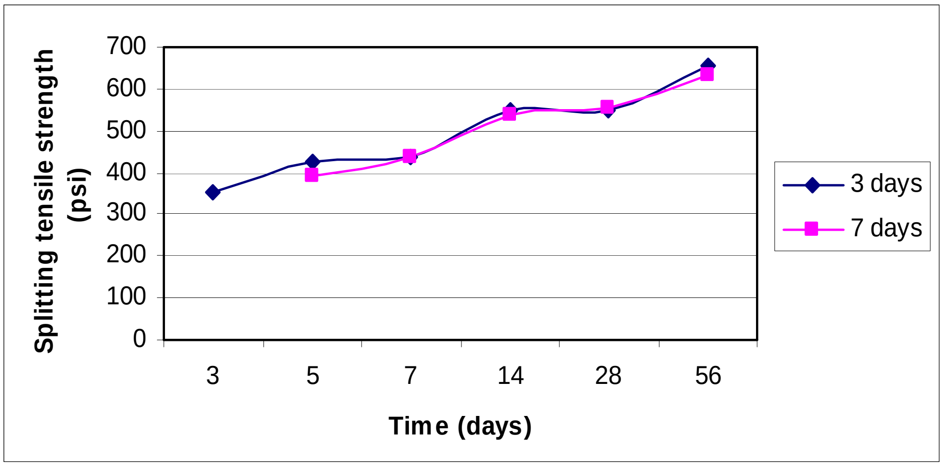


Figure 4-18 Effect of curing time in SCC-30-FA.

4.2.4 COMPRESSIVE STRENGTH (ASTM C 39)

The test results for compressive strength of mixes cured for 3 and 7 days are shown in Table 4-9. The values of compressive strength were taken at 7, 28, and 56 days after casting. The compressive strength was represented by the average of two specimens for each curing condition. As in the splitting tensile strength, the control mix presented the greatest strength in every day testing and in both curing conditions. The percentage reduction in compressive strength of the SRA and fly ash mixes compared with that of the control mixes cured for 3 and 7 days are presented in Table 4-10 and Table 4-11, respectively.

Effect of SRA and fly ash in compressive strength

The impact of the SRA and fly ash content in compressive strength is shown in Figure 4-19 and Figure 4-20. Figure 4-21 shows the influence of fly ash without SRA in compressive strength of mixes cured for 3 and 7 days. It was found that SRA reduced the compressive strength in concrete mixes made with and without fly ash. According with the results presented in Table 4-10 and Table 4-11, in the SCC mix, the reduction percentage was lower tested at 7 day and that reduction was increased over time. Contrary to this, mixes with SRA and fly ash showed higher reductions in strength at early ages that were decreasing over time, but did not reach the compressive strength of the control mix. At 3 and 7 days curing the development was very similar. This reduction in compressive strength was expected at early ages, but not necessary at 56 days, where fly ash was supposed to develop long term strength. In that case it would be necessary to monitor the strength of concrete with fly ash up to 90 days and identify the influence of fly ash at long term.

The results for compressive strength can be summarized as follows: SRA reduced the compressive strength in mixes cured for 3 days in 7%, 14%, and 10% tested at 7, 28, and 56 days, respectively. For 7 days curing, the reduction was 7%, 10%, and 12% tested at the same ages. The average reduction was similar for 3 days and 7 days curing at around 10%.

Thus the curing time did not significantly influence the compressive strength of mixes, as mentioned before. In mixes containing fly ash and SRA cured for 3 days the average reductions were 21%, 31%, 32% and 50% for mixes with 10, 20, 30 and 50% of fly ash contents, respectively. At 7 days curing the percentages were very similar. It can be seen that the reduction was not proportional with the content of fly ash. In mixes with 20% and 30% of fly ash the influence of fly ash content was negligible; both mixes presented the same reduction in compressive strength when cured for 3 days and very similar when cured for 7 days.

Table 4-9 Compressive strength of concrete mixes in different curing times.

Mixes	Testing Age (days)	Compressive Strength (psi)					
		Curing time					
		3 days			7 days		
		1	2	Average	1	2	Average
PCC-00-FA	7	5081	5125	5103	4995	5041	5018
	28	6573	6544	6559	6632	6571	6602
	56	6704	7011	6858	6912	7295	7103
PCC-30-FA	7	3813	3744	3778	3360	3480	3420
	28	5013	4932	4972	4939	5142	5041
	56	5632	5140	5386	5464	5677	5570
SCC-00-FA	7	4735	4768	4752	4620	4697	4658
	28	5596	5655	5625	5855	6022	5939
	56	6213	6147	6180	6265	6268	6266
SCC-10-FA	7	4362	4048	4205	4088	4041	4064
	28	4859	5056	4958	5263	5279	5271
	56	5403	5313	5358	5837	5923	5880
SCC-20-FA	7	3339	3108	3224	3236	3388	3312
	28	4666	4305	4486	4798	4861	4829
	56	5127	5129	5128	5320	5308	5314
SCC-30-FA	7	3213	3189	3201	3055	3110	3082
	28	4430	4518	4474	4112	4413	4263
	56	4730	5260	4995	4893	5184	5038
SCC-50-FA	7	2122	2104	2113	2175	2256	2215
	28	3438	3429	3433	3524	3631	3578
	56	3906	3844	3875	4045	3778	3911

Table 4-10 Reduction percentage in compressive strength of the SRA and fly ash mixes as compared with the control mixes cured for 3 days.

Testing Age (days)	% Reduction in Compressive Strength of SRA and FA Mixes over Control						
	Compared to PCC-00-FA						PCC-30-FA
	PCC-30-FA	SCC-00-FA	SCC-10-FA	SCC-20-FA	SCC-30-FA	SCC-50-FA	SCC-30-FA
7	26	7	18	37	37	59	15
28	24	14	24	32	32	48	10
56	21	10	22	25	27	43	7
Average	24	10	21	31	32	50	11

Table 4-11 Reduction percentage in compressive strength of the SRA and fly ash mixes as compared with the control mixes cured for 7 days.

Testing Age (days)	% Reduction in Compressive Strength of SRA and FA Mixes over Control						
	Compared to PCC-00-FA						PCC-30-FA
	PCC-30-FA	SCC-00-FA	SCC-10-FA	SCC-20-FA	SCC-30-FA	SCC-50-FA	SCC-30-FA
7	32	7	19	34	39	56	10
28	24	10	20	27	35	46	15
56	22	12	17	25	29	45	10
Average	26	10	19	29	34	49	12

Comparing the compressive strength of 30% fly ash mix with that of the control mix, the presence of fly ash in the mix reduced the compressive strength an average of 25%. The same mix with SRA reduced the compressive strength in 33%; therefore it confirms once again that the SRA reduced the compressive strength of concrete. The reduction in compressive strength for the dosage of SRA used in this research was approximately 10%. These results were very similar in both curing conditions. The study indicated that the SRA and fly ash reduced the compressive strength, independently if the mixes were cured for 3 or 7 days.

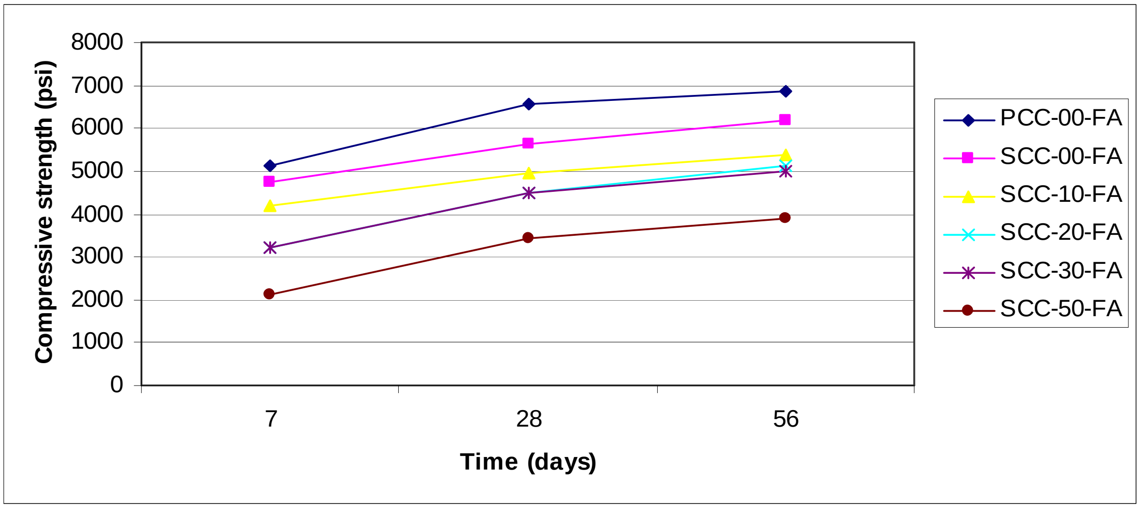


Figure 4-19 Influence of SRA and fly ash content in compressive strength of mixes cured for 3 days.

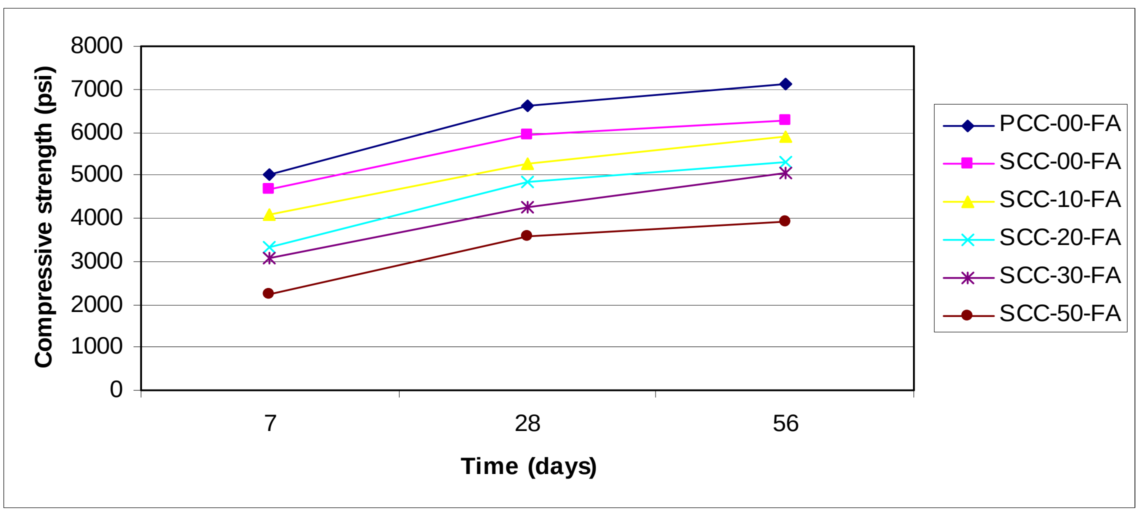


Figure 4-20 Influence of SRA and fly ash content in compressive strength of mixes cured for 7 days.

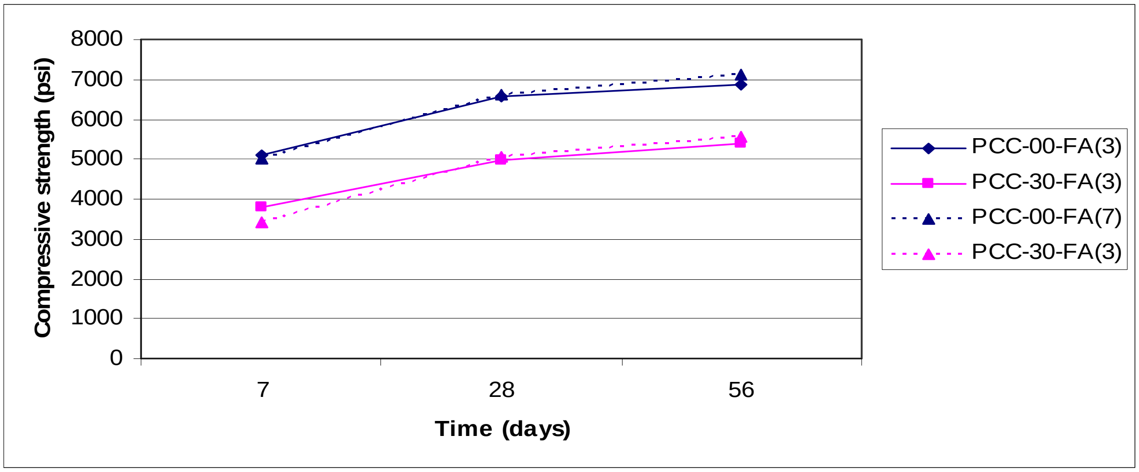


Figure 4-21. Influence of Fly Ash in Compressive Strength.

Effect of curing time in compressive strength

The difference between three and seven days of moist curing in the concrete mixes did not significantly improve the compressive strength in PCC or concrete containing the specified dosage of SRA and different contents of fly ash. Figure A2- 1 to Figure A2- 6 in the Appendix A present the compressive strength versus days of testing in every mix cured for 3 days and 7 days. Figure 4-22 represents a typical curve for the mixes cured for 3 and 7 days.

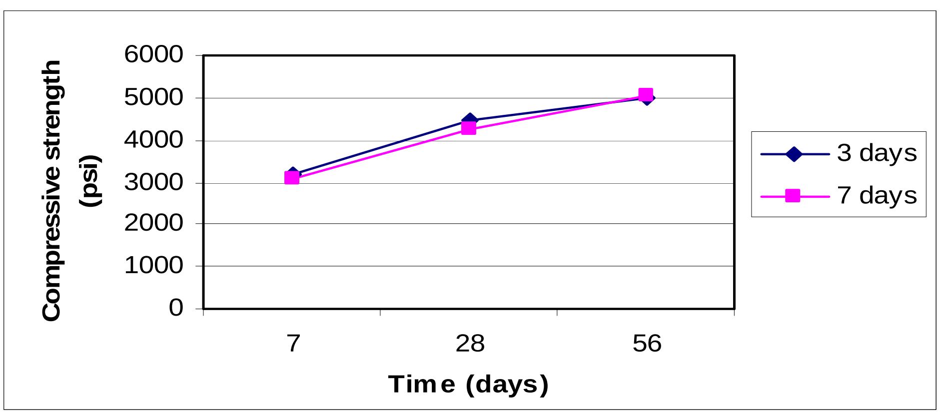


Figure 4-22 Effect of curing time in SCC-30-FA

4.2.5 *RELATIONSHIP BETWEEN SPLITTING TENSILE STRENGTH AND COMPRESSIVE STRENGTH*

Because compressive strength is the principal material property that is measured for hardened concrete, the relationship between tensile and compressive strength is of particular interest. It has been found previously that the tensile strength of concrete was much lower than the compressive strength in each specific concrete mix, as well known, this result was expected.

Figure 4-23 shows the relationship of the splitting tensile strength and compressive strength of all the mixes cured for 3 days. Figure 4-24 shows the same relation but in mixes cured for 7 days. Tensile strength equations based on the splitting tensile strength of normal-weight concretes provided by Ahmad and Shah [15] were used for comparison purposes. The equations are shown in the Figure 4-23 and Figure 4-24. The two equations were plotted against the results of splitting tensile strength. One curve represented the upper bound of expected tensile strength, while the second curve represented the lower bound of the expected tensile strength.

As Figure 4-23 and Figure 4-24 indicate, the splitting tensile strength for all mixes varied from 300 to 800 psi and the compressive strength ranged from 2000 to 7000 psi. The data did not show the effect of curing in the splitting tensile strength and compressive strength. These results suggest that the equations of Ahmad and Shah [15] underestimate the relationship between tensile and compressive strength for mixes made with SRA and fly ash.

In Table 4-12 and Table 4-13 were calculated the ratio of tensile to compressive strength of all the mix designs at 7, 28, and 56 days tests. The data indicated that in general as age and strength increased, the ratio of tensile to compressive strength (f'_t/f'_c) decreased or remained constant. The average (f'_t/f'_c) ratio was 0.13 for each curing condition. Thus, the (f'_t/f'_c) ratio was not affected by the curing time. The data also indicates that the higher (f'_t/f'_c) ratio was presented in mixes with 50% fly ash. Based in these results, the conclusion would be that the fly ash decreased more the compressive strength than the tensile strength.

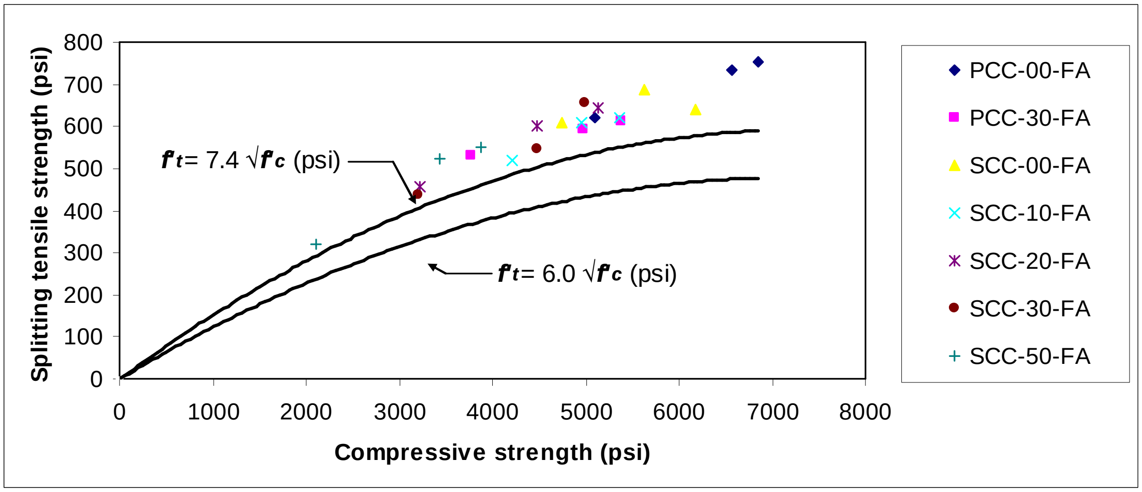


Figure 4-23 Splitting tensile strength vs. compressive strength of concrete mixes cured for 3 days.

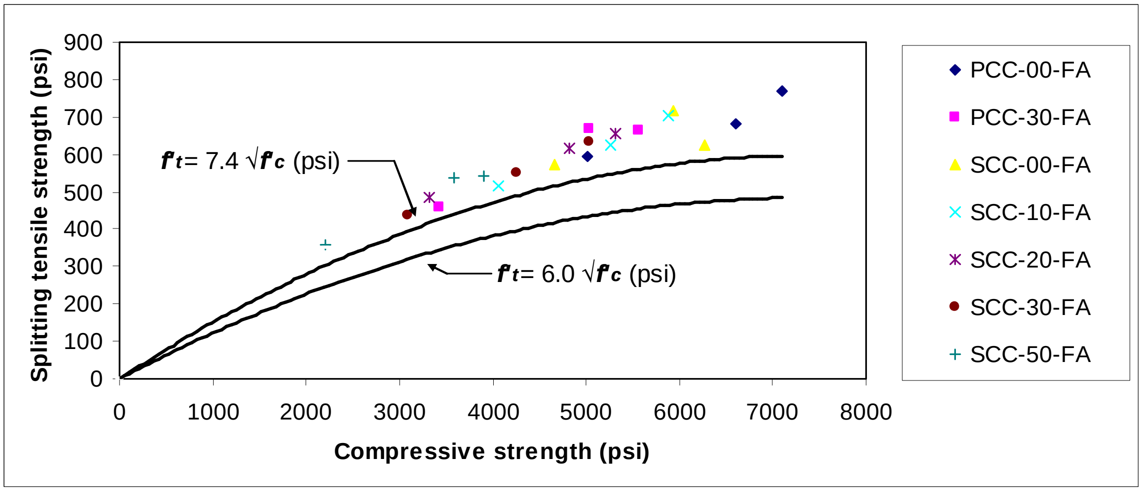


Figure 4-24 Splitting tensile strength vs. compressive strength of concrete mixes cured for 7 days.

Table 4-12 Relationship between splitting tensile strength and compressive strength for mixes cured for 3 days.

Mix	Testing age (days)	f'_t (psi)	f'_c (psi)	f'_t / f'_c
PCC-00-FA	7	620	5103	0.12
	28	732	6559	0.11
	56	752	6858	0.11
PCC-30-FA	7	532	3778	0.14
	28	594	4972	0.12
	56	613	5386	0.11
SCC-00-FA	7	610	4752	0.13
	28	688	5625	0.12
	56	639	6180	0.10
SCC-10-FA	7	517	4205	0.12
	28	609	4958	0.12
	56	622	5358	0.12
SCC-20-FA	7	457	3224	0.14
	28	601	4486	0.13
	56	644	5128	0.13
SCC-30-FA	7	437	3201	0.14
	28	546	4474	0.12
	56	657	4995	0.13
SCC-50-FA	7	319	2113	0.15
	28	523	3433	0.15
	56	551	3875	0.14

Table 4-13 Relationship between splitting tensile strength and compressive strength for mixes cured for 7 days.

Mix	Testing age (days)	f'_t (psi)	f'_c (psi)	f'_t / f'_c
PCC-00-FA	7	595	5018	0.12
	28	682	6602	0.10
	56	768	7103	0.11
PCC-30-FA	7	461	3420	0.13
	28	669	5041	0.13
	56	662	5570	0.12
SCC-00-FA	7	572	4658	0.12
	28	718	5939	0.12
	56	623	6266	0.10
SCC-10-FA	7	516	4064	0.13
	28	623	5271	0.12
	56	704	5880	0.12
SCC-20-FA	7	487	3312	0.15
	28	616	4829	0.13
	56	657	5314	0.12
SCC-30-FA	7	438	3082	0.14
	28	552	4263	0.13
	56	634	5038	0.13
SCC-50-FA	7	357	2215	0.16
	28	537	3578	0.15
	56	543	3911	0.14

4.2.6 INFLUENCE OF CURING TIME IN STRENGTH

As explained in Section 3.5, two more mixes were made to analyze and compare the influence of 3, 7 and 28 days curing in the splitting tensile strength and compressive strength of mixes with SRA and fly ash.

Influence of curing time in splitting tensile strength

The splitting tensile strengths of the two mixes evaluated are presented in Table 4-14. The values of tensile strength represent the average of two specimens tested. Each mix was subjected to three different curing conditions and tested for splitting tensile strength at 28 days and 56 days. Figure 4-25 and Figure 4-26 show the influence of curing time in splitting tensile strength of PCC and SCC mixes, respectively.

Table 4-14 Splitting tensile strength of PCC-00-FA and SCC-30-FA.

Splitting Tensile Strength (psi)					
Curing time	PCC-00-FA		Curing time	SCC-30-FA	
	Test day			Test day	
	28	56		28	56
3	575	534	3	573	605
7	638	567	7	578	592
28	646	640	28	547	577

Figure 4-25 shows that the splitting tensile strength for a PCC mix was increased when the curing time increased from 3 to 7 days and then from 7 to 28 days in mixes tested at 28 days and 56 days. Nevertheless that increment was not significant between 7 and 28 days curing.

In SCC mix with fly ash, an opposite effect to that of the conventional mix was observed. The splitting tensile strength tested at 28 and 56 days decreased over curing time, as seen in Figure 4-26. The tensile strength for 3 and 7 days curing may be considered the same and when cured for 28 days the strength was reduced in about 5%.

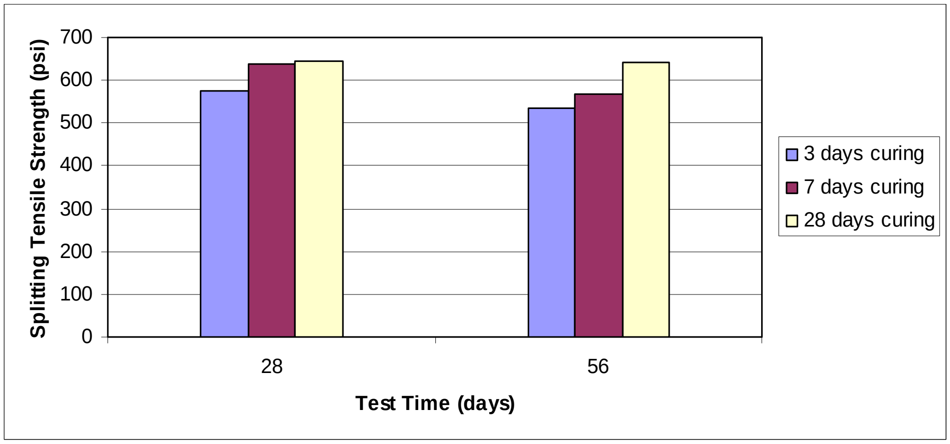


Figure 4-25 Effect of curing time in splitting tensile strength of PCC-00-FA mix.

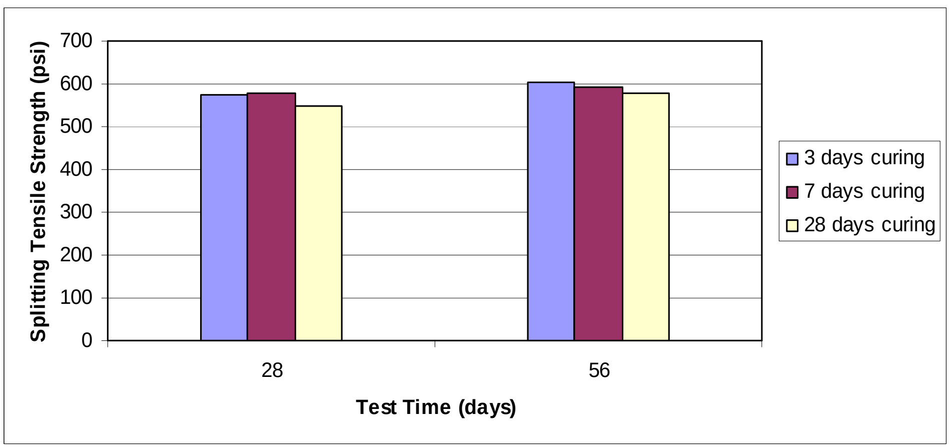


Figure 4-26 Effect of curing time in splitting tensile strength of SCC-30-FA mix.

Influence of curing time in compressive strength

The compressive strengths of the two mixes evaluated are presented in Table 4-15. The values of compressive strength represent the average of two specimens tested. Each mix was subjected to the same curing conditions mentioned above. Figure 4-27 and Figure 4-28 show the influence of curing time in compressive strength of PCC and SCC mixes, respectively.

Table 4-15 Compressive strength of PCC-00-FA and SCC-30-FA.

Compressive Strength (psi)					
Curing time	PCC-00-FA		Curing time	SCC-30-FA	
	Test day			Test day	
	28	56		28	56
3	4546	4680	3	4311	4226
7	4944	4766	7	4759	5079
28	5064	5450	28	4818	5443

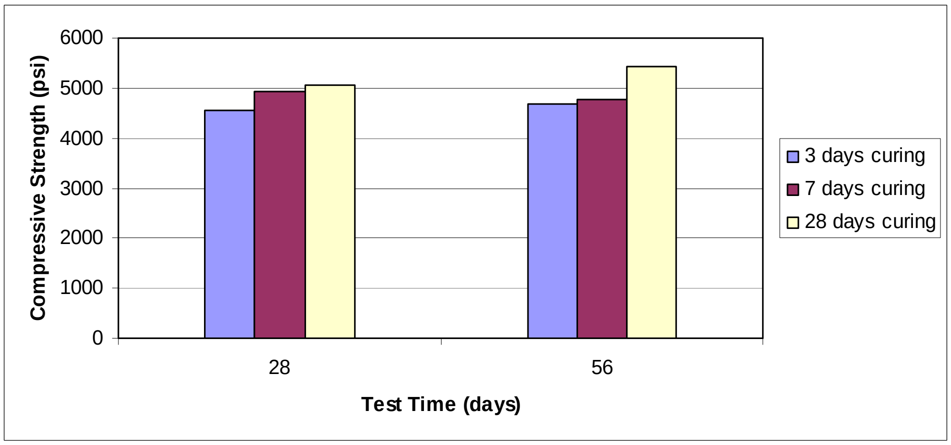


Figure 4-27 Effect of curing time in compressive strength of PCC-00-FA mix.

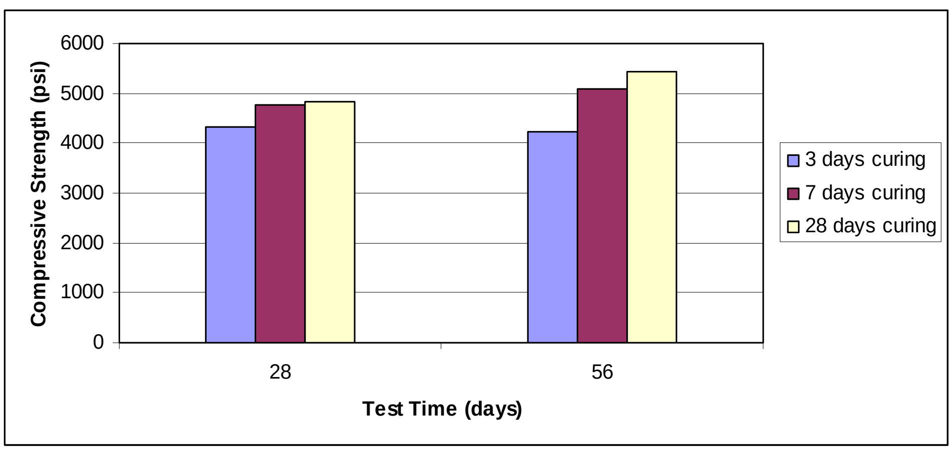


Figure 4-28 Effect of curing in compressive strength of SCC-30-FA mix.

It can be appreciated in Figure 4-27 and Figure 4-28 that the compressive strength in every mix was increased with curing time. In the PCC mix the compressive strength increased an average of 9% between 3 and 7 days curing and 12% between 3 and 28 days curing at 28 testing day. In the fly ash mix, the compressive strength was slightly increased at 28 testing day, but at 56 days the increase in strength with the curing time was more substantial.

4.3 DISCUSSION OF THE RESULTS

In this experimental work it was found that SRA had little effect on slump. In all mixes the use of fly ash enhanced the workability of concrete. Then, mixes with SRA and fly ash showed the highest slump. It could be observed that the increase in slump varied almost linearly with the content of fly ash. As mentioned in the literature review, the spherical shape of the fly ash particles contributes to the workability of concrete by reducing the friction of the aggregate paste interface. Thus, the increased in slump of concrete mixes with fly ash was expected.

Regarding the engineering importance of this effect, one is that the use of fly ash as a partial cement replacement makes possible to reduce the amount of water required for a given consistency and the other is that the decrease in the inter-particle friction make fly ash concrete well suited for delivering using concrete pumps. Nevertheless, that reduction will depend on the mix proportioning, shape and fineness of the fly ash particles, and the shape factor of the aggregate [36]. This effect of fly ash in workability is well known and studied. But the increased in slump with the use of SRA was also found by Shah *et al.* [40], and others [27] [42] [43].

The results also showed that the addition of SRA significantly reduced the free shrinkage. Fly ash alone also reduced the free shrinkage strains in concrete. Then, SRA and fly ash produced substantial reduction in free shrinkage for all mixes. Both admixtures produced expansion in most of the mixes up to 14 days. The percentage reduction in shrinkage for mixes cured for 3 days varied from 55% to 99% at 28 days and from 27% to 72% tested at 56 days. Mixes cured for 7 days had higher reductions ranging from 41% to 102% tested at 28 days and from 40% to 98% tested at 56 days. Those differences indicated that 7 days of moist curing significantly reduced the drying shrinkage of concrete. This effect of curing time could be because the initial expansion was longer with the applied curing days.

It was remarkable that the mix without SRA or fly ash shrinks over the 400 microstrain, that is considered as a limit for reducing the probability of shrinkage cracking. The other mixes shrink under this deformation. Mix with 20% of fly ash and SRA presented the lower shrinkage. That mix was able to almost completely compensate the shrinkage up to 56 days. Nevertheless mix with 50% of fly ash presented a higher shrinkage compared to that in mixes with less contents of fly ash. That indicated that the reduction in shrinkage due to fly ash was not linear with respect to the content of fly ash.

The effect in shrinkage for 50% fly ash mix could be explained because the high volumes of fly ash in the mix was not able to react with the amount of calcium hydroxide $Ca(OH)_2$ in the cement paste. There is, theoretically, only enough $Ca(OH)_2$ in cement paste to react with 25% of Class F fly ash [4]. Then in the mix with 50% of fly ash there was too much unreacted water in the mix and thus a larger shrinkage. This effect could be minimized reducing the *w/cm* ratio of the mix. According to Atis [45], the use of high volumes of fly ash lowered the shrinkage in concrete when low *w/cm* ratios and water reducing admixtures were used.

Reduction in shrinkage due to the use of SRA was also observed in some studies mentioned in the literature review. Investigations related with the use of SRA and fly ash, as the study made by Tia *et al*. [47], concluded that mixes with 20% and 35% of fly ash decreased the free shrinkage and improved the resistance to shrinkage cracking of concrete.

SRA and fly ash behavior in shrinkage concrete was analyzed first, before talking about the tensile strength of concrete. The objective was to be able to draw conclusions taking into account the shrinkage effect in the splitting tensile strength. According to the results presented, the effect of SRA in the tensile strength was not proportional. It could be seen that the splitting tensile strength was reduced only at 5 and 56 days tested. That reduction was in about 12% and in the other testing days the tensile strength was almost the same as that of the control mix. But in the fly ash mixes the tensile strength was clearly reduced an average of 9% with the use of SRA. These results were in the middle range between the studies made by Shah ***et al.*** [40] and others [41] [42] which pointed out an reduction in splitting tensile strength due to the use of SRA. While Naik [43] and Tia [47] found that the SRA did not affected the splitting tensile strength.

The combined effect of SRA and fly ash decreased the splitting tensile strength of concrete mixes, as much as 35% at 56 days. And that reduction was higher at early ages (3, 5 and 7 days). The reduction could be explained because the fly ash in concrete behaved as an inert addition so that the cement reacted with a high content of water; the water/cement (***w/c***) ratio was too high. Nevertheless, SRA and fly ash postponed the shrinkage up to 21 days in some mixes, so the shrinkage strains occurred at a time when the concrete has attained higher tensile strength. However it is important to remember that reductions in early strength can be offset by lowering the ***w/cm*** ratio. That may even be possible maintaining the same workability in concrete. Also, the use of water-reducing admixture could be very effective reducing the water requirement. Other alternative is the use of fly ash as a partial replacement of aggregates with the method explained by Simons in 2007 [39].

On the other hand the compressive strength was also evaluated in this research, and found that it also was reduced with the use of SRA and fly ash. SRA reduced the compressive strength an average of 10%, while mixes with both admixtures decreased it up to 50%. The same actions mentioned above can be done to increase the compressive strength. This research also showed that the relationship between the splitting tensile strength and compressive strength for all mixes was about 0.13. The relationships in mixes with SRA and fly ash were higher than the control mix and were not affected with the curing time.

Finally, the effect of curing time in tensile and compressive strength was evaluated. It was found that the curing time had an adversely effect in the splitting tensile strength. In mixes with SRA and fly ash the splitting tensile strength tended to decrease while the curing days increased. Thus a poor curing seems to be a better option in the development of tensile strength. Regarding the compressive strength, it was increased with curing time. It should be noted that between 3 and 7 days of curing, the difference in strength was almost negligible, but between 7 and 28 days occurred a substantial increase. Higher compressive strength due to the curing time also was found in studies made by As-Sha [46] and others [4] [31] [40] [42] [47]. But most of them found that the increase was also in the splitting tensile strength. Only in studies made by Ramey *et al.* [41] [57], was found an increased in splitting tensile strength when the mixes were poorly cured.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Mixes with and without shrinkage-reducing admixtures and different contents of fly ash were evaluated in this research. For all mixes the splitting tensile strength, compressive strength and the free shrinkage test were performed. The following conclusions are based on the test results obtained from the experimental program and the interpretation of the results:

- The results of free shrinkage test indicated that the SRA investigated showed an excellent capability to reduce the free shrinkage of concrete mixes with and without fly ash.

- The addition of Class F fly ash reduced the free shrinkage of concrete with and without SRA.

- An increase in curing time reduced shrinkage of the concrete mixes analyzed. In this study, a reduction in shrinkage was observed when the curing time was increased from 3 to 7 days. Especially in mixes with 20% and 30% of weight of cement replaced by Class F fly ash was observed a significant reduction. The reduction in shrinkage was not proportional to the content of fly ash.

- The SRA used reduced slightly the splitting tensile strength and compressive strength of concrete. But that reduction was higher in the compressive strength.

- The use of fly ash and SRA decreased the tensile strength of concrete mixes during the days of study and that reduction was higher at early ages. However, as the fly ash mixes had a better workability, the *w/cm* ratio could be reduced in fly ash mixes, and then produce an increase in strength.

- The compressive strength was reduced with the use of Class F fly ash.

- The relationships between splitting tensile strength and compressive strength of fly ash mixes were higher than that of the control mix.

- The equations of Ahmad and Shah [15] related to the splitting tensile strength of concrete mixes underestimate the relationship between tensile and compressive strength for mixes made with SRA and fly ash.

- It was found that curing time did not increase the splitting tensile strength of mixes made with different contents of fly ash. Actually, the splitting tensile strength was slightly reduced when curing time was increased.

- The compressive strength of mixes was increased when curing time increase. The results indicated that the difference between 3 and 7 days of moist curing was not significant in terms of strength gain of concrete mixes, but it helped to reduce the shrinkage of concrete made with SRA and fly ash.

- The use of fly ash postponed the shrinkage up to 21 days in some mixes, so the shrinkage stresses occurred at a time when the concrete has attained higher tensile strength. With this observation, one could say that SRA and fly ash improved the resistance to shrinkage cracking of concrete.

5.2 RECOMMENDATIONS

The following recommendations are made based on the results of this study:

- The addition of shrinkage-reducing admixture should be considered in mix designs for future projects in Puerto Rico for reduce the probability of shrinkage cracking in structures.

- The use of Class F fly ash in concrete mixes should be considered to reduce the free shrinkage of concrete.

- It is recommended that an additional study be conducted to evaluate the tensile and compressive strength of SCC mixes made with fly ash varying the *w/cm* ratios of the mix designs.

- Another study with a longer period of time should be considered, to see the effect of the SRA and fly ash in strength and free shrinkage after 56 days.

- The use of other types of aggregates available in Puerto Rico is also recommended for an additional study.

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APPENDIX A

A1 Influence of 3 and 7 days curing in splitting tensile strength of mixes

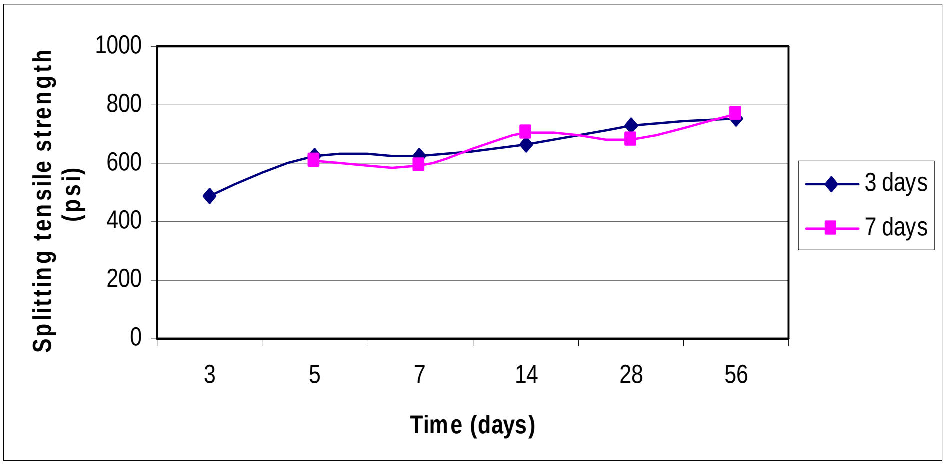

Figure A1- 1 Effect of curing time in control mix.

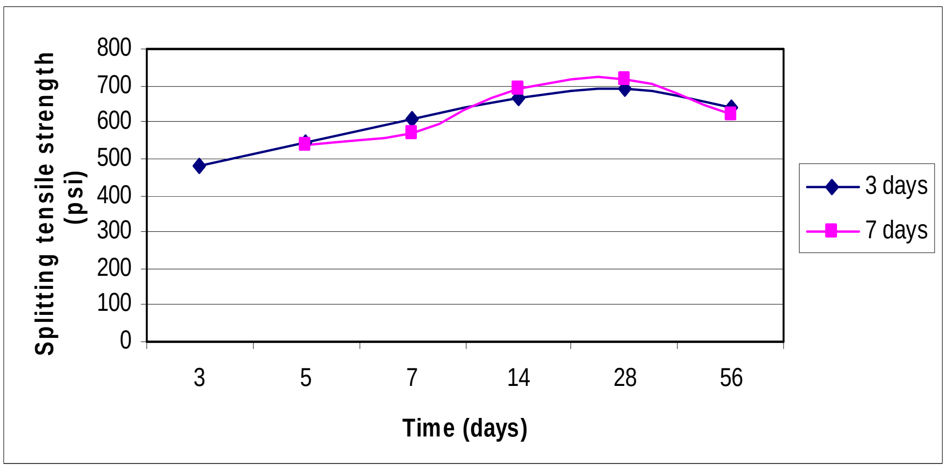

Figure A1- 2 Effect of curing time in SCC-00-FA.

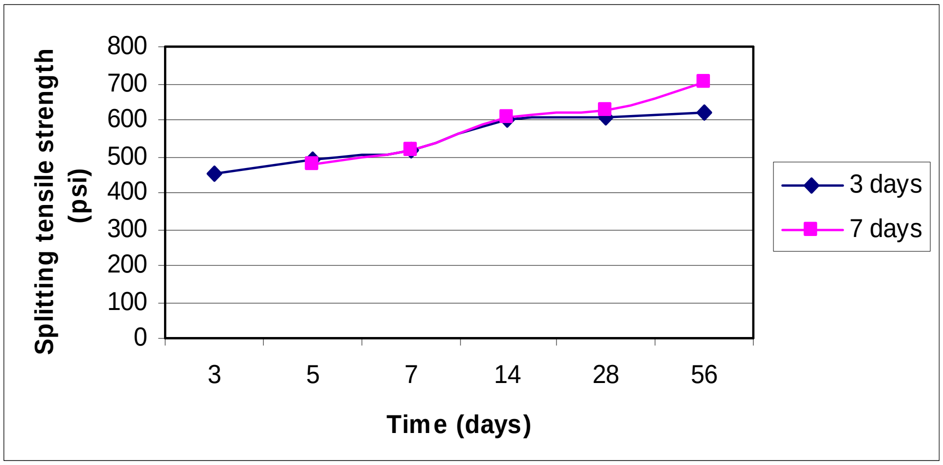

Figure A1- 3 Effect of curing time in SCC-10-FA.

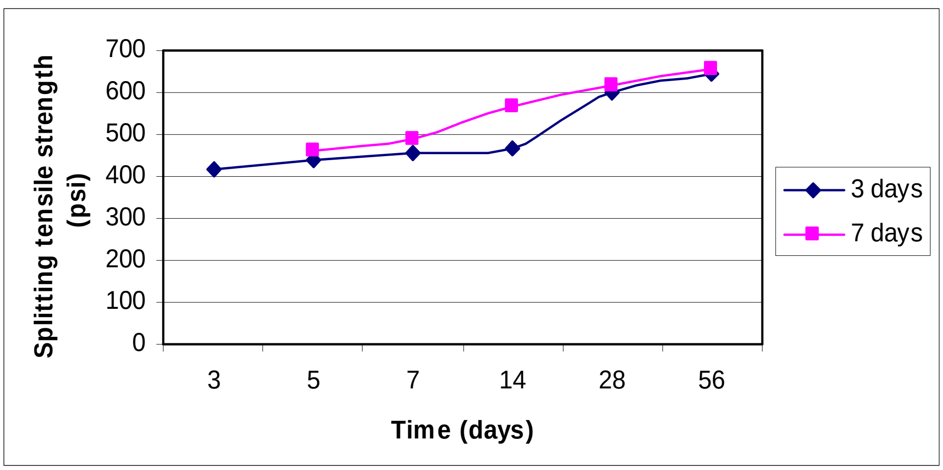

Figure A1- 4 Effect of curing time in SCC-20-FA.

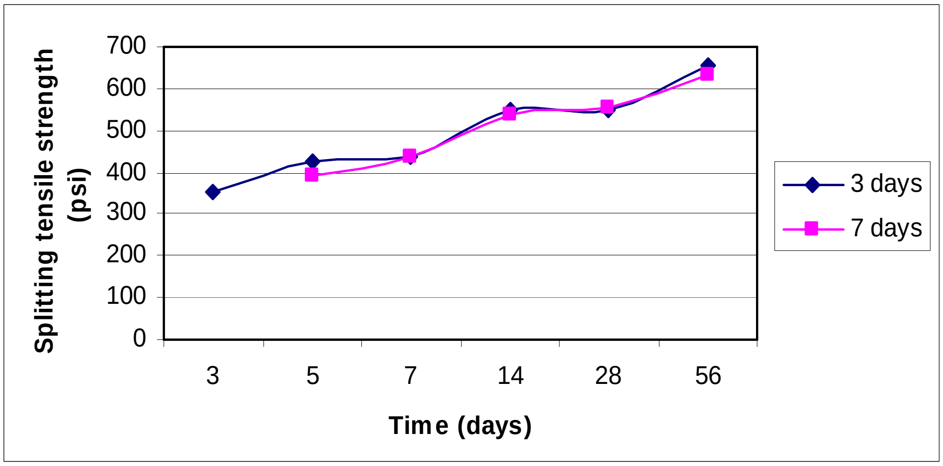

Figure A1- 5 Effect of curing time in SCC-30-FA.

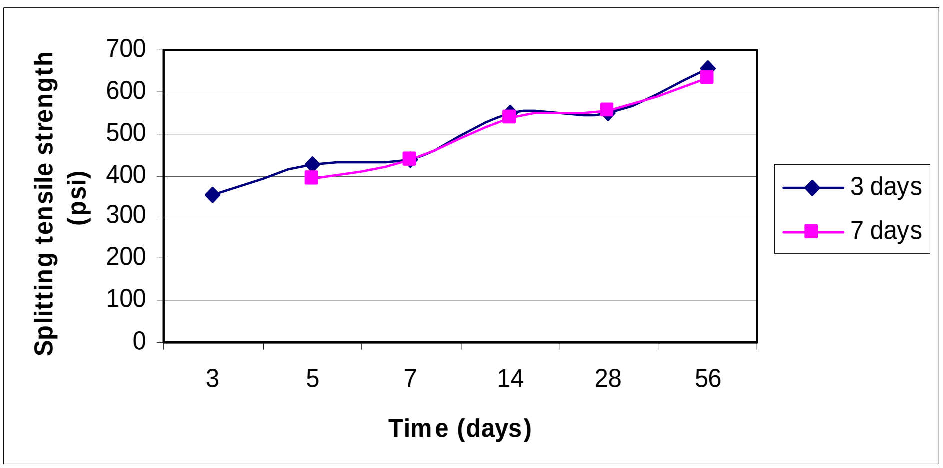

Figure A1- 6 Effect of curing time in SCC-50-FA.

A2 Influence of 3 and 7 days curing in compressive strength of mixes

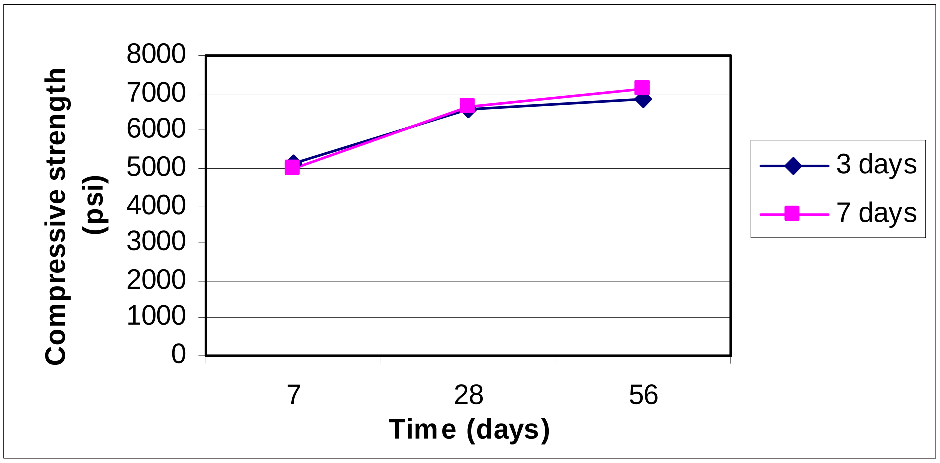

Figure A2- 1 Effect of curing time in control mix.

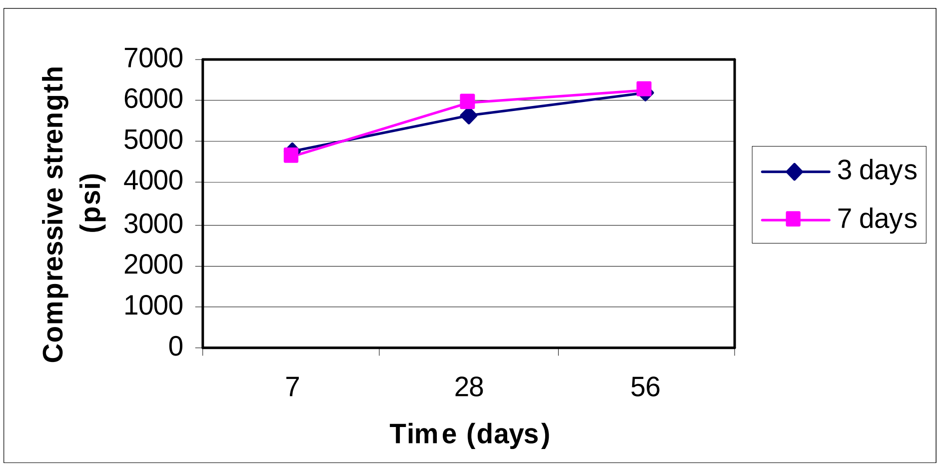

Figure A2- 2 Effect of curing time in SCC-00-FA.

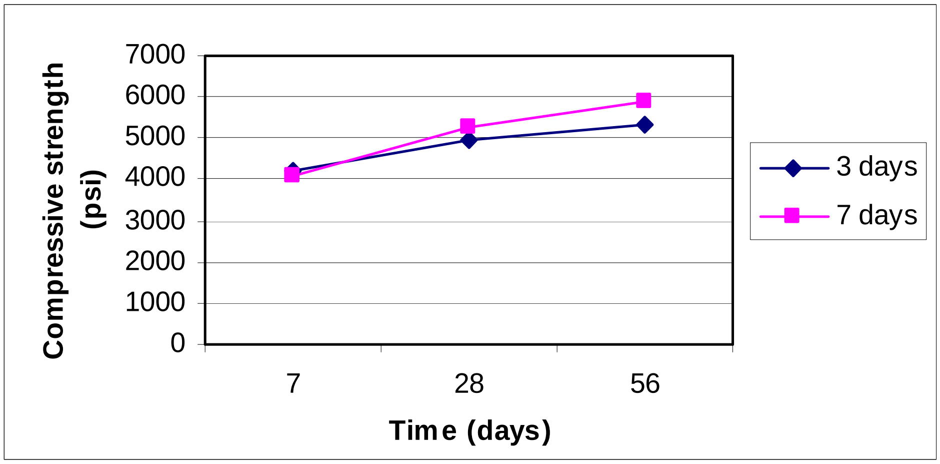

Figure A2- 3 Effect of curing time in SCC-10-FA.

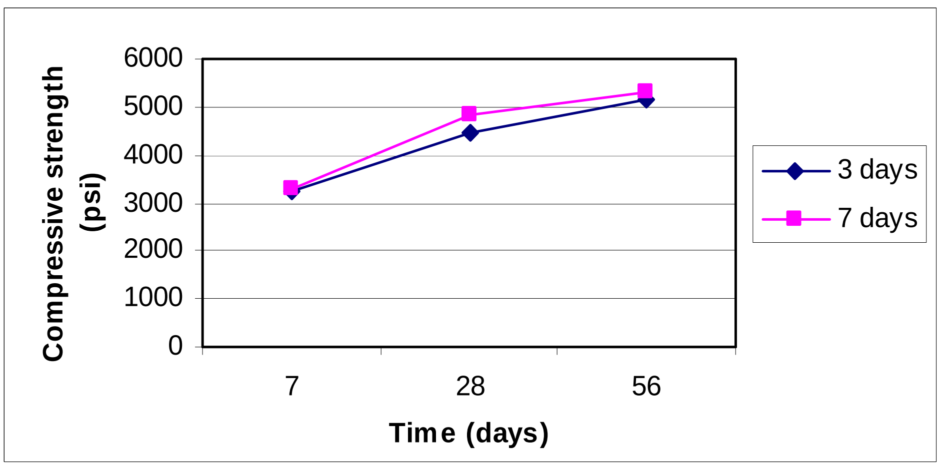

Figure A2- 4 Effect of curing time in SCC-20-FA.

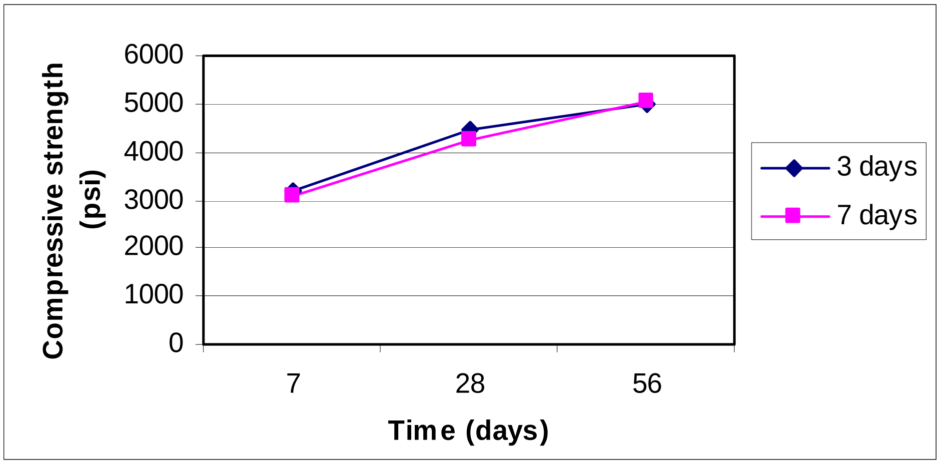

Figure A2- 5 Effect of curing time in SCC-30-FA.

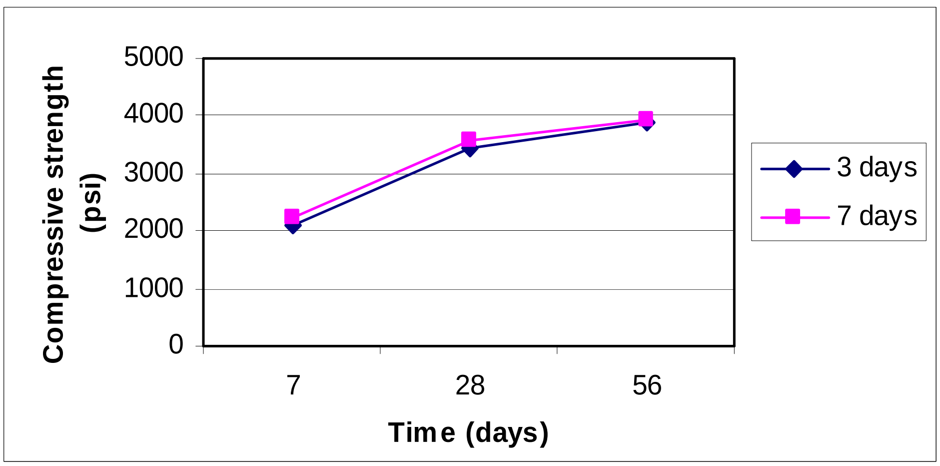

Figure A2- 6 Effect of curing time in SCC-50-FA.