UNIVERSITY OF GAZIANTEP
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USE OF SHRINKAGE REDUCING ADMIXTURE AND STEEL FIBER TO CONTROL SHRINKAGE CRACKING OF LIGHTWEIGHT CONCRETES

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BY
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Use of Shrinkage Reducing Admixture and Steel Fiber to Control Shrinkage Cracking of Lightweight Concretes

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Alaa Mohamadameen

ABSTRACT

USE OF SHRINKAGE REDUCING ADMIXTURE AND STEEL FIBER TO CONTROL SHRINKAGE CRACKING OF LIGHTWEIGHT CONCRETES

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This thesis presents the results obtained from an experimental study conducted to investigate the effect of shrinkage reducing admixture (SRA) and steel fiber addition on some of the properties of lightweight aggregate concrete (LWAC). A total of seven LWAC mixes with SRA or steel fibers were produced at the same water-cement ratio using cold-bonded fly ash coarse aggregates. The percentage of steel fiber volume fractions used in the mixes was 0.25, 0.75 and 1.25. The amounts of SRA used in the mixes were 0.75%, 1.5 % and 3 % by weight of cement. Ring type specimens were used for the restrained shrinkage cracking test. Free shrinkage weight loss, compressive and split tensile strength tests were also undertaken. The results demostrated that the use of steel fibers has little effect on compressive strength but it enhances the split tensile strength. The addition of SRA diminishes compressive strength without influencing tensile strength. Moreover, the utilization of steel fiber or SRA extends the cracking time and reduces the crack width of LWAC resulting in finer cracks associated with lower free shrinkage.

Keywords: Lightweight concrete, Mechanical properties, Shrinkage cracking, Shrinkage reducing admixture, Steel fiber.

ÖZET

RÖTRE AZALTICI KİMYASAL KATKININ VE ÇELİK LİF DONATININ HAFİF BETONLARDA RÖTRE ÇATLAĞI OLUŞUMUNUM AZALTILMASINDA KULLANILMASI

MOHAMADAMEEN, Alaa
Yüksek Lisans Tezi, İnşaat Mühendisliği
Danışman: Doç. Dr. ERHAN GÜNEYİSİ
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Bu tezde, rötre azaltıcı katkı maddesinin ve çelik lif kullanımının, hafif agregalı betonun bazı özellikleri üzerindeki etkileri üzerine yapılan deneysel çalışmadan elde edilen sonuçlar sunulmaktadır. Rötre azaltıcı katkılı veya çelik lifli, soğuk bağlı uçucu kül agregası kullanılarak sabit su çimento oranında toplam yedi hafif agregalı beton üretilmiştir. Beton karışımlarında üç farklı (0.25, 0.75 ve 1.25) çelik lif hacim fraksiyonu ve çimentonun ağırlığınca üç farklı miktarda (0.75%, 1.5% ve 3%) rötre azaltıcı katkı maddesi kullanılmıştır. Kısıtlanmış rötre deneyi için halka tipi numuneler kullanılmıştır. Serbest rötre ağırlık kaybı, basınç dayanımı ve yarmada çekme deneyleri yapılmıştır. Sonuçlar çelik lifin kullanılmasının, basınç dayanımı üzerinde çok az etkisi olduğunu ancak yarmada çekme dayanımını iyileştirdiğini göstermiştir. Rötre azaltıcı katkı maddesinin kullanılması basınç dayanımını azaltırken çekme dayanımı üzerinde önemli bir etki göstermemiştir. Ayrıca, çelik lif ve rötre azaltıcı katkı maddesi kullanımı çatlama süresini uzatmanın yanısıra, düşük serbest rötre davranışı ile uyumlu olarak, daha ince çatlak oluşumunu sağlamıştır.

Anahtar kelimeler: Hafif beton, Mekanik özellikler, Büzülme çatlaması, Büzülme azaltıcı katkı, Çelik lif.

To my dear parents,

brothers, sisters, and

daughters

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LIST OF SYMBOLS/ ABREVIATIONS

LWAC	Light Weight Aggregate Concrete
NWC	Normal Weight Concrete
LWC	Light Weight Concrete
LWCA	Light Weight Coarse Aggregate
FA	Fly Ash
SF	Silica Fume
St	Steel Fiber
Vf	Volume Fraction of Fiber
l/d	Aspect ratio of Fibers
W/C	Water/Cement ratio
W/b	Water/Binder ratio
LWA	Light Weight Aggregate
OPC	Ordinary Portland Cement
NWAC	Normal Weight Aggregate Concrete
MK	Meta-Kaolin
GGBFS	Ground Granulated Blast-Furnace Slag
HPC	High Performance Concrete
FRC	Fiber Reinforced Concrete
HPFC	High Performance Steel-Fiber Reinforced Concrete
SRA	Shrinkage Reducing Admixture
SP	Super-Plasticizer

TZ	Transition Zone
ASTM	American System for Testing Materials
ACI	American Concrete Institute
C-S-H	Calcium Silica Hydrated (Gel)
ACIFC	American Concrete Institute for Fiber Reinforced Concrete
RH	Internal Relative Humidity

CHAPTER 1

INTRODUCTION

1.1 Background

The utilization of lightweight aggregate concrete (LWAC) for structural purposes especially takes place in some of the constructions where the dead weight of concretes is the major part of the total load. LWAC which can easily be produced in the strength range of 30–80 MPa has some certain characteristics unlike the normal weight concrete (NWC), namely, low unit mass, well reinforcing steel–concrete connection, durability performance, tensile strain capacity, and fatigue resistance (Zhang et al., 1991; Videla et al., 2000; Khaloo, 1999; Haque et al., 2004; Al-khayat and Haque, 1999; Haque and Al-khayat, 1999; Mor, 1992). Since the wide variety of the lightweight aggregate produces some distinctive individual behavior among LWACs, the characteristics of LWAC should be studied independently for every kind of lightweight aggregates (Kayali and Haque, 1999).

Shrinkage cracking in concrete structures may cause to accelerate other forms of damage in concrete (e.g., corrosion, freezing and thawing) and subsequently shorten the service life of structures (Know and Shah, 2008; Scheissl, 1998; Wang et al., 1997). Shrinkage cracking can potentially be reduced by introducing a shrinkage reducing admixture (SRA) in concrete mixtures. When concrete is losing moisture (i.e., through drying or self-desiccation), SRA significantly reduces the magnitude of capillary stresses and shrinkage strains by lowering the surface tension of concrete's pore fluid (Shoya and Sogita; Sato et al., 1983; Tomita et al., 1986; Shoya and Sogita, 1990; Shah et al., 1992). The other way of reducing the shrinkage cracking may be adding steel fiber in concrete mixtures. Additions of steel fiber to concrete can be an effective way to enhance the concrete's tensile stress, fracture toughness, impact strength and durability (Bayramov et al., 2004; Banthia and Soleimani, 2005; Balendran et al., 2002; Balaguru and Najm, 2004). The properties and performance of fiber reinforced concrete (FRC) vary in terms of the variations in the concrete formulation, their characteristic material behavior as well as geometry, distribution, orientation and concentration of fibers (Zollo, 1997).

Most researches indicated that the shrinkage of cementitious materials is reduced by the use of SRA (Shah et al., 1992; Bentz et al., 2001; Folliard and Berke, 1997; Nmai et al., 1998; Shah et al., 1998; Weiss et al., 1999). This reduction of drying shrinkage of concrete containing SRA may be up to 50% (Shoya and Sogita, 1990; Shah et al., 1992; Folliard and Berke, 1997; Nmai et al., 1998; Berke et al., 1997). It subsequently increases the age of cracking and reduces the corresponding crack width (Shah et al., 1992; Folliard and Berke, 1997; Nmai et al., 1998; Weiss et al., 1999; Weiss and yang, 1999; Shah et al., 1997; Wiess et al., 1998). The addition of SRA also affects the strength properties and pore structure of concrete. The compressive strength of concrete containing SRA may be reduced by 10 to 25% (Shah et al., 1992). This reduction however is highly dependent on the curing conditions (Shah et al., 1998). Even 28% compressive strength reduction is reported compared to that of the control concrete (Brooks and Jiang, 1997).

As far as the concrete containing steel fiber is concerned, the compressive strength is improved with an increase in fiber volume at each fiber aspect ratio (Marar and Eren, 2002). This increase of compressive strength of concrete containing steel fiber (St) may be up to 20% (Daniel and Loukili, 2002; Song and Hwang, 2004; Yazici et al., 2007; Atis and Karahan, 2009). The splitting tensile strength however benefits better from the fiber-reinforcement which provides up to 98% improvements in terms of the increase in volume fraction of steel fiber (Song and Hwang, 2004; Yazici et al, 2007; Atis and Karahan, 2009). Some researches indicated that the addition of fibers to the concrete influences the drying shrinkage minimal and helps in reducing the cracks formed due to restrained shrinkage (Swamy and Stavarides, 1979; Grzybowski and Shah, 1990).

The basic information on the mechanical properties of steel fiber-reinforced lightweight high-strength concrete has provided by Gao et al. (1997) and Balenderan et al. (2002). Kayali et al. (1992) investigated the effects of both fly ash and fiber reinforcement on the drying shrinkage of lightweight aggregate concrete.

Although, several studies have been carried out to establish the influence of SRA and steel fiber additions on the properties of normal weight concrete, only few studies have focused on the influence of using SRA and steel fiber on lightweight aggregate concretes. This thesis attempts to tackle these limitedly known effects of SRA and steel fiber addition on some the properties of lightweight aggregate concretes.

1.2 Outline of the Thesis

Chapter 1 Introduction: Aim and objectives of the thesis are introduced

Chapter 2 Literature Review and Background: A literature review was conducted on the cracking in concrete. The previous studies on the use of fly ash for producing lightweight aggregate are investigated. The use of shrinkage reducion admixture and steel fibers in reducing shrinkage in concrete as well as reducing width of crack

Chapter 3 Experimental Study: Materials, mixtures, casting, curing conditions, and test methods are described

Chapter 4 Test Results and Discussions: Indication, evaluation, and discussion of test results are presented

Chapter 5 Conclusion: Conclusion of the thesis are given

CHAPTER 2

LITERATURE REVIEW

This chapter reviews the history and recent development of LWACs, cracking in concrete, mechanism of shrinkage cracking in concrete, shrinkage in LWACs, shrinkage reducing admixtures; steel fiber reinforced concrete and the combined application of LWACs and steel fibers in the concrete as well.

2.1 Introduction

In general, concrete under goes volumetric variations when it is open to environment, depending chiefly on proportional humidity, temperature, volume of the member as well as properties of the mix proportions. These volumetric variations are mainly classed into two great classifications: thermal shrinkage (expected to temperature lowering and chemical effect) and drying shrinkage (expected to wetness loss). Thermal shrinkage is not important in narrow concrete members. Though, drying shrinkage is significant, and happens faster. When concrete is restrained as of shrinking tensile stresses develop, which may causes cracking of concrete. It should be well known that in pure life, the constructional members of hardened concrete are usually under restraint, in general as of sub grade friction, near members, reinforcing steel, otherwise as of different stresses between the outside and inside of the concrete. Cracks so formed to lower the load carrying capability of the concrete element. As well as effect corrosion of steel reinforcement, increment the possibility of alkali silica reaction in addition to sulfate attack, and effect another durability trouble, resulting in raised maintenance expenses and decreased service-life. Therefore, decreasing or controlling shrinkage cracking, like delaying the time of visual crack in concrete members are considerably significant to limits the factors of cracking (Shah et al., 1992; Wiess et al, 1998).

2.2 Lightweight aggregate concrete

2.2.1 Definition

At present, various explanations are used in systems and standards to define LWAC, chiefly established on its density. the higher limitations of LWAC variety as of air-dry density of 1840 kg/m^3 to oven-dry density of 2100 kg/m^3, according to EuroLightCon " Document of LWAC Definitions and International Consensus Report (1998) ". As for constructional LWAC, its compressive strength with density is needed together. In ACI 213-87, constructional LWAC is explained as concrete that has 17.2 MPa at 28 days as a lowest cylinder compressive strength with equivalent air-dry density not passing 1850 kg/m^3.

2.2.2 Historical development and significance of LWA & LWAC

There are two main kinds of LWA, natural LWA and artificial LWA. Natural LWA’s extend in the world like pumice in addition to scoria have been recognized since the early years of Roman Empire, and the structure of the Pantheon in Rome, constructed by lighter pumice mortar, is the evidence of this (Wilson, 1988). Though, constructional LWAC was not used greatly up to the time of the LWA could be produced industrially as a final century. Because of the homogeneity of the produced LWA, it becomes potential to manufacture concrete with stronger strength. The initial utilization of expanded clay LWA took place throughout World War I for the structure of ships. With the good appearance of these ship caused to an increased use of LWAC in structures and bridges. The offshore oil activities gave possibilities to use LWAC for platform structure, as of the 1950s. Since then, additional buildings have been constructed, fully or partially by LWAC.

By which LWAC differentiates itself from NWAC since the mainly significant characteristic of LWAC is its lower density. It was identified that the main obstruction in the use of constructional concrete is high self-weight. In addition to long span bridges, properties of concrete such as larger strength and lightweight are suitable for high-rise structures. Sometimes, the density of the concrete is further significant than the strength. So, it is possible to lowering the cross-section of the members and decreasing the volume of foundation by using concrete with low densities. Additionally, the frame work will be subjected to a lower force than the case with NWC by using lighter concrete, as well as with a consequent increment in productivity the total weight of materials to be handled is decreased. LWAC can play a significant role in situations where the self-weight is significant since it is proportionally low density constructional. The EuroLightCon document (LWAC Material Properties, 1998) reported that the lowering of dead load are the mainly useful causes for choosing LWAC, in addition to the flexibility in the plan, the saving of building expense, and excellent long-time durability.

2.2.3 Characteristics of LWA and LWAC

It is recognized that the mainly significant characteristics of LWAC are the low density, high volume of insulation and wetness transportation mechanism between aggregate and paste. Clearly, those are closely related with the characteristics of the

LWA used in this kind of the concrete, especially the porosity, the shape and top surface characteristics as well as pore size structure, and the water absorption of LWA.

The surface characteristic of LWAs can change substantially depending on the various raw material and production procedures as of rough to smooth. Zhang (1989) study on LWA manufactured as of revolving kilns and stated great change in the surface porosity such as (Liapor, expanded clay) and that manufactured from sintering method such as (Lytag, sintered fly ash). Many difference between the relative dense outside shell and the porous inside shown in the expanded clay aggregate. Though, there is no many difference in structure for the sintered fly ash aggregate. The water absorption and strength of LWA is associated to its porosity, which as well influences its density.

Concrete including aggregate, mortar, and interface between these two constituents (TZ) can be considered over a three-phase composite material (Figure 2.1). In NWAC used, usually of structural uses, the mechanical properties of the concrete and its durability are strongly determined by the properties of TZ, since it is usually the weakest bond. For LWAC, since, LWA supports the structure of a denser TZ by a higher porosity and rough surface of the LWA. However, the surface characteristics, initial moisture content and the pore structure of the aggregates are factor effect on the properties of TZ. Furthermore, the absorption of mixing water into the LWA may decrease the water to binder ratio near the aggregate surfaces that avoid the increase of bleeding water process (Zhang et al., 1989).

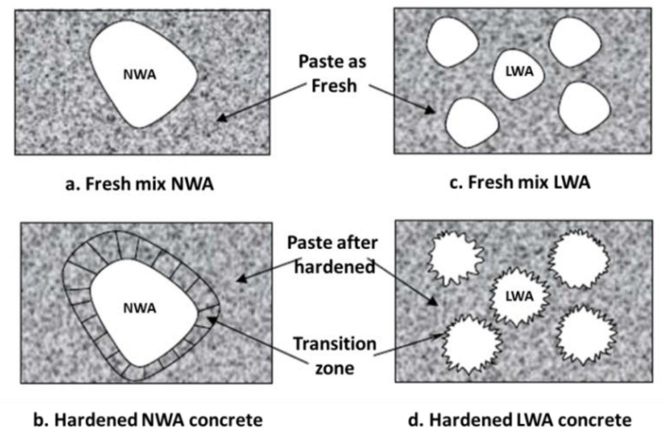


Figure 2.1 Figure show difference of structure of LWAC and NWC on the meso-level (Zhang et al., 1989)

2.2.4 Water absorption of lightweight aggregate (LWA)

Due to LWAs porous properties, it is tend to absorb more water than normal-weight aggregates (NWA). This procedure of mix water absorbed by the LWA will have important effects on the characteristics of the fresh mix, the hydration of cement, the effective w/b ratio, and the performance of LWAC. LWA absorb water at different ratios depending on the different types of LWA. Kayali (1999) stated that the ratio and total quantity of water absorption depend on the pore structures, initial water content and the properties of aggregate surface. The present of water in the porous aggregate may influence the moisture condition in the hardened concrete, and then, concern the cement hydration and shrinkage in concrete.

The loss of workability of LWACs is another significant result of the water absorption of LWA if the aggregate used is not saturated. In mix design, water absorbed in pure water for one hour through setting is generally assumed to be equal to that absorption by LWA in concrete (Wasserman et al., 1996).

2.3 Lightweight Aggregate Production with Fly Ash

A practical way for recycling of waste materials is the main purpose using fly ash (FA) for LWA manufacture. Only small quantities of fly ash are used in the worldwide. Productions of fly ash LWA can be obtained by two major ways are sintering and cold-bonding methods.

2.3.1 Sintering Method

In this method firstly fly ash with clay is blended with water and pelletized. Secondly the pellets are exposed to a temperature immediately of about 1100 $^{\circ}$C in the ignition chamber which uses recycled oil to fire the carbon in the pellets. At last the pellets are exposed to drying procedure, crushing, sintering and cooling, finishing up with a fly ash lightweight aggregate. At the end of procedure, the finishing pellets are mechanically separated or obviously. Next the material after passing over an initial screen that is smaller than 2.5 mm is pulled off. The material above 2.5 mm is moved throughout the conveyor for second screening, to the necessary sizes for the suitable market (Ramadan, 1995; Gesoglu, 2004).

2.3.2 Cold Bonding

In this procedure the cement or lime is attached to fly ash, together with other materials such as limestone, shale or clay if it is found. The principal of production procedure for fly ash LWA includes two major process pelletizing and curing.

2.4 Pelletization Procedure

2.4.1 Definition of the Pelletization Procedure

Is a procedure for production pellets, with shape as a sphere of fly ash manufactured by agglomeration of moisturized fines in a revolving disc. Binder addition may also produce as fines materials earlier to procedure. The result is called as "the fresh pellet” at the end of the procedure. Anderson, a Swedish investigator, in 1912 was the first, who suggested the pelletization procedure, and then Brackelsberg in Germany, who designed a similar balling procedure, was a studied procedure by the fit of binder to the fines agglomerate, and at high temperatures for the period of manufacture the pellets strengthened. Researcher on the pelletization procedure began in United States in 1920 due to request of sintering applications that were used in Taconite-ore dressing process (Doven, 1996; Jaroslav et al., 1987).

2.4.2 Theory of Pelletization

When a powdered material is treated by water, they forms a narrow moisture film on the surface of the particles, which forms a bridge between the particles as shown in Figure 2.2 a. Then, when these particles are revolved in a balling disc, they forms structures at sphere shape with enhanced bonding strengths among particles due to centrifugal as well as gravitational forces that shown in Figure 2.2 b and c. The force developed in this procedure on the pellets expels the air that present between the particles. As the particles obtain closer, the form becomes denser, which enhances the form consistency as well as makes the fresh pellets have a suitable strength for handling and storing (Pietsch, 1991).

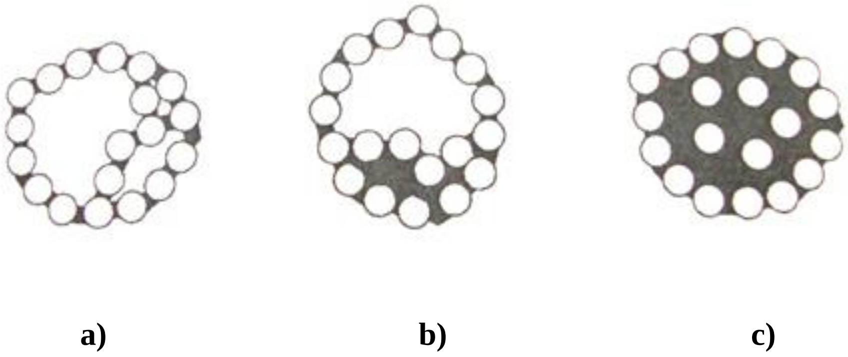
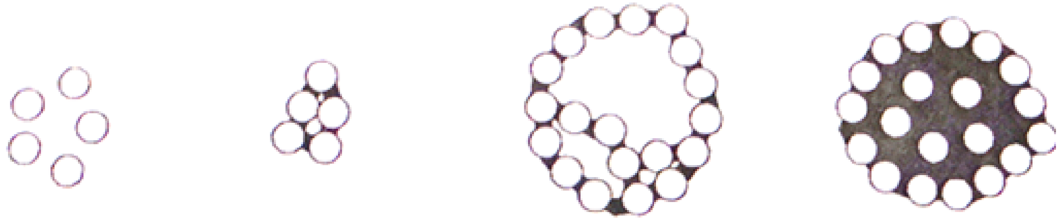


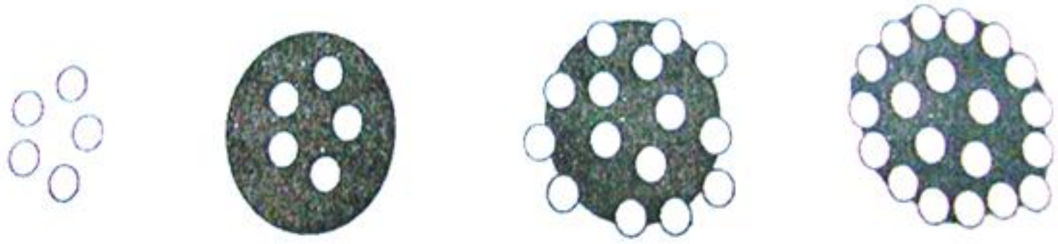
Figure 2.2 Mechanism of pellet formation (Jaroslav et al., 1987)

If all the capillaries are filled by water through manufacture the pellets will obtain maximum strength. In the condition of absence the adequate water causes aired voids will entrapped inside the pellets structure, which limits the capillary activity. In the situation of fly ash LWA, the best water content must be in the middle of 20 and 25%. It is also more significance in the pelletization process the granulometric distribution. This may be controlled through the pelletization procedure by monitoring the feeding percentage of the binder and moisture content. The process of ball formation for the water content is fewer than the best condition as shown in (Figure 2.3). In this condition, the wetness particles become connected with water bond bridges and move closer. While the mechanism of sphere structure is indicated by wetness content above perfect, as was shown in Figure 2.4. In this condition, the capillary strength is reduced because of father moistening and the structure is softer. Now the structures are random sized and because it is fresh and may be easily destroyed by the mechanical forces produced in the balling disc (Doven, 1996; Gesoglu, 2004; Jaroslav et al., 1987; Pietsch, 1991).



a) b) c) d)

Figure 2.3 Mechanism of ball nuclei formation (when water content under best state) (Jaroslav et al., 1987)



a) **b)** **c)** **d)**

Figure 2.4 Mechanism of ball nuclei formation (when water content above best state) (Jaroslav et al., 1987)

2.5 Cracking in concrete

Cracks may be produced at many different conditions and may variety from highly small internal micro cracks that happen on the application of the modest quantity of stress to rather great cracks produced by poor construction errors in structural design, unsuitable connections with the environment, which can be generated by structural and non-structural effects.

2.5.1 Plastic shrinkage cracking

It is a surface cracks and it happens when the evaporation of water content as of the top surface of fresh concrete is too quick to be replaced by bleed water. Upon drying, the restraint as of the concrete below the surface effects in the growth of tensile strains in the weak fresh concrete with the shrinking of the surface of concrete. These tensile strains are the starters of shrinkage cracking in fresh concrete. Usually, plastic shrinkage cracks are surface cracks of differing depths also are generally moderately large at the surface. It is requires to decrease the different volume variation in the plastic concrete to avoid plastic shrinkage cracking (Shah et al., 1998; Weiss et al., 1999).

2.5.2 Drying shrinkage cracking

It can be described as the time dependent linear strain at the constant temperatures calculated on an unloaded sample that is let to dry. Generally, NWC in construction has an ultimate shrinkage strain of $600x10^{-6}$ strain, which is greater than the natural tensile-strain capability of concrete of $150x10^{-6}$ strain or smaller (ACI 224, 2001). When the inner tensile stresses pass the tensile strength of the concrete, drying shrinkage cracking happens (Figure 2.5). This result is particularly important in constructions with high surface to the volume percentage, such as highway pavement, parking garages, industrial stages, and bridge decks (Wiegrink et al., 1996).

2.5.3 Thermal cracking

Thermal stresses grow when a temperature gradient happens inside the concrete member. Variations in ambient temperature may cause a variance in temperature between parts of concrete structure otherwise unequal heat dissipation rates of cement hydration. As a result, different size changes may take place. Cracking will take place when the developed thermal stresses pass the tensile stress capability of concrete; temperature difference due to heat dissipation is generally related with mass concrete such as big columns, dams and piers. For flat constructions such as highway pavement, parking garages, industrial stages, and bridge decks, thermal shrinkage is not important (Neville, 1997).

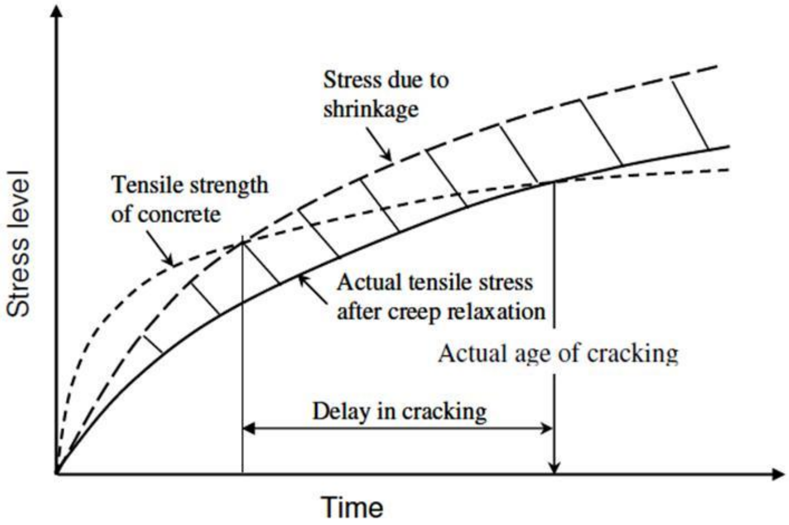


Figure 2.5 Effect of strength, shrinkage and creep on shrinkage cracking of concrete (Neville, 1997)

2.6 Mechanism of shrinkage cracking

Concrete can be subjected to crack when the tensile stress passes the tensile strength of concrete (Figure 2.5). In practice, the tensile stress developed expected to restrained shrinkage in concrete member is lesser than that projected at Hooke’s rule (Mehta and Monteiro, 1997).

Likewise, it follows that if the strength of concrete is usually larger than the advanced stresses, no cracking will take place (Mindess et al., 2003).

Moreover, shrinkage cracking is a composite happening that depends on many causes: the amount of shrinkage, stress relaxation, rate of shrinkage, the volume/geometry of the structure, degree of structural restraint and age dependent material property growth (Weiss et al., 2000; Shah et al., 1998; Igarashi et al., 1999).

2.7 Shrinkage of concrete

Shrinkage, after set of concrete, is the reduction in concrete volume with time. The reduction is expected to variations in the water content of the concrete (ACI 209, 2003). The inverse is swelling, which indicates the volumetric increase expected to wetness increase in the hardened concrete. Shrinkage is a significant characteristic in addition to the strength and durability as a necessary concern for the structure of concrete constructions. The significance of shrinkage in constructions is mostly associated to crack. Usually, shrinkage is grouped as plastic shrinkage, drying shrinkage, and thermal shrinkage according to their characters such as a period of happening.

2.7.1 Drying shrinkage

Drying shrinkage takes place in hardened concrete as a reaction of the water moves. Drying shrinkage is considerably the mainly common factor of shrinkage. In concrete reaction, cement and water react and effect in the formation of calcium-silicate-hydrate gel (C-S-H) with water supplied places. The volume of the pores in the water-filled place changes from smaller voids filled by adsorbed water (0.5~0.25 nm), and great capillary pores (> 5 nm). The graphic diagram of factors of drying shrinkage of cement paste is seen in Figure 2.6. As drying takes place, disjoining pressure removes adsorbed water as of these pores and capillary stresses from a meniscus that apply stresses on the C-S-H structure producing the cement paste to shrink (Kayali et al., 1992).

Neville (1997) stated that the w/c required for finished hydration is normally assumed to be nearly 0.42 depending on the quantity of gel porosity that is affected.

Since one of the mainly considerable causes influencing free shrinkage is the w/c ratio the quantity of water has a clear effect on the magnitude and size of the porosity that meaning high w/c pastes have high porosity. Thus, samples with a lesser w/c have a lesser quantity of pore water and subsequently, show lower drying shrinkage.

Drying shrinkage due to its significant effect on the total shrinkage deformation of concrete is said to be the direct cause of cracking in concrete. The porosity and consistency of the concrete are factors that influence drying shrinkage in concrete which is affected by the w/c ratio, water and cement content and relative volume of aggregate, the aggregate properties and external effects such as the relative humidity of the environment, the size/geometry of the concrete member, drying time and also the curing condition as follow described (Neville, 1997).

2.7.1.1 Internal relative humidity (RH)

The RH of the surrounding environment has a main effect on the rate of shrinkage and the final shrinkage. Troxell et al. (1958) stated that the increase the outside RH of the surrounding in comparison to the inside RH of the concrete, the lower would be the rate of shrinkage and the final shrinkage of the concrete.

2.7.1.2 Drying time

The volume changes of concrete increase with rapid drying. If the stress is applied slowly as concrete can resist stronger tensile strains, in order to avoid early age cracking expected to drying shrinkage the rate of drying of concrete should be monitored. Rules to avoid quick drying contain the use of curing compounds, even after water curing (Shah et al., 1998; Igarashi et al., 1999).

2.7.1.3 Size/ geometry of member

The volume and form of the concrete members affects the shrinkage rate of concrete, because it considerably affects the rate of drying of concrete. Concrete sample with a greater surface/volume ratio indicated higher drying rate. In other words, for a given concrete, it is noted that with an increase in the size of the sample at a given period the shrinkage reduces. Upon drying, wetness gradient develops as of the outside to the inside of the sample. Shrinkage strain reduces towards the center where wetness content is highest and shrinkage stain is largest at the drying surface where wetness content is lowest. This provides increase to the development of the non-uniform internal stresses: tensile stresses at, and near the surfaces and compressive stresses grow at and near the core (Weiss et al., 2000; Kayali et al., 1992).

2.7.1.4 Curing

The period of wetness curing doesn't have considerably resulted on the final amount of drying shrinkage. As far as the cracking trend of the concrete is troubled, extended moist curing may not be useful. A general suggestion is to keep on wet curing for at least seven days (ACI 224, 2001). Investigation by the California Department of Transportation (1963) indicates that concrete that was moist-cured for 7, 14 and 28 days before drying began, gives the same final shrinkage.

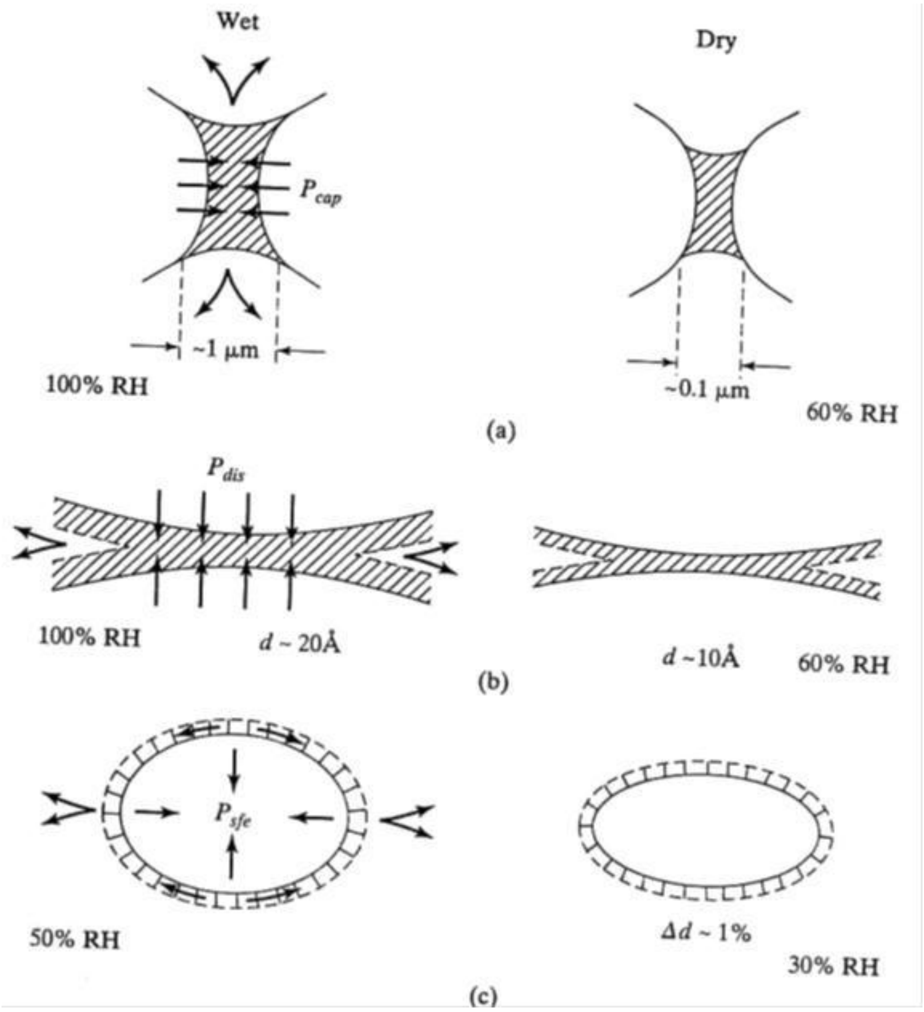


Figure 2.6 Causes of drying shrinkage of cement paste (a) Capillary stress, (b) Disjoining pressure, and (c) Surface tension (Mindess et al., 2003)

2.7.2 Shrinkage of lightweight aggregate concrete

The very early research on shrinkage of LWAC was by Shideler (1957) on mixes made by various kinds of LWA with 20 MPa and 30 MPa compressive strength grades. It was stated that in the larger strength level, the shrinkage of LWAC is usually lower than that of NWC, and some of the LWAC was indicated smaller shrinkage than the NWC at early ages, while, at six months, it was 30% higher than the shrinkage of associate NWC. While, the shrinkage of LWAC was fewer than that of NWC at six months in higher strength level, and at one year, the shrinkage of LWAC was similar or slightly higher than NWC. In comparison to Shideler research, Pfeifer (1968) stated that the shrinkage of LWACs was in many situations with 20 MPa lesser than related NWC, while most of LWACs with 35 MPa had higher shrinkage than the related NWC, and shrinkage of LWAC with 35 MPa were greater than with 20 MPa LWACs.

Neville et al. (1983) suggested that the concrete prepare with LWA expected to the higher water move and the lesser modulus of elasticity of the LWA than the normal-weight aggregate (NWA) results that LWA have 5 to 40% higher shrinkage than the NWA. The level of restraint gave of aggregate causes by the elastic charastaristic of it; such as expanded shale lead to 1/3rd more, and the steel aggregates to shrinkage 1/3rd, fewer, than NWA. Nielsen and Aitcin (1992) studied the drying shrinkage of LWAC containing expanded shale. They establish that the LWAC had 30 to 50% lesser shrinkage than comparable NWC after 28-day of curing and 56 days of drying, unlike as of Neville. They applied this to the attendance of the water inside the LWA. Similarly, that determined even though the shrinkage of all-LWAC was 1 to 1.5 times higher than NWC by Newman (1993), he stated also that LWAC with dense fine aggregates exposed like shrinkage performance as NWC.

Kayali et al. (1999) investigated on LWAC prepared by Lytag aggregates had a complete cementitious material's component of 785 kg/m3, where the NWC with a total cementitious material's content of 485 kg/m3, stated that the drying shrinkage about 1000 * 10^{-6} was approximately twice that of NWC later 400 days. Also, Al-Khaiyat and Hague (1999) studied the drying shrinkage performance of Lytag aggregate. The demolded samples, exposed to long period drying after 6 days of curing, caused shrinkage of about 640 * 10^{-6}, which was slightly high at the age of three months. Gesoglu et al. (2004) investigate on LWAC made with cold-bonded fly ash aggregates. They reported that the shrinkage strains were higher for concretes including higher amounts of LWA and the cause given since the extra water in the mixture was provided by the saturated LWA. The shrinkage of LWAC although investigated by Zhang et al., (2005) they used expanded clay aggregate and NWC. They indicated that, the shrinkage of NWC was higher than LWAC in the initial six months for similar mixture proportions, while after one-year NWC had lower shrinkage than LWC.

It is strongly obvious that various type of LWA generally effect in highly unlike behavior as much as shrinkage is worried, according to the produced report on shrinkage of LWAC (Nielsen and Aitcin, 1992; Newman, 1993; Kayali et al., 1999; Gesoglu et al., 2004; Zhang et al., 2005).

2.8 Shrinkage cracking

The significance of shrinkage in constructions is mainly associated to crack. It is the cracking trend expected to shrinkage that is of further concerns because the appearance of cracking depends not only on the possible shrinkage but as well on the ability of concrete to extend, its durability, and its grade of restraint to the deformation that may cause a crack.

2.8.1 Methods to control shrinkage cracking

To control cracking in concrete consists of decreasing cracking trend to a smallest, using suitable structure practices and structure joints, using suitably and sufficient placed reinforcement (ACI 224, 2001). Some of the properties which may control the shrinkage of concrete were given below.

2.8.1.1 Reducing shrinkage

The main factor is w/c ratio, since decrease w/c ratio generally connects to decreasing shrinkage of concrete by standard w/c ratio because low water is present for evaporation and is the mainly evident system to decrease shrinkage cracking as well as decrease the material shrinkage (Neville, 1997). Using aggregates with better stiffness and higher amount of aggregate can also be efficient in lowering shrinkage. Lastly, by suitable curing conditions shrinkage can be decreased because it reduces evaporation losses.

2.8.1.2 Use of expansive cements

These materials are collected of an ASTM C-150 Type I with II cement by additions of Type K, M and S cement. Cements have been advanced to balance for the shrinkage that takes place by expands through curing. Although to give restraint for expansion the inside reinforcing steel was used causing the concrete to be efficiently pre-stressed through curing. The shrinkage balancing concrete has been used on many structures to increase construction joint spacing by reducing the effects of shrinkage cracking (Keith et al., 1996). When expansive concrete is used, specific preparations must be applied. The concrete can self-destroy, if adequate restraint is not given due to expansion; furthermore, the steel must be proportioned and set properly to prevent the influence of difficulties that can contain buckling. Though, these materials are not greatly acceptable in practice.

2.8.1.3 Use of fiber reinforcement

Because concrete is a brittle materials, the advancement of higher tensile strength materials would enhance the performance of concrete constructions, although improves strength are usually caused increase in brittleness. Fiber reinforcement used to enhance the crack interesting mechanisms in cement as well as in concrete. It has been indicated that fibers, even in low volume fraction (Vf), will decrease crack widths and improve the materials resistance to cracking. It has been also newly investigated to capture shrinkage cracking using short randomly distributed fibers. Although it have been examined in many different fiber types involving: steel (Swamy et al., 1979; Paillere et al., 1989; Grzybowski and Shah, 1989), polypropylene (Krenchel and Shah, 1987), Glass (Mirza and Soroushian, 2002), and natural fibers (Sarigaphuti et al., 1993).

2.8.1.4 Use of shrinkage reducing admixtures

Onada expan used in Japan for concrete is an expansive addition presently. Onada expands at the time of concrete hydration, without strength loss using calcium silicate and glass interstitial substitute rather than CaO. This material is stable. However, it must be moist cured and need longer mixing. Tetragard has been suggested as an admixture liquid otherwise powder. This material has been useful to standing concrete, and shrinkage has been decreased. Since it weakens capillary tension, decreases heat of hydration, creep and buckling. Another admixture is Eclipse which is a fluid admixture that restrains shrinkage of concrete. It has been reported that Eclipse reduce the shrinkage at early periods when concrete is mainly at risk. Tazawa and Miyazawa, (1997) reported on mineral admixtures to prevent autogenous shrinkage. Though, while using the shrinkage reducing admixtures (SRA) attention must be taken in using these products because it is many depend on expansion to decrease shrinkage.

2.8.2 Systems to estimate shrinkage cracking

2.8.2.1 Free shrinkage

The standard system to investigate the free shrinkage of concrete is specified in ASTM C-341. The process contains the assessment of the time-dependent variation in length of a (400*100*100) mm prism. The knowledge obtained from this system can be used for comparative researchers. Though, this is not a significant material limitation to describe constructional effects since effect of the geometry, stiffness, creep as well as rupture. It should be well known that for the shrinkage to be applicable to a given construction a similar surface to the volume ratio should be used for the free shrinkage sample (Shahe et al., 1992).

2.8.1.2 Plate tests

This method was advanced in many research laboratories, by using it to decrease plastic shrinkage cracking in concrete with low volume content polymer fibers (Kraai, 1985; Yokoyama et al., 1994). Kraai (1985) used restrained thin plate samples to research the influence of material characteristic on shrinkage cracking as shown in (Figure 2.7). It is established on casting concrete in a slab specimen by restraint which obtained by reinforcement at the edges of the slab. The top surface is open to drying, obtained by air blown by a fan, assuming the windy surrounding conditions. Because of mainly constructions are two-dimensional in the nature, the knowledge achieved from this system can be assigned to a specific construction. The principal disadvantage of this system is to give adequate restraint to the sample. Therefore, the results obtained from this method may depend on sample geometry as well as the material characteristic.

2.8.1.3 Longitudinal tests

This method can be classified into three types. (1) In this test the longitudinal geometry that used to measure cracking only applied as longitudinal qualitative (Banthia et al., 1993, Figure 2.8; Berke and Dallaire, 1994). The crack was measured and computed in relations between crack width and length of the cracks. (2) This type is partially machine to measure the restraining forces and stresses. The experiment is passive in nature, because the restraint is obtained by longitudinal bars at which strain measures are set up directed to as longitudinally-passive. (3) In this test, which an ended hoop controlled method if operating to modify the grip position and set it to the same position while record the load in the restrained and free specimens directed to as a longitudinal closed hoop instrumented. Bloom and Bentur (1995) who firstly use this idea, a completely automatic testing device, which is a closed loop personal computer monitored was advanced by the Kovler (1994) which it indicated in Figure 2.9. In this method, one end was fixed, while another one was combined to a centrifugal motor by a natural joint; when shrinkage takes place and its degree accesses a stress of 5×10^{-6}, the centrifugal motor automatically begins to take the sample backward to the basic situation, keeping the distance of the sample at 1000 mm. The load chamber record the load caused in this movement. Though, it is difficult to provide enough restraint, to produce cracking by linear specimens, specifically when cross-section dimensions are great. In addition, difficulties in practice to getting sufficient end restraint like to difficulties related to testing of concrete in direct tension which is done by Neville (1997).

2.8.1.4 Ring specimens

The ring experiment is a favorite system for estimating the restrained shrinkage cracking in concrete. In this method, a sample of the ring specimens was cast inside steel ring. When concrete exposed to drying condition, the concrete ring specimen trend to contract, however, steel ring avoids the shrinkage; the concrete ring specimen raises tensile strain in the circular radiance. The significant dimensions of the sample can be chosen in such a method to approximate uniaxial strain as a result of restraint in the ring specimens. Since the center symmetrical in nature of the ring concrete specimens, it can be corresponded as a long space slab exposed to tension stresses. The ring experiment is simple to produce of concrete in the laboratory without difficulties to providing enough end restraint to the tensile samples (Weiss et al., 1998). The summarized data on restrained shrinkage cracking in concrete systems and determination methods used for a separate kind of concretes, and mortar was shown in Table 2.1.

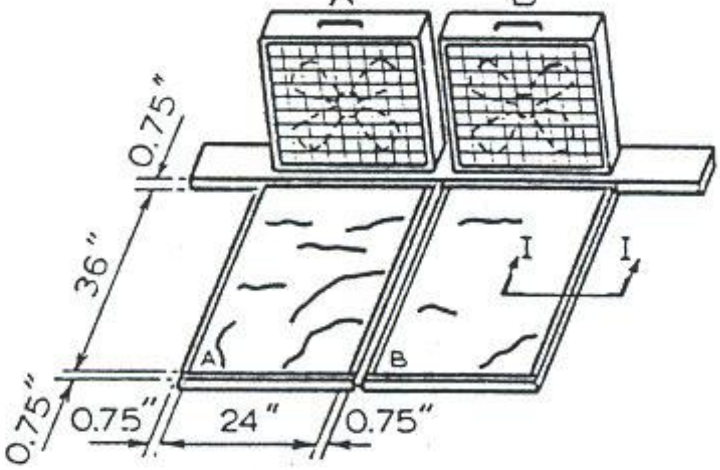


Figure 2.7 Plate experiment study for restrained shrinkage cracking (Kraai, 1985)

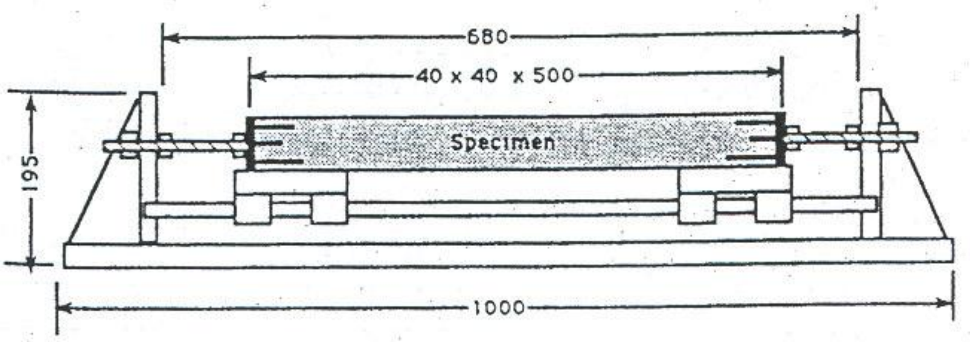


Figure 2.8 Longitudinal restraining ring experiment that advanced by Banthia et al. (1993)

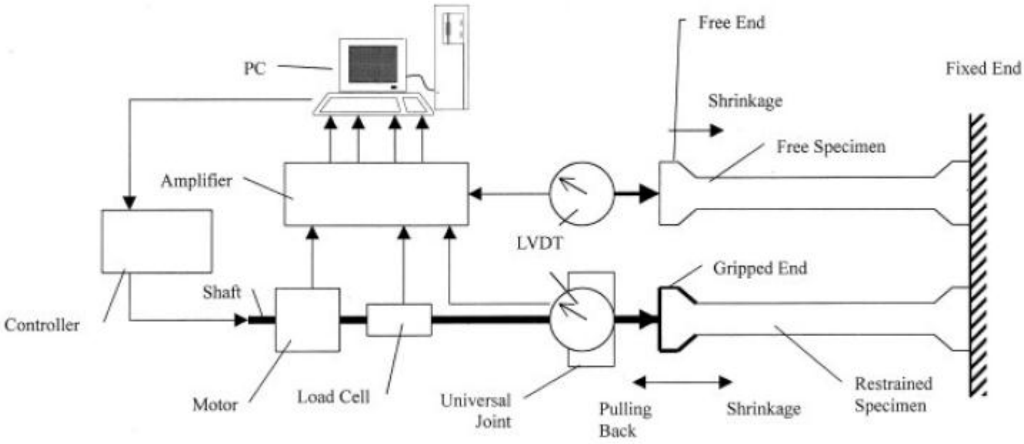


Figure 2.9 Graphic explanation of the ended circle instrumented restraining method advanced by Kovler (1994)

Table 2.1 Summary of restrained shrinkage cracking techniques and measuring systems for unlike concretes

#	Researcher	Type of Test	Details of samples	Concrete type	Measurement technique	Conclusions/Remarks
1	Swamy et al. (1979)	Ring test	Steel ring: ØD 508 mm and thickness 32 or 44 mm; Concrete ring: ØD 660 mm, thickness 76 mm and 102 mm height.	Mortar, Fiber reinforced mortar and NWC	Strain equivalence established on the theory of elasticity was recommended on a simulation that the theoretical distribution of the diagonal stress in the concrete and steel is parabolically.	Early age researches were carried out. The stresses in steel ring were taken using strain-measurements. The development of the ring system for evaluating shrinkage strains in concretes has been stated.
2	Kraai (1985)	Plate/slab test	900 mm long, 600 mm wide and 20 mm thick	Fiber reinforced mortars	The high performance of concrete is measured by total crack length, highest crack width, number of cracks per unit area, and total crack area.	Plastic shrinkage cracking was experimented. The restraint being obtained by reinforcement steel at the ends of plate. The top surface is open to drying, which is obtained at hot air played by a fan.
3	Carlson and Reading (1988)	Ring test	Steel ring: ØD 175 mm and thickness 25 mm; Concrete ring: ØD 200 mm, thickness 25 mm and 38 mm height.	NWC and mortar	Testing concrete ring randomly to conclude the extending term of cracking. Drying was allowed only as of the circumference.	It was established that larger stresses before cracking when open to low RH than when open to high RH. This ring experiment was advanced by Carlson in 1939.

4	Grzybowski and Shah (1989)	Ring test	Steel ring: ØD 170 mm and thickness 26 mm; Concrete ring: ØD 250 mm, thickness 40 mm and 40 mm height.	Steel Fiber reinforced NWC	Total width of cracks and number of cracks at the end of experiment was considered for correlation by other researcher.	The analytical model was advanced contains many of the key significant variables. The incorporating of 0.25% fibers reduce the average crack width which is one-third that of models without fibers, further than 0.5% has proportionately smaller enhancement.
5	Grzybowski and Shah (1989)	Ring test	Steel ring: ØD 305 mm and thickness 25.5 mm; Concrete ring: ØD 375 mm, thickness 35 mm and 140 mm height.	NWC; Fiber reinforced	To calculate crack width a specific microscope arrangement planned.	No effect with 0.1% by amount of polypropylene fibers was stated. Steel fibers used were further efficient compare to polypropylene fibers.
6	Shah et al. (1993)	Ring test	Steel ring: ØD 305 mm and thickness 25.5 mm; Concrete ring: ØD 375 mm, thickness 35 mm and 140 mm height.	SRA NWC with Polypropylene and steel fibers	To assess the performance of type of fibers and volume fraction of fibers on the cracking action of fiber reinforced concrete, they used age of cracking, number of cracks and total crack width.	As compared with ordinary concrete a great lowering in crack width happens, depending on the kind and percentages of SRA used.
7	Sarigaphuti et al. (1993)	Ring test	Steel ring: ØD 305 mm and thickness 25.5 mm; Concrete ring: ØD 375	Cellulose fiber reinforced	To estimate the effect of Cellulose fiber reinforced on shrinkage cracking and compare to	Cellulose fiber reinforcement and comparable performance with polypropylene fibers a significant

			mm, thickness 35 mm and 140 mm height.	NWC	polypropylene fibers in NWC.	decrease in crack width was stated within the shrinkage Cracking and toughness experiments.
8	Banthia et al. (1993)	Longitudinal test: qualitative	40 x 40 mm cross section and 500 mm Long with restraint generated by end grips.	Fiber reinforced cementitious composites	To describe the cracking behavior though the total crack with total crack width, the number and width of cracks are noted, and cracking is studied by a microscope travel above the sample.	The mold itself is prepared on two frictionless rolls that are free to slide in the longitudinal direction, and the entire assembly is placed in an environmental office. Sample is cast inside a mold by a treble bar anchors at its ends. These anchors are rigidly attached to a 50 mm thick bottom plate by vertical poles.
9	Kovler (1994)	Longitudinal test: Closed loop controlled	40 x 40 mm cross section and 1000 mm long with wider at two ends to fit into the grips	NWC	The satisfying phases commanding the performance of the instrumented shrinkage testing method and free shrinkage and creep can be considered as of the test documents.	In this test, When shrinkage takes place and its level accesses a strain of 5 x 10^{-6} the centrifugal automatically begins to extract the sample back to the basic situation, to carry on the length of the sample. One gripped end was fixed, and another was combined to a centrifugal by a general joint. The load chamber record the load caused in

						this movement.
10	Bloom and Bentur (1995)	Longitudinal test: active	40 x 40 mm cross Section and 1000 mm long with wider at two ends to fit into the grips.	Micro concrete with 7 mm aggregate size (NWC)	Early age cracking of hardened concrete and plastic shrinkage cracking was investigated. Strain curves were caused under restrained shrinkage situation and the age at which the strain drop was the sign of cracking.	In this test setup, one grip was set, while another was free to motion. So total restraint was obtained by coming back the grip to its first location. The move of the free grip was observed by particular gauge. As the concrete shrink during shrinkage, the mobile grip might be retain back to its first location by a screw assembly connected to the grip, capable of controlling the load applied exerted
11	Banthia et al. (1996)	Substrate restrained test	100 x 100 mm crosssection and 1010 long with restraint generated by matured concrete base.	Fiber reinforced cementitious composites	To describe the cracking action though total crack with and total crack extended, the number and width of cracks were noted.	Shrinkage samples were set on a 40 mm deep substrate of 1010 mm long and 100 mm wide cured for three days. A 100 mm deep layer of the overlay material was later set on the substrate.
12	Shah et al. (1998)	Ring test	Steel ring: ØD 305 mm thickness 25.5 mm Concrete ring: ØD 375 mm, thickness 35 mm	NWC – normal and high strength	To predict the diagonal shrinkage cracking action of concrete ring exposed to drying shrinkage theoretical model established on	The age of cracking of the ring was predicted by comparing the difference between calculated free shrinkage and the assessed creep to the greatest

			and 140 mm height.		nonlinear rupture mechanism was advanced.	acceptable tensile stress. Using rupture variables and rupture resistance curve of the ring sample, the maximum acceptable tensile strain considered established on energy equilibrium during shrinking of concrete ring.
13	Weiss et al. (1998)	Slab specimens	24 x 100 x 1000 mm of RE and 35 x 100 x 1000 mm restrained base and end slabs	NWC	For slab samples using the rupture variables and free shrinkage and assessed creep documents like the type of examination also recommended.	Age of cracking was calculated, established the reactions and stresses.
14	AASHTO PP-34-99 (1999)	Ring test	Steel ring: ØD 330 mm and thickness 12.5 mm. Concrete ring: ØD 406 mm, thickness 38 mm and 152 mm height.	NWC	To observe the strains over period and sudden variations in the steel stain are used to sign the age of cracking the model contains the use of strain gauges, which are set at the mid height on the internal circumference of the steel ring.	This experiment used to gauge restrained drying shrinkage strains that improve in concrete. Drying from the circumference of the concrete ring was used.
15	Mirza abd Soroushian (2002)	Ring test	Steel ring: ØD 306 mm and thickness 28 mm Concrete ring: ØD 366	LWAC (perlite aggregate)	It assessed established on the total number of cracks and maximum crack widths.	Alkali-resistant glass fibers were stated to be considerably efficient in examining restrained shrinkage

			mm, thickness 30 mm and 370 mm height.	Glass fiber reinforced		cracking of LWC.
16	See et al. (2003)	Ring test	Steel ring: ØD 330 mm and thickness 12.5 mm; Concrete ring: ØD 406 mm, thickness 38 mm and 152 mm height.	NSC and HPC-NWC with and without SRAs	Using the tensile strength, free shrinkage and tensile creep data restrained shrinkage examination was carried.	SRA considerably enhanced the cracking resistance of concrete by lowering both the shrinkage possible and shrinkage rate. The tensile creep must be considered in assessing the risk of cracking under restrained shrinkage.
17	Hossain and Weiss (2004)	Ring test	Steel ring: ØD 300 mm and thickness 3.1, 9.5, 19 mm; Concrete ring: ØD 450 mm, thickness and height is 75 mm.	mortar, Concrete, (NWC)	The preparation stress advancement using contracted change access was advanced. The stains in the steel ring were taken using stain measures and used to analyses the strains in the concrete ring specimen.	Risk of cracking established on the percentage of substantial stress in the concrete ring to tensile strength of concrete was also recommended. Drying of ring was permitted from upper and base of the concrete ring.
18	Gesoglu et al. (2004)	Ring test	Steel ring: ØD 305 mm and thickness. 25.5 mm; Concrete ring: ØD 375 mm, thickness 35 mm and 140 mm height.	LWAC (cold bonded Fly ash aggregate was used)	To compare the shrinkage cracking performance of LWAC with and without SF and with various w/c age of cracking and total crack width was considered.	Results express qualitatively without any stress information.

2.9 Shrinkage reducing admixture (SRA)

References of SRA in scientific literature area their origins in Japan since 1980s, these admixtures are usually organic polymers that decrease the surface tension of water. When SRAs are distributed in the water used for concrete, the capillary pressures inside the pore structure of drying concrete are reduced, lead to decreasing the shrinkage of concrete (Gettu et al., 2002; Shoya et al., 1990; Balogh et al., 1996). Some admixtures, which are included during the mixing of the concrete, have been designed for a special purpose to decrease the surface tension and. the capillary pressures inside the pore structures that are responsible for shrinkage process in concrete when exposed to dry (Roncero et al., 2003; Gettu et al., 2002).

SRAs provide a technique to decrease the strains produced in concrete at drying shrinkage as well as reducing drying shrinkage stresses. Benefits of use SRA is concrete mix design component and mixing process stay uniformly changeless (Berke et al., 2003).

2.9.1 The Ability of Shrinkage Reducing Admixtures (SRA)

The ability of SRA to reduce the degree of long-term distortion in concrete is a more significance in constructional design. Examination of the influence of a common available called glycol-based SRA, on the shrinkage also the creep behavior of concretes exposed to drying and sealed situation, and it is the influence on the mechanical characteristic of the concrete especially compressive strength properties were begun by Gettu and his companions (Roncero et al., 2003; Gettu et al., 2002). Over a term of two years, show a strange decrease of the shrinkage strains and specific creep exposed to drying conditions, when associated to a concrete without

SRA. Though, the samples with SRA practiced a slight reduction on the compressive strength (Roncero et al., 2003).

Weiss et al. (1999) stated that during setting of concrete, the present of SRA causes a decrease in the maximum internal temperature and a reduction in rate of heat development. This was applied to a potential acceleration of the hardening caused by the addition of SRA. The suggestions of this action are that lower temperatures will happen in mixtures with SRA lead to lower shrinkage (Newberry et al., 2001).

A significant disadvantage of the addition of SRA is the decrease of the 28-day compressive strength. However, the decrease in strength can be cancelled using lower w/b ratio, without changing the workability, like that was done by Weiss et al. (1999).

It is famous that concrete when it exposed to drying shrinks through the first days after casting. It was decided to add SRA inside the mixture to compensate for the concrete shrinkage when it exposed to drying. The addition of SRA decreased the surface tension of the water within the capillaries and pores inside the cement paste that reported by Newberry et al. (2001).

Because low w/cm ratios eliminate more of durability concerns, the concrete is significantly over designed for strength, in these cases, the reduction of heat that obtained by addition of SRA can be an important influence in decreasing the probability of cracking, this is more practice for bridge decks, car parks, multi-stages and marine constructions (Newberry et al., 2001).

2.9.2 Long-Period Performance of Concrete Including SRA

SRA allow the reduction of specific unsuitable aspects of the behavior of concrete such as shrinkage and creep which is father important in constructional design. The shrinkage and creep behavior of concretes including glycol-based SRA was estimated by Gettu et al. (2002). Over a period of six months, they obtained result and indicate a significant decrease in the total shrinkage strain and creep coefficient under drying situation, when compared by control concretes without SRA. Though, addition of SRA have a negative influence on the compressive strength that were slightly lower than the control concretes (Gettu et al., 2002).

2.9.3 Property of SRA on Restrained Shrinkage Cracking of Concrete

A research on the ability of SRA in controlling restrained shrinkage cracking of concrete by Shah et al. (1992) they explained that the effect of three different kinds and rates of SRAs were used. The first one was a commercial substance involving an alkoxylated alcohol; the second one was like to alkoxylated-based oligomer, while the third one was a provisional alcohol-based material. Free and restrained shrinkage tests were carried out. The effects of concrete mix including SRA were compared with those including steel fibers, polypropylene fibers, and wire mesh. Weight losses were calculated using same free-shrinkage samples. Furthermore, pore-size distribution was concluded, also the flow test of fresh mixture's concrete was calculated. They observed that the addition of SRA considerably decreased free shrinkage. The effect of SRA on restrained shrinkage was a considerable decrease in crack width; extend the age of cracking appearance (Shah et al., 1992).

They also indicated that the addition of SRA had a negative effect on the compressive strength of concrete. The effects change, depending on the period of curing and dosage and type of SRA used, use more amounts of SRA caused a larger decrease of free shrinkage, and greater reduction in compressive strength. The size of macro-pores structure was substantially smaller in concrete, including SRAs than those without SRAs, depending on the type and dosage of SRAs used; a substantial decrease in crack width took place compared with ordinary concrete. The effect of SRAs on flow of concrete was significantly increased in the flow of concrete (Shah et al., 1992).

2.9.4 Control of Cracking with Shrinkage-Reducing Admixtures

Controlling restrained shrinkage cracking of concrete is the ability of SRAs that was examined by Shah et al. (1996). They used ring sample for restrained shrinkage cracking tests. A propylene glycol unoriginal was used as a SRA for this investigation, which was used at 1% and 2% by mass of cement. Free shrinkage, weight loss, fracture toughness, and compressive strength were also investigated. The effects of SRA concrete mixtures were compared by that of ordinary concrete without SRA with the same water-to-cement (w/c) ratio. A theoretical system established on nonlinear fracture mechanism was advanced for estimating diagonal cracking of the concrete ring sample generated by drying shrinkage. The model estimation of the period to cracking compared correctly with the test documents. The system can be enlarged expanded to different geometries and measurements than those considered in the investigation stated by Shah et al. (1996).

2.10 Steel fiber reinforced concrete (SFRC)

As old times, fibers similar to straw and horsehair have been used to support bricks, plaster, and masonry mortar (ACI 544. 1R-96, 1996). At present, a large variety of fibers is used in further and further engineering programs. The significances in supporting concrete by steel and different fibers have been development stably in the previous thirty years, and many investigation reports have been produced through its use and mechanical characteristic.

SFRC usually used in constructional applications, in an additional role to control cracking in concrete, enhance resistance to, dynamic load or impact, and to resist material breakdown. It is used in applications where the present of continuous steel reinforcements is not necessary to security of the construction such as walkways, shotcrete and overlays, the fibers can be used to decrease structural thickness or enhance performance, or else both, this related to the enhancements in flexural tensile strength. The advantages of using fiber reinforcement is as well associated to improve long-term service life of constructions, providing the designed role up its considered service life (Chanvillard, 2000; and Naaman, 2000).

Brittle materials such as concrete are reviewed to have no considerable post cracking tensile strength. When exposed to tension, the brittle concrete, firstly, failure elastically accompanied by micro cracking, transport from macro cracking and at last rupture, the addition of fibers inside concrete result good enhancement in post cracking behavior of fibers, the range of the enhancement depends on a sum of influences such as the strength of concrete and the type, aspect ratio (l/d), modulus, strength, surface properties, and volume fraction (Vf) of fibers. Many of the engineering characteristic of concrete especially the effect of fibers contained on impact strength and flexural toughness, which are considerably enhanced by the addition of fibers (Newman, 1993; Kayali et al., 1999; Shah et al., 1992).

2.10.1 Types of fibers

Present there are several types of fiber, in different sizes and shapes, available for trade and test use. The essential fiber classifications are steel, glass, artificial and natural fiber materials. However, steel, structural synthetic, and polypropylene fiber reinforced concrete is the three chief kinds of fiber, which are used as a substitute of ordinary steel structure reinforcement (ACIFC, 1999).

2.10.2 Steel Fibers

The major applications for steel fiber concrete are pavements and industrial floors are. In the United Kingdom, over the past ten years, more than 2 million m^3 of steel fiber reinforced slabs have been placed (ACIFC, 1999). The stresses taking place in a concrete slab are composite depending on the type of load. Sharp becomes from branching lift trucks, shrinkage and thermal property, and impact loads are causes make stresses to be hard for measure (Knapton, 2003). Compared to conventional fabric reinforcement, these fibers have a tensile strength normally 2-3 times greater and a significant greater surface area to improve the bond with the concrete matrix (ACIFC, 1999).

2.10.2.1 Types of Steel Fibers

Several productions have been constructed in current years to optimize the shape of steel fibers to improve fiber dispensability in the concrete mixture, and to obtain enhanced fiber-matrix bond properties. Based on the product used in their production

ASTM A- 820 provides a classification for four universal types of steel fibers (ACI Committee 544. 1R, 1996):-

- Cut sheet
- Melt extracted
- Cold-drawn wire
- Other fibers

A little of the more common types of steel fibers being indicated in figure 2.10 by Knapton (2003), straight steel fibers having standard cross sections between 0.15mm and 0.41mm thickness with 0.25mm to 1.14mm widths are manufactured by cutting sheet or crushing wire, straight steel fibers are manufactured by chopping or cutting wire, normally having a diameter ranged from 0.25mm to 1.0mm. Deformed steel fibers are manufactured either with full length crimping or bent at the ends only. Some fibers have been ordered into bundles to ease handling and mixing. During mixing, the bundles separate from individual fibers. A number of fibers are distorted by bending or flattening to increase bonding and ease handling and mixing (Concrete Society, 1994). Fibers are also manufactured as of cold drawn wire that has been shaved down in order to make steel wool. Furthermore, steel fibers are manufactured by the melt-extraction procedure (ACI Committee 544.1R, 1996).

The length of steel fiber range from 19 to 60mm, the aspect ratio (length /diameter) range from 30 to 100, whereas the ultimate tensile strength range from 345-1700 MPa, and the young’s modulus is 205 MPa (ACI Committee 544.1R, 1996).

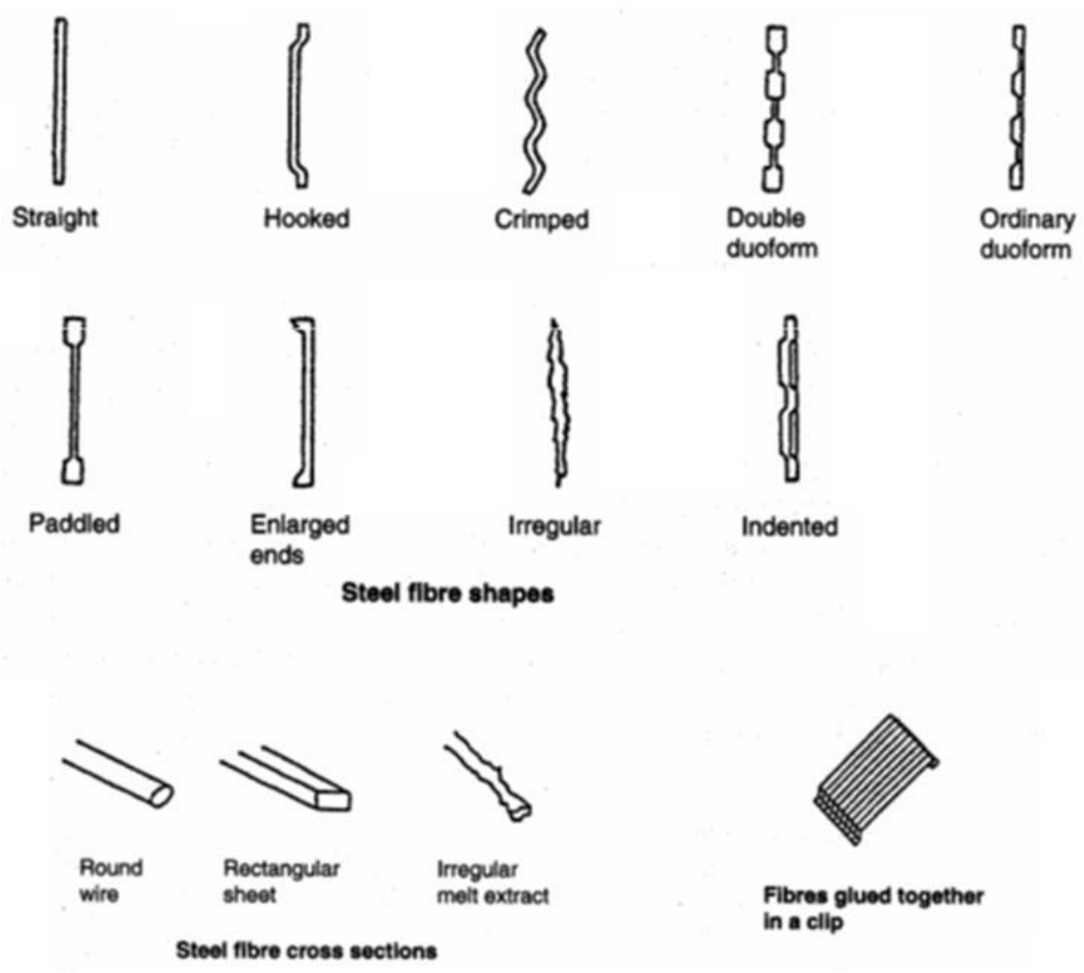


Figure 2.10 Different types of steel fiber (Knapton, 2003)

2.10.3 Production of steel fiber reinforced concrete

2.10.3.1 Composition and Quality

FRC mixtures usually have higher cement and smaller components and finer aggregates compared to plain concrete. Since the slump of concrete reduces as an increase in the fiber (Newman et al., 2003; ACI Committee 544.1R, 1996). The ACI committee has following guidelines to serve the purpose of SFRC mix design:

i. Coarse aggregates should be limited to 55% of the total aggregate.
ii. W/C ratio should be kept below 0.55 (0.35 is recommended).
iii. Minimum cement content of 320 kg/m^3 should be used.
iv. Practical sand content of 750-850 kg/m^3 is recommended.

v. Maximum aggregate size should be 19 mm.

vi. The workability could by improved.

2.10.3.2 Addition and Mixing (Steel Fiber)

Newman et al. (2003) stated that the fibers are added finally to the fresh concrete, attention being obtained to ensure that no balling are added, and the fibers are quickly moved as of the entrance point to the mixer. Otherwise, they may be added on the aggregate on the conveyor region. As long as the aspect ratio of the fiber is smaller than 50, the fibers may be distributed immediately without any danger of balling. Some producers use particular packing material methods to decrease the danger by higher aspect ratios (ACI Committee 544.1R, 1996). Although, Knapton (2003) reported that to check fiber distribution is acceptable a visual check during casting is necessary.

2.10.3.3 Placing, Finishing, and Curing

Approved mixing, placing, finishing and excellence control processes are accompanied needs of good character and economic structure with SFRC (ACI Committee 544.1R, 1996). Place concrete as near to its last place as possible is a good concrete usage. This is always sincerer for SFRC since it reduces flow properties (Unwalla, 1982; Swamy, 1974).

Traditional instruments, apparatus and process may successfully be used for placing, finishing and curing of SFRC (Knapton, 1999; Killen et al., 1997; Swamy, 1974; ACI Committee 544, 1993). Later compaction and leveling, anti-wear results and cement are generally spread on the surface of the concrete (Knapton, 2003). As plain concrete, SFRC should be cured and covered by the same systems and methods. Met in ordinary concrete not enough curing systems can cause plastic and shrinkage cracking (Knapton, 1999; ACI Committee 544, 1993; Swamy, 1974).

2.10.4 Mechanical Properties of Fresh Steel Fiber-Reinforced Concrete

One of the mainly significant difficulties caused when using SFRC is obtaining sufficient workability. The incorporation of the fibers inside the concrete mixture affects its workability, with increasing in the fiber volume and aspect ratio lead to lowered workability (Hannat, 1978; Swamy, 1974). The addition of steel fibers may decrease the calculated slump of the mixed as compared to plain concrete in the variety of 25 to 102mm, in the standard varieties of volume fractions (Vf) used for SFRC (0.25 to 1.5 volume percent of volume of concrete) that stated by ACI Committee (1996). Furthermore, considering workability of a SFRC mix with the V-B test, which assumes the effects of vibration, is recommended rather than the accepted slump measurement, though compaction by automatic vibration is recommended for mainly SFRC applications. To maintain good workability (120-150 mm) is necessary inclusion of superplasticiser. In addition to the above consideration, the balling of fibers might be prevented.

2.10.5 Mechanical Properties of Hardened Steel Fiber-Reinforced Concrete

The delay and control of tensile cracking in the composite concrete is the mainly important concern of fiber addition to concrete (Ramakrishnan, 1988). Many of the mechanical characteristic of the composite concrete are enhanced, through cut off micro-cracks. It depends on the volume fraction and type of fiber, compared to plain concrete, the level of enhancement obtained (ACIFC, 1999).

Under all modes of loading, steel fibers enhance the tensile of concrete. But, their efficiency in enhancing strength changes in compression, tension, shear, torsion, split, and flexure.

The addition of fibers moderately influences on the compressive strength of concrete, with noticed improves ranging as of 0 to 15%, in addition to enhanced considerably 30 to 40%, on the direct tensile strength, likewise, shear and torsion usually increased, while there are small information dealing practices strictly with the shear and torsion (ACI Committee 544.1R, 1996; Amir, 2002). Considerably greater influence on the flexural strength than on either compressive or tensile strengths, with an increase of further than 100% has been stated (Johnston, 1974; Khaloo et al., 2005). The post-crack flexural performance is a mainly significant section of the uses of steel fiber concrete allowing decreases of thickness to be constructed in parts subject to flexure or point load. Excellent increase on impact strength and toughness, that explained as energy immersed to failure (Hauwaert et al., 1999), the improved in toughness effects as of the increased as the space under the curve of load deflection in flexural and tension (Newman et al., 2003). It is generally claimed increased resistance to fatigue and dynamic load (Concrete Society, 1994), it appears to be associated to the distribution of the fibers in concrete (Cachim et al., 2002).

Furthermore, compare to plain concrete it has 15% higher resistance to wear. When the volume fraction of fiber is smaller than 2%, modulus of elasticity and Poisson's ratio are usually obtained as same to those of corresponding non-fibrous concrete (ACI Committee 544.1R, 1996).

Usually, compare to plain concrete steel fiber concrete is further durable, having a beneficial effect on the shrinkage action of concrete by decreasing the number and controlling the width of cracks as well as the extent of the crack occurrence (Concrete Society, 1994; ACI Committee 544.1R, 1996). The corrosion of fibers will be express to the top surface of the concrete if the concrete was compacted well (ACI Committee 544. 1R, 1996), in open environment these fibers will corrode quickly. Furthermore, the deterioration produced by freeze-thaw cycling can decrease by fibers (ACI Committee 544. 1R, 1996), and even at low volume of fibers they decrease the permeability of cracks (Rapoport et al., 2001).

CHAPTER 3

EXPERIMENTAL STUDY

3.1 Materials

3.1.1 Cement

Ordinary Portland cement was used in this study (Portland cement CEM, I 42.5R) conforming to the TS EN 197-1 (which mainly based on the European EN 197-1). It had a specific gravity of 3.15 g/cm3 and Blaine fineness of 326 m^2/ kg. It was utilized in the production of both artificial aggregates and concretes. Physical and chemical properties of the cement are given in Table 3.1.

Table 3.1 Chemical compositions and physical properties of Portland cement and FA

Analysis Report (%)	Cement	Fly ash
CaO	62.58	4.24
SiO_2	20.25	56.2
Al_2O_3	5.31	20.17
Fe_2O_3	4.04	6.69
MgO	2.82	1.92
SO_3	2.73	0.49
K_2O	0.92	1.89
Na_2O	0.22	0.58
Loss on ignition	3.02	1.78
Specific gravity	3.15	2.25
Blaine fineness(m^2/kg)	326	287

3.1.2 Fly Ash

Fly ash (FA) used in the manufacture of lightweight aggregates was a class F type according to ASTM C 618 (2002) was supplied from Ceyhan Sugözü thermal Power Plant. It had a specific gravity of 2.25 g/cm3 and the Blaine fineness of 287 m^2/ kg. Physical and chemical properties of the fly ash are given in Table 3.1.

3.1.3 Superplasticizer

A commercially available sulphonated naphthalene formaldehyde-based superplasticizer was used to achieve the target workability. Its properties are given in Table 3.2.

Table 3.2 Properties of Superplasticizer

Property	Superplasticizer
Name	Daracem 200
Color	Dark Brown
State	Liquid
Specific Gravity [kg/lt]	1.19
Chemical	Sulfonated Naphthalene Formaldehyde

3.1.4 Shrinkage reducing admixture (SRA)

A shrinkage reducing admixture (SRA) used in this study was colorless, liquid of blend of glycols and having the specific gravity of 1.04. Its properties are given in Table 3.3.

Table 3.3 Properties of shrinkage reducing admixture

Property	Shrinkage reducing admixture
Name	Eclipse® Floor 516
Color	colorless
State	Liquid
Specific Gravity [kg/lt]	1.04
Chemical	Blend of glycols

3.1.5 Steel fibers

A steel fiber Kemerix$^{®}$ used in this study were cold drawn steel wire fibers with the hooked ends for an optimum anchorage, having the specific gravity of 7.85, the length of 30 mm and the diameter of 0.75 mm indicating the aspect ratio of 40. As shown in figure 3.1.

Figure 3.1 Photo of steel fiber

3.1.6 Aggregates

3.1.6.1 Lightweight Aggregates (LWAs)

The cold-bonded fly ash lightweight coarse aggregates were produced for this study to be used in the concrete mixes. A dry powder mixture of 90% fly ash and 10% ASTM Type I Portland cement by weight was pelletized through moistening in a revolving tilted pan at ambient temperatures. The pelletizer used has a pan diameter of 80 cm and a depth of 35 cm (Figure 3.2, and Figure 3.3). A typical manufacture period seized about 20 min while the water was sprayed throughout the initial 10 min on the fly ash–cement fine particles mixture to act as a binder. Quantity of sprayed water was about 18-20 % by weight of the dry powder mixture. The second half of the pelletization period was devoted to the further stiffening of the fresh pellets (Figure 3.4). Subsequently, they were maintained in sealed plastic bags and stored for hardening in a curing room at a temperature of 20 ^{o}C and a relative humidity of

70% for 28 days (Beaucour et al., 2009) as shown in Figure 3.5, thereafter the hardened fly ash aggregates was sieved into fractions of 4-14 mm sizes to be used in LWC production (Figure 3.6). In determining properties of LWA, specific gravity and the water absorption tests were carried out as per ASTM C127, while crushing strength test was performed as per BS 812, part 110. It was found that water absorption after 24 hr. was 12.7% while specific gravity of LWA for bulk; apparent and saturated surface dry conditions were 1.73, 2.32, and 1.98 g /cm^3 respectively. Moreover, crushing strength of LWA is shown in Figure 3.7.

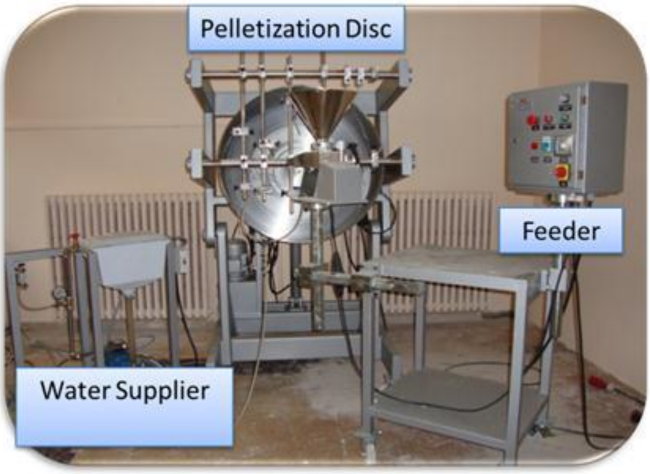


Figure 3.2 General view of the pelletization disc

Figure 3.3 Side view of the pelletization disc

Figure 3.4 Fresh artificial lightweight aggregates

Figure 3.5 Fresh artificial aggregates will kept in sealed plastic bags

Figure 3.6 Hardened aggregate sieved by (10, and 4) mm sieve

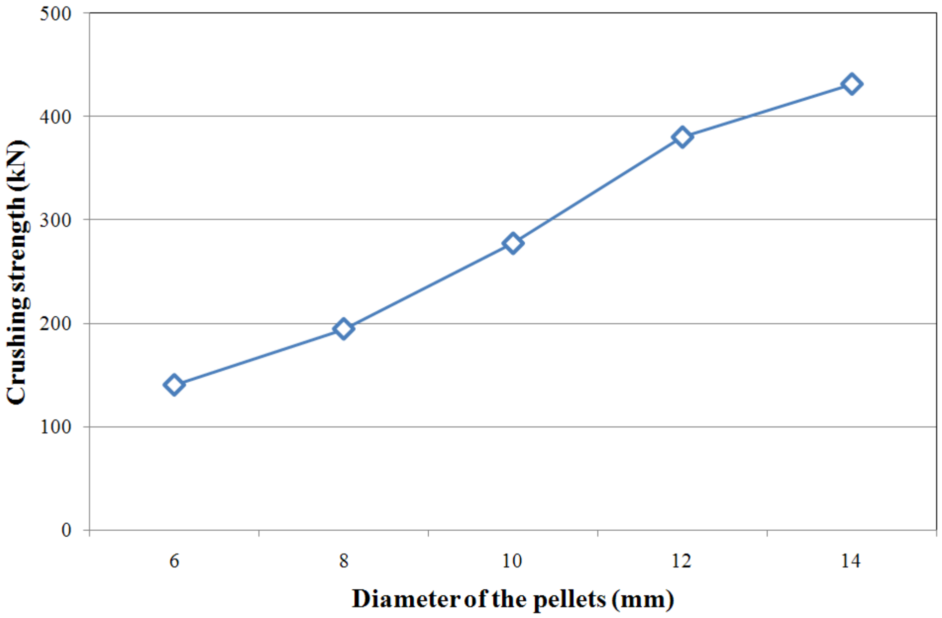


Figure 3.7 Crushing strength of artificial fly ash aggregates

3.1.6.2 Natural fine aggregate

The river and crushed sands were used as the fine aggregate. Specific gravity of the river and crushed sands were 2.66 and 2.45, respectively. Sieve analysis and the physical properties of fine aggregate used in this study are shown in Table 2.

Table 3.4 Sieve analysis and physical properties of normal weight fine aggregate

Sieve size (mm)	**Fine aggregate (%)**	
	River sand	Crushed sand
31.5	100	100
16.0	100	100
8.0	99.7	100
4.0	94.5	99.2
2.0	58.7	62.9
1.0	38.2	43.7
0.50	24.9	33.9
0.25	5.40	22.6
Fineness modulus	2.79	2.38
Specific gravity (gm/cm$^{3)}$	2.66	2.45

3.2 Mix proportioning and casting of concrete

LWAC specimens were produced using the mixture containing ASTM Type I Portland cement, lightweight fly ash course aggregate, natural sand, water, superplasticizer, SRA and steel fiber. Table 3.5 shows the seven different concrete mixtures prepared in this study. The amounts of SRA used were 0.75%, 1.50% and 3.00% by weight of cement content. The percentage additions of steel fiber were 0.25, 0.75, and 1.25 by total volume of concrete. The water-cement ratio and the cement content were kept constant for all mixtures as 0.40 and 450 kg/m3, respectively. The all mixtures were prepared using the lightweight coarse aggregate added as 50% by volume of total aggregate in the mixture and for the remaining 50%, the natural and crushed sands were used with the amount of 37% and 13%, respectively.

A special procedure was followed for batching, mixing, and casting of concrete to minimize the early slump loss due to the high-water absorption of lightweight aggregates. Concrete mixtures were designed to have a 130±20-mm slump as shown in Figure 3.9, which was realized by using a superplasticizer. Lightweight fly ash aggregates were first immersed in water for 30 minute for saturation and then laid on a lower sized sieve for an additional 30 minute for the seepage of excessive surface water as shown in Figures 3.8. All concretes were mixed in accordance with ASTM C192 standard in a power driven rotating pan mixer with a 20 L capacity. First, the saturated-surface-dry lightweight aggregate was mixed with the Portland cement. Then, the natural sand was added into the mixer. Finally, the water containing the superplasticizer and shrinkage-reducing admixtures (if it used) was added gradually to this mixture, The steel fibers were added at last (if it used), and it is continued to be mixed for about four minutes. Slump and density were then measured. After that, the concrete mixture was poured into the steel molds in two layers, each of which being vibrated for a couple of seconds.

Table 3.5 Concrete mix design

Mix No	W/C	Cement (kg)	Water (kg)	SP (kg)	SRA (kg)	Fiber Steel (kg)	Vol. Agg. (kg)	LWCA (kg)	Crushed sand (kg)	Natural sand (kg)	Density (kg/m3)
Plain	0.4	450	180	5.4	0	0	0.6706	644	214	660	2153
0.75% SRA	0.4	450	180	5.4	3.38	0	0.6672	641	213	657	2149
1.5% SRA	0.4	450	180	5.4	6.75	0	0.6639	637	211	653	2144
3.0% SRA	0.4	450	180	5.4	13.5	0	0.6572	631	209	647	2136
0.25% Steel fiber	0.4	450	180	9.0	0	19.625	0.6676	641	213	657	2150
0.75% Steel fiber	0.4	450	180	10.0	0	58.875	0.6667	640	212	656	2149
1.25% Steel fiber	0.4	450	180	12.4	0	98.125	0.6647	638	212	654	2146

a)

b)

Figure 3.8 View of production stages

a)

b)

Figure 3.9 Slump test for two mixtures in production of LWAC's

3.3 Details of test specimens

Concrete cube specimens of 150 mm in size, the cylindrical specimens having the dimensions of Ø100 200 mm, the prism specimens with 75 75 285 mm and ring specimens with the dimensions given in Figure 3.10 were cast in steel moulds to perform compressive strength, splitting tensile strength, free shrinkage, weight loss and restrained shrinkage tests. Free and restrained shrinkage specimens were cured for 24 h at 20 °C with 100% relative humidity and then were demoulded. After the outer steel ring had been stripped off, the top surface of the concrete ring was sealed off using silicon rubber as shown in Figure 3.11, so that the drying would be allowed only from the outer circumferential surface. After that, the specimens were exposed to dry in a humidity cabinet at 23±2 °C with 50±5% relative humidity for about 50 days as shown in Figure 3.12, as defined by ASTM C157-75. The other test specimens were first kept under plastic sheets for 24 h and then were demoulded. Specimens for the compressive and splitting tensile strength tests were cured in water after demoulding.

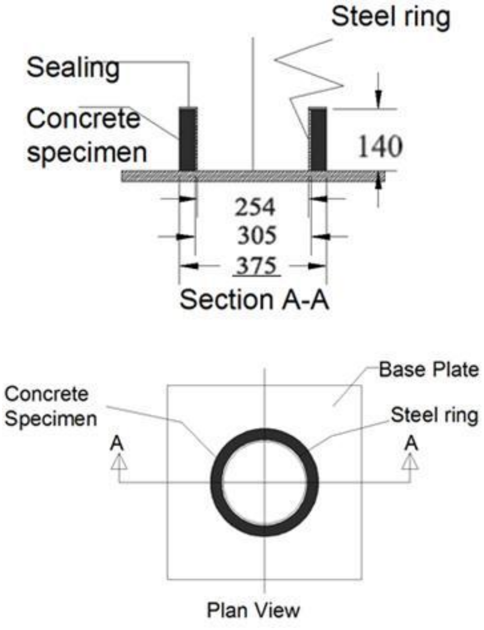


Figure 3.10 Restrained shrinkage ring specimen (in mm)

Figure 3.11 Covering the top of ring specimen by silicon

Figure 3.12 Photographic view of ring, prisms specimen in curing room

3.4 Measurements and testing

Ring-type specimens were used in this study to observe the restrained shrinkage-induced cracking of concrete. The schematic view showing and the dimensions of the ring mould, and the photograph of a cracked specimen are shown in Figure 3.13. It can be assumed that the concrete annulus was essentially subjected to a uniform, uniaxial tensile stress when it was internally restrained by the steel ring. In addition, the width of the specimen was four times its thickness, so that a uniform shrinkage along the width of the specimen can be assumed (Shah et al., 1992; Wiegrink et al., 1996; Grzybowski and Shah, 1990; Sarigaphuti and Shah, 1993). To measure the crack widths on ring specimens, a special microscope setup was used as proposed in some researches (Shah et al., 1992; Wiegrink et al., 1996; Grzybowski and Shah, 1990; Sarigaphuti and Shah, 1993). The microscope was attached to an adjustable scaled locator connected to a vertical bar passing through the inner steel ring and fixed at the center of the base plate allowing the microscope to move around the specimen. A locator was connected to the horizontal bar, permitting up-and-down movement, so that the whole circumferential surface of the specimen could be observed with the microscope. The crack widths reported herein were the average of three measurements: one at the center of the ring and the other two at the centers of the top and bottom halves of the ring. The surface of the specimens was examined for new cracks, and the measurements of the existing crack widths were performed every 24h during the first seven days after cracking, and then every 48 h. Crack width measurements of concrete were conducted on two ring specimens from each mixture.

Free shrinkage measurements were performed according to ASTM C157-75. The length change was measured by a dial gage extensometer with a 200 mm gage length as shown in Figure 3.14. Measurements were carried out every 24 h for the first three weeks and then three times a week. At the same time, weight loss measurements were also made on the same specimens as shown in Figure 3.15. Free shrinkage measurements of concrete were conducted on four prisms samples from each mixture.

The compression test was carried out on the cube specimens having the dimensions of 150×150×150 mm according to ASTM C39 by using a 3000 kN capacity testing machine as shown in Figure 3.16. The strength measurements of concrete were performed at the ages of 3, 7 and 28 days. Three specimens from each mixture were tested at each testing age.

The splitting tensile strength was conducted on the cylinder specimens having the dimensions of Ø100 200 mm according to ASTM C496. The splitting tensile strength measurements of concrete were performed at the ages of 28 days and three specimens from each mixture were tested.

Figure 3.13 Photographic view of a cracked ring specimen (M4- 0.25% Steel fiber)

Figure 3.14 Dial gage extensometer for free shrinkage measurement (1 division = 0.002 mm)

Figure 3.15 Sensitive digital balances for weight loss measurement

Figure 3.16 Photograph of compressive strength test

CHAPTER 4

EXPERIMENTAL RESULT AND DISCUSIONS

4.1 Fresh concrete properties

LWAC mixes were produced having the slump values within 130±20 mm as seen in Figure 3.10, which was achieved by using superplasticizer which was kept constant for the mixtures with SRA and varied for the mixes including the steel fiber since the use of steel fiber resulted in a reduction in workability of LWAC mixes. Fresh densities of the concretes are ranged from 2153 to 2136 kg/m3 as shown in Table 3.5. The fresh densities seem to be slightly high for LWACs. Therefore, these concretes may be considered as semi-lightweight concretes. This might be attributed to three reasons. First, w/cm was low, and the cement content was high. Second, specific gravity of the fly ash was rather high resulting in artificial aggregates having a specific gravity of 1.92, which was slightly large for use in LWC. Finally, the main reason was the use of natural sand as a fine aggregate, which caused all the concretes to exceed the ACI limitation as far as the density of the concrete was concerned. However, similar results were reported in previous studies (Chang et al., 1996; Yang et al., 1997; Mor, 1992). Air contents of the mixtures were determined through calculating the actual compositions, and the values were in the range of 1.5–2.5%.

4.2 Compressive Strength

Figure 4.1 shows the effects of SRA and steel fiber usages on the compressive strength test results of LWACs at the testing ages of 3, 7 and 28 days. The 28 days compressive strength values are ranged between 38.86 and 50.12 MPa and satisfied the lower limit of 17.2 MPa to be used for structural purposes (ACI Committee 213-87). It is clear that SRA causes a decrease in the compressive strength of LWAC while the amount of SRA increases. As indicated in Figure 4.1, the addition of SRA with the amount of 0.75%, 1.50% and 3.0% causes a reduction in 28 day compressive strength values about 3%, 11% and 19%, respectively. Several researchers similarly reported that the use of SRA in normal weight concrete reduces the compressive strength about 10-28% (Shah et al., 1992; Nmai et al., 1998; Brooks and Jiang, 1997). Figure 4.1 also indicates that the use of steel fiber increases the compressive strength of LWAC about 4-5% regardless of the variations in volume fraction utilization of steel fiber for the testing ages of 28 days. The previous researches on normal and lightweight concrete generally state the similar results of incrimination in compressive strength for the case of using steel fiber in concrete (Balendran and Soleimani, 2005; Marar et al., 2002; Yazici et al., 2007).

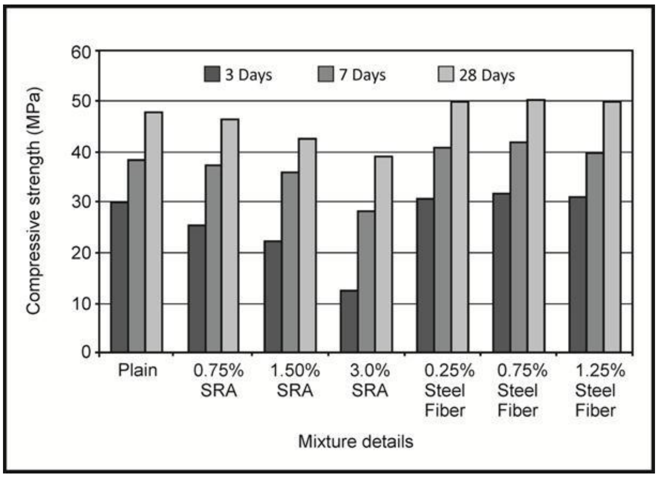


Figure 4.1 Variation in compressive strength for different concrete mixes

4.3 Splitting-tensile strength

Figure 4.2 indicates the influence of using SRA or steel fiber on the split tensile strength test results of LWACs at the testing age of 28 days. It is clearly demonstrated in Figure 4 that the use of SRA is almost not affecting the tensile strength of LWAC. Due to the mechanical properties of steel fibers which improves the bond strength of concrete, a relatively significant incrimination in the tensile strength values were observed as shown in Figure 4.2 which demonstrates that the addition of steel fibers with the amount of 0.25%, 0.75%, and 1.25% in LWAC increases the tensile strength about 19%, 26%, and 39%, respectively. Although relatively high values of aspect ratio and fiber volume fraction were used in some previous researches on normal and lightweight concretes, a significant improvement on tensile strength was reported (Song and Hwang, 2004; Gao et al., 1997).

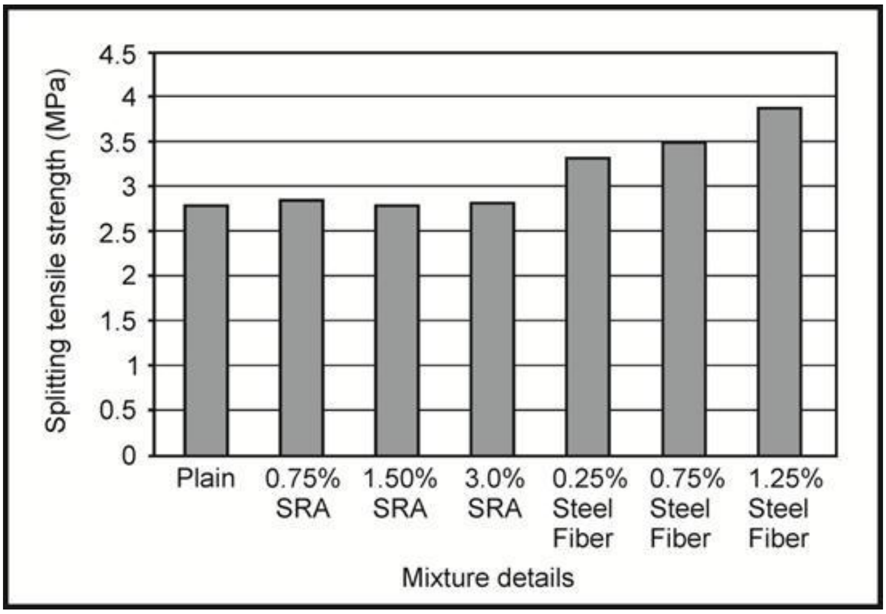


Figure 4.2 Variation in Split tensile strength for different concrete mixes

4.4 Free shrinkage and weight loss

The obtained free shrinkage and weight loss results are shown in Figures 4.3 and 4.4 for the studied LWACs produced with SRA or steel fiber, and the comparison is made with the results from plain LWAC. The effects of SRA on free shrinkage and weight loss of LWACs are demonstrated in Figure 4.3. Although the free shrinkage strains were comparable for the early ages of drying period, a clear distinction was observed at the later periods for LWAC with different amount of SRA. As indicated in Figure 4.3, the plain LWAC shows the highest free shrinkage strain which is 790 micro-strains at the end of the 50 days drying period. In case of using SRA in LWAC, the free shrinkage significantly reduces with an increase in the amount of SRA. The use of SRA with the amounts of 0.75%, 1.50% and 3.0% causes a reduction in free shrinkage about 18%, 39% and 42%, respectively. These free shrinkage reduction effects of SRA in LWAC have also observed for normal weight concretes as reported (Shoya and Sogita, 1990; Shah et al., 1992; Folliard and Berke, 1997; Nmai et al., 1998; Berke, 1997) and were related with the main compound of SRA which is assumed causing to reduce the surface tension of pore water and subsequently reducing free shrinkage (Shoya and Sogita, 1990).

As shown in Figure 4.3, the weight loss values for LWAC containing SRA are considerably lower than that of plain LWAC. The weight loss values of LWAC with 1.5% and 3.0% SRA are almost identical and cause to reduce the weight loss values about 25%. The use of 0.75% SRA in LWAC reduces the weight loss about 8% compared to the results obtained from the plain LWAC.

As indicated in Figure 4.4, although the use of steel fiber in LWAC reduces free shrinkage strain and weight losses about 8% and 5% compared to the plain LWAC, respectively, the variations in free shrinkage and weight loss values seem almost unaffected with the increase in the amount of steel fiber utilized in LWAC. Similar results were also observed for normal weight concrete by some of the previous studies (Grzyboski and Shah, 1990; Edgington et al., 1974).

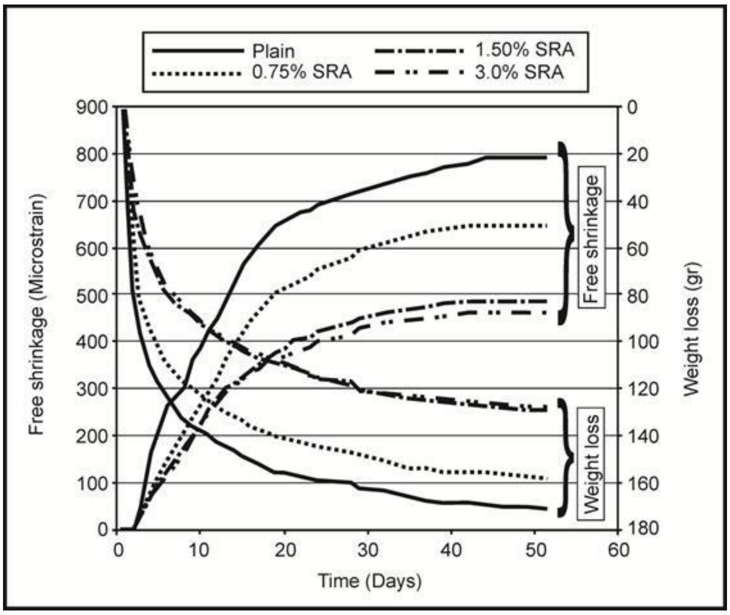


Figure 4.3 Free shrinkage and weight loss results with varying SRA values

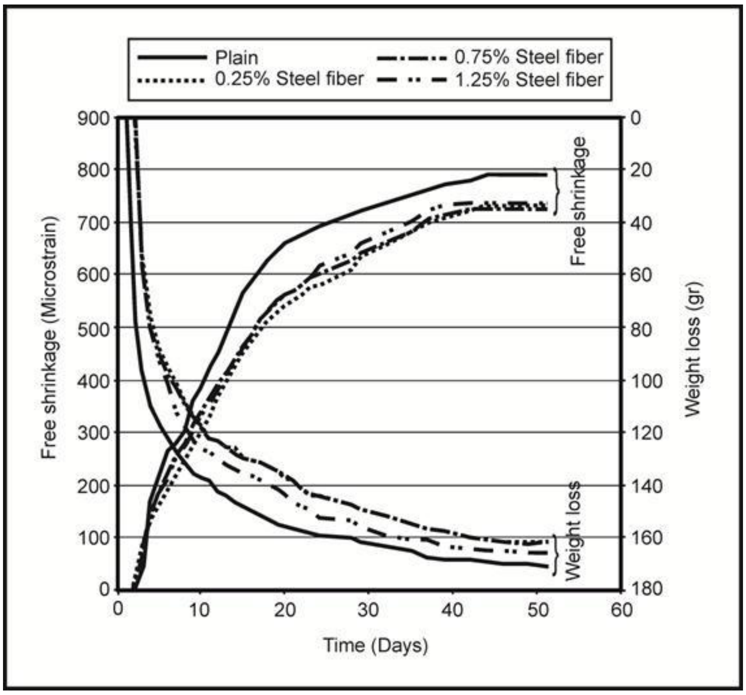


Figure 4.4 Free shrinkage and weight loss results with varying steel fiber values

4.5 Restrained shrinkage cracking

Figure 4.5 indicates the development of crack width with the age of cracking for the ring specimens of plain LWAC and LWAC containing SRA. It shows that the plain LWAC cracked at 8 days, whereas the cracking of LWAC incorporating 0.75%, 1.5% and 3.0% of SRA occurred at the days of 14, 20, and 42, respectively. This may be due to the mechanism of SRA which reduces shrinkage of LWAC and subsequently extends the age of cracking by providing the reduction in the tensile stress. The crack width development during the drying time period is shown in Figure 4.5 for LWAC including SRA. It indicates that when the results are compared with that of obtained from the plain LWAC; the use of SRA with the amount of 0.75%, 1.5% and 3.0% in LWAC reduces the maximum crack width values about 35%, 62% and 76%, respectively. Some of the results in the previous researches indicated similar results for normal weight concrete such as the addition of SRA with the amount of 2% caused considerable reduction in crack width as 20-76% (Shoya and Sogita, 1990; Shah et al, 1992).

Figure 4.6 shows the development of crack width with the age of cracking for the ring specimens of plain LWAC and LWAC containing steel fibers. It demonstrates that the cracks were first seen at the days of 14, 19 and 26 for LWAC with the steel fiber amounts of 0.25%, 0.75%, and 1.25%, respectively. Maximum crack width in plain LWAC is about 1.13 mm while the maximum crack widths in LWACs with 0.25%, 0.75%, and 1.25% steel fibers are 0.553 mm, 0.16 mm and 0.126 mm, respectively. The steel fiber in LWAC allows bridging the crack by preventing to widen the cracks. As shown in Figure 4.5, only one penetration crack is formed in the concrete specimen with 0.25% volume fraction of steel fiber and the number of cracks is increased in terms of the increment in volume fraction of steel fiber and it initiates after the first penetration crack is formed. The cracking time and the crack width at 50 days after drying are shown in Table 4.1. It can be seen in Table 4.1 that when the volume fraction of steel fiber is increased, the crack width decreases, the number of cracks increases, and cracking time is delayed.

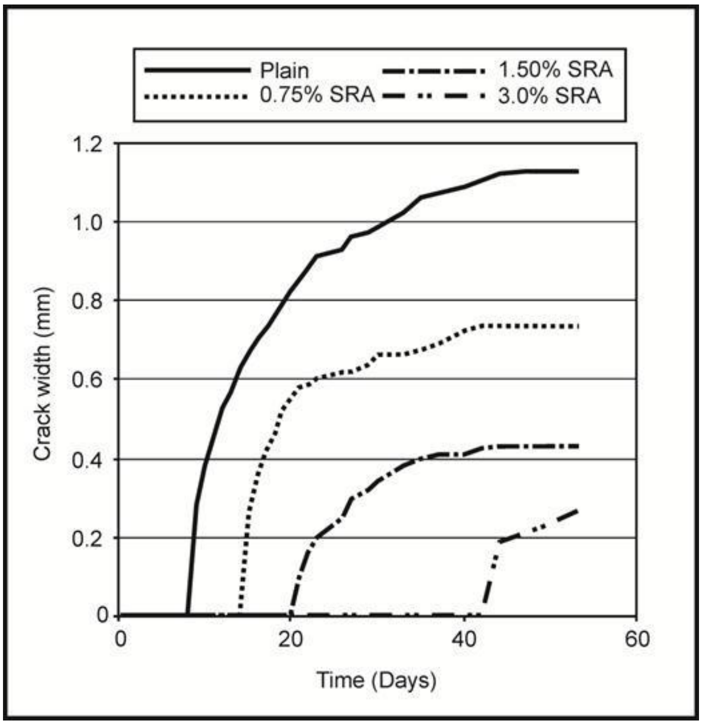


Figure 4.5 Effects of time and SRA values on crack width

Table 4.1 Cracking time and crack width at 50 days

Mix Description	Cracking Time (days)				Crack Width (mm)			
	1st	2nd	3rd	4th	1st	2nd	3rd	4th
Plain	8	-	-	-	1.13	-	-	-
0.75% SRA	14	-	-	-	0.733	-	-	-
1.50% SRA	20	-	-	-	0.43	-	-	-
3.00% SRA	42	-	-	-	0.266	-	-	-
0.25% Steel Fiber	14	-	-	-	0.533	-	-	-
0.75% Steel Fiber	19	35	40	42	0.16	0.06	0.06	0.04
1.25% Steel Fiber	26	42	42	-	0.126	0.08	0.053	-

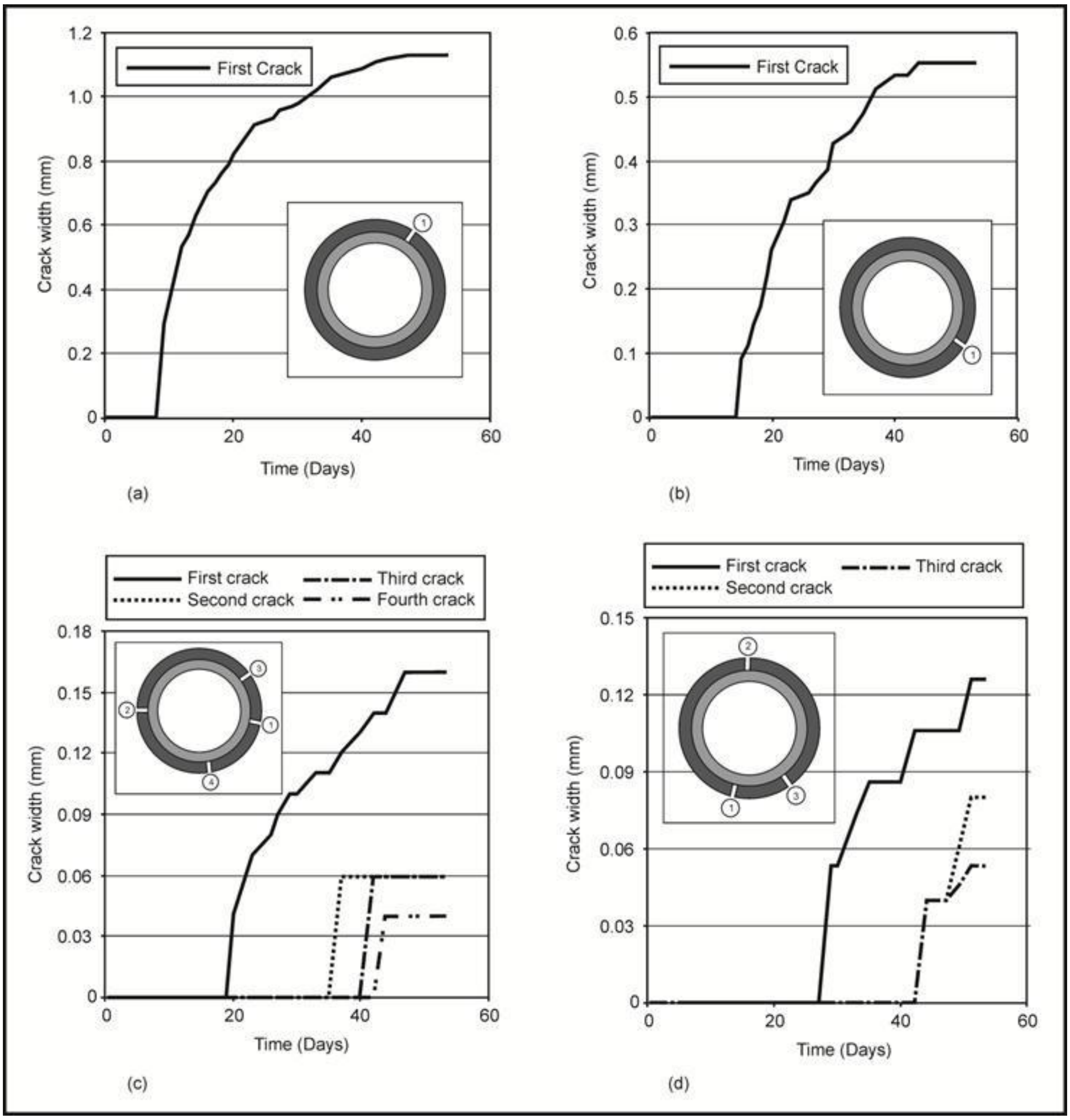


Figure 4.6 The effects of time and steel fiber values on crack width (a) for plain concrete, (b) for fiber-reinforced concrete with 0.25% volume fraction of steel fiber, (c) for fiber- reinforced concrete with 0.75% volume fraction of steel fiber, (d) for fiber reinforced concrete with 1.25% volume fraction of steel fiber.

CHAPTER 5

CONCLUSIONS

Based on the findings of the experimental program presented above, the following conclusions may be drawn:

- The addition of steel fiber into LWAC causes a little increase in the compressive strength regardless of the amount of steel fiber, while the use of SRA leads a gradual decrease in compressive strength by the incrimination in SRA content.
- The use of SRA in LWAC causes an insignificant effect on split tensile strength. However, the use of steel fiber significantly raises split tensile strength with an incrimination in steel fiber content. This increment is about 19-39% compared to plain LWAC.
- In case of using SRA in LWAC, free shrinkage significantly reduces with an increase in the amount of SRA. The use of SRA with the amount of 0.75-3.0% causes a reduction in free shrinkage about 18-42% compared to plain LWAC. The use of steel fiber in LWAC reduces free shrinkage strain about 8% and it is unaffected with the increase in the amount of steel fiber compared to plain LWAC.
- The addition of SRA with the amount of 0.75-3.0% reduces the weight loss in LWAC about 8-25% while the use of steel fiber decreases about 5% compared to the results obtained from the plain LWAC.

- The use of SRA and steel fiber in LWAC extends the age of cracking and reduces the crack width without the need of reducing the amount of water content. The plain LWAC cracked at 8 days, whereas the cracking times of LWAC incorporating 0.75%, 1.5% and 3.0% of SRA were occurred at the days of 14, 20, and 42, respectively. The use of SRA with the amount of 0.75-3.0% in LWAC reduces the maximum crack width about 35-76%, while the addition of steel fiber with 0.25-1.25% decreases the maximum crack width about 51-89%, compared to plain LWAC.

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APPENDIX-A

Figure A.1 Photographic view of pelletization system

Figure A.2 Form of artificial lightweight fly ash aggregate

Figure A.3 Fresh lightweight aggregate kept in sealed bags for air curing

Figure A.4 Hardened lightweight aggregate sieved and ready for mixes

Figure A.5 Lightweight aggregate immersed in water before mix to get SSD aggregate (saturated surface dry aggregate)

Figure A.6 Test specimens after mixing vibrating and finishing

Figure A.7 Ring specimens after mixing, vibrating and finishing

Figure A.8 Covering ring specimens by silicon rubber after 24h of casting

Figure A.9 Measurement of free shrinkage

Crack in 0.25% steel fiber mix

Crack in 0.25% SRA mix

Crack in 0.75% SRA mix

Crack in 0.75% steel fiber mix

Crack in control mix

Figure A.10 Crack view in ring specimens due to restrained shrinkage for different mixes