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IMPROVING FRESH AND HARDENED PROPERTIES OF SELF COMPACTING COLD BONDED FLY ASH LIGHTWEIGHT AGGREGATE CONCRETES WITH BINARY AND TERNARY BLENDS OF SILICA FUME AND FLY ASH

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EMAD AMJAD BOOYA

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Improving Fresh and Hardened Properties of Self compacting Cold bonded Fly Ash Lightweight Aggregate Concretes with Binary and Ternary Blends of Silica Fume and Fly Ash

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By

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Emad BOOYA

ABSTRACT

Improving fresh and hardened properties of self compacting cold bonded fly ash lightweight aggregate concretes with binary and ternary blends of silica fume and fly ash

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This thesis presents the results of an experimental study on the fresh and hardened properties of self-compacting lightweight concretes made with cold bonded fly ash lightweight aggregates. Binary and ternary use of fly ash (FA) and silica fume (SF) blends have been investigated in the production of self-compacting cold bonded fly ash lightweight concrete (SCLWCs). A total of 9 SCLWC mixtures were proportioned having constant water-binder ratio of 0.35 and the total binder content of 550kg/m^3. The control mixture contained only Portland cement (PC) as the binder while the remaining mixtures incorporated binary and ternary blends of PC, FA, and SF. The fresh properties of the SCLWC were tested for T_{500} slump flow time, slump-flow diameter, V-funnel time and L-box height ratio. While the properties that include compressive strength and ultrasonic pulse velocity, chloride ion penetration, gas permeability, water absorption by total immersion and by capillary rise were investigated at two curing ages of 28 and 56 days. The results indicated that the combination use of FA and SF together decreased the slump flow time and V-funnel flow time. L-box height ratio, on the other hand improved significantly. The results also revealed that hardened characteristics of SCLWCs dependent on the type and amount of mineral admixture used.

Keywords: Fly ash; Fresh properties; Gas permeability; Self compacting lightweight concrete; Silica fume; Water absorption.

ÖZET

Soğuk bağlama yöntemiyle üretilmiş uçucu kül hafif agregalı kendiliğinden yerleşen betonların taze ve serleşmiş özelliklerinin silis dumanı ve uçucu külün ikili ve üçlü birleşimlerinin kullanılarak iyileştirilmesi

BOOYA, Emad

İnşaat Mühendisliği Yüksek Lisans

Danışman: Doç. Dr. Erhan GÜNEYİSİ

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100 sayfa

Bu tezde, soğuk bağlama yöntemiyle üretilmiş uçucu kül hafif agregası kullanılarak hazırlanan kendiliğinden yerleşen hafif betonların (KYHFB) taze ve sertleşmiş özelliklerinin incelendiği deneysel bir çalışmanın sonuçları sunulmuştur. KYHFB üretiminde uçucu kül ve silis dumanının ikili ve üçlü sistem birleşimleri kullanılmıştır. Sabit su-bağlayıcı oranı 0.35 ve toplam bağlayıcı miktarı 550 kg/m^3 olan toplam 9 karışım tasarımı yapılmıştır. Kontrol karışımı bağlayıcı olarak sadece çimento içerirken diğer karışımların hazırlanmasında portland çimentosu, uçucu kül ve silis dumanının ikili ve üçlü birleşimleri göz önünde bulundurulmuştur. KYHFB'lerin taze özellikleri T_{500} yayılma süresi, yayılma çapı V-hunisi akış süresi ve L-kutusu yükseklik oranı bakımından test edilmiştir. Sertleşmiş betonlar için basınç dayanımı, ultrasonik ses dalgası geçiş hızı, hızlı klorür iyonu geçirimliliği, gaz geçirimliliği, toplam su emme ve kılcal su emme deneyleri 28. ve 90. günlerde gerçekleştirilmiştir. Elde edilen sonuçlara göre uçucu kül ve silis dumanının birlikte kullanılması yayılma ve V-hunisi akış sürelerini azaltmıştır. Öte yandan, L-kutusu yükseklik oranı önemli düzeyde iyileşmiştir. Ayrıca, KYHFB'lerin sertleşmiş özelliklerinin, kullanılan mineral katkının tipinden ve miktarından önemli oranda etkilendiği görülmüştür.

Anahtar kelimeler: Gaz geçirimliliği; Kendiliğinden yerleşen hafif beton; Silis dumanı; Su emme; Taze özellikler; Uçucu kül

To my dearest
parents and brothers

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LIST OF SYMBOLS/ABREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
ACV	Aggregate Crushing Value
ASTM	American Society for Testing and Materials
CANMET	Canada Center for Mineral and Energy
CSF	Condensed Silica Fume
EFNARC	European Federation of Specialist Construction Chemicals and Concrete Systems
FA	Fly Ash
GGBFS	Ground Granulated Blast Furnace Slag
HPC	High Performance Concrete
HVFA	High Volume Fly Ash
Ka	Gas Permeability Coefficient
LWA	Lightweight Aggregates
LWC	Lightweight Concrete
NWC	Normal Weight Concrete
PC	Portland Cement
RHA	Rise Husk Ash
SCLWC	Self-compacting Lightweight Concrete
SCC	Self Compacting Concrete
SCLWC	Self Compacting Cold Bonded Lightweight Aggregate Concrete
SEM	Scanning Electron Microscope
SF	Silica Fume
SLWA	Saturated Lightweight Aggregate
SP	Superplasticizer
TEM	Thermal Electron Microscope
UPV	Ultrasonic Pulse Velocity

CHAPTER 1

INTRODUCTION

1.1 General

The lightweight aggregates (LWA) have been used since many years ago for structural applications, which are normally employed in structures because of the dead load participates in the main portion of the overall load. Many types of lightweight aggregates, for instance, shale or expanded clay, and sintered fly ash, can be easily acquired via heat treatment 1000 to 1200 °C [1]. Another technique for production of lightweight aggregate with minimum energy consumption and an environmental impact is the agglomeration of fly ash particles through cold-bonding method, where the water is the wetting agent acting as coagulant, so the damp mixture would be pelletized in inclined rotating pan while Portland cement used as binder. By utilizing such type of aggregates, structural lightweight concrete easily can be produced with compressive strength up to 30 MPa at 28 days [2, 3].

Low unit weight, durability performance and better reinforcing steel-concrete bond, are special properties of LWCs that make it obviously different from normal weight concrete (NWC) [4, 5, 6]. The wide diversity of the source and production methods of the lightweight aggregate caused distinguishing behavior among the LWCs. Thus, the characteristics of LWCs have to be examined individually for every sort of lightweight aggregate [7].

Incorporations of mineral and chemical admixtures in the normal concrete contributed in existence of new trends in concrete technology in the terms of strength and durability [8]. Thus, at the end of the eighties, self-compacting concrete (SCC) characteristics have been achieved for tailored preparations by Japan.

Its investigation represents a revolution in concrete technology which led to improve the concrete quality, enhanced the conditions of working on site and increased productivity [9]. SCC is the concrete that has ability to flow through congested steel reinforcement areas by its own, without any need for compaction and vibration during casting process [10]. The content of coarse aggregate is limited in the production of self-compacting concrete and commonly chemical and mineral admixtures are employed. In the literature several studies conducted for investigation the influence of mineral admixtures in improve the properties of self-compacting concrete [9-11].

Permeability is of importance for the structures under severe environmental effects such as freezing-thawing, chemical attacks, etc. Therefore, transport properties of concrete play an important role in a wide variety of processes of environmental and technological concern. In recent years, some researchers have been investigating the gas permeability of concrete in order to evaluate the pore structure [12, 13].

An extensive experimental investigation was performed in this study to demonstrate the compression strength and ultrasonic pulse velocity, chloride ion penetration, gas permeability, water absorption by capillary rise and by total immersion behavior of self-compacting cold bonded fly ash lightweight aggregate concrete (SCLWC) mixtures with different level of replacement of fly ash (FA) and silica fume (SF). Cold bonded fly ash aggregate was utilized as coarse aggregate. A total of 9 different SCLWC mixtures were proportioned having constant water-binder ratio of 0.35 and the total binder content of 550 kg/m^3. The control mixture contained only Portland cement (PC) as the binder while the remaining mixtures incorporated binary and ternary blends of PC, FA, and SF. Depending on the experimental results obtained from this study; the effects of FA and/or SF upon concrete properties were discussed. In the literature, there is a dearth of research concerning the usage of the cold bonded fly ash lightweight aggregate in the production of SCC. The possibility to design SCLWC concrete with the earlier mentioned aggregates appears particularly attractive because this composite material might join the high strength, better durability performance, etc.

1.2 Research Significance

The properties of the lightweight concretes mainly count on the properties and the amount of the lightweight aggregates utilized. So that, many studies conducted to examine how the mechanical characteristics of lightweight aggregate concrete is affected by the specific properties of the aggregates utilized but much of investigations focused on a few types of lightweight aggregates available. Concretes have been easily produced with comprising cold-bonded fly ash aggregates but, its usage in the production of self-compacting concretes has not obtained enough attention in the literature especially when binary and ternary blends of FA and SF are incorporated as mineral admixtures with different replacement levels. Therefore, to achieve more sustainable and environment friendly concretes, the use of fly ash lightweight aggregates may be an alternative to conventional concretes.

1.3 Outline of the Thesis

Chapter 1-Introduction: Objectives and aim of the thesis are described.

Chapter 2-Litrature Review: Presents a literature survey and general background on the types and sources of lightweight aggregate, production of self-compacting concrete and the use of mineral admixture in the production of concrete.

Chapter 3-Experemintal Study: Materials, concrete mixture details and casting, test methods are described.

Chapter 4-Test Results and Discussion: list of results, figures, evaluation, and indication are presented and discussed.

Chapter 5-Conclusions: Summarize the thesis, and the main outcomes are revealed.

CHAPTER 2

LITRATURE REVIEW

2.1 Mineral Admixtures

Pozzolan is the most often used mineral admixture in the concrete industry. The American Concrete Institute (ACI) defines the pozzolan, as it is that siliceous or siliceous and aluminous materials that own in themselves little or no cementitious value but with presence of moisture and when finely divided, they will react chemically, with calcium hydroxide at ordinary temperatures, to form compounds possessing cementitious properties.

There are two main kinds of pozzolan, namely natural pozzolan and synthetic pozzolan. The origins of natural pozzolan are volcanic, such as trass, perlite, certain pumicites, and kaoline. The synthetic pozzolans obtained by product from industrial like fly ash, silica fume, rise husk ash (RHA), and ground granulated blast furnace slag [14].

2.1.1 Fly Ash

Fly ash is a material result from the combustion operation of coal-fired electric generating plants. The coal milled and blown inside the burning chambers and the heavier ash particles (bottom ash or slag) fall to the bottom of the chamber and the lighter ash particles (fly ash) fly out with exhaust gas, thus called fly ash. Different methods used to collect the fly ash before leaving the stack, such as bag houses, electrostatic precipitators or others (Figure 2.1) [15]. Fly ash is a pozzolanic material that contains active silica and alumina and it is not cementitious by itself. However, in a finely divided form, in presence of moisture, it chemically reacts with calcium hydroxide at ordinary temperature to form cementitious compound.

Many factors affect the properties of fly ash, for instance, chemical composition of the coal and burning system, the composition of feed coal, type of power plant, and the method of deposition of fly ash.

Fly ash has wide range of uses comprising as a binder additive when partially replaced with cement, as a material in lightweight alloys, as a concrete aggregate, in flowable fill materials, in roadway construction, as roofing granules, in structural fill materials, and as a grouting material.

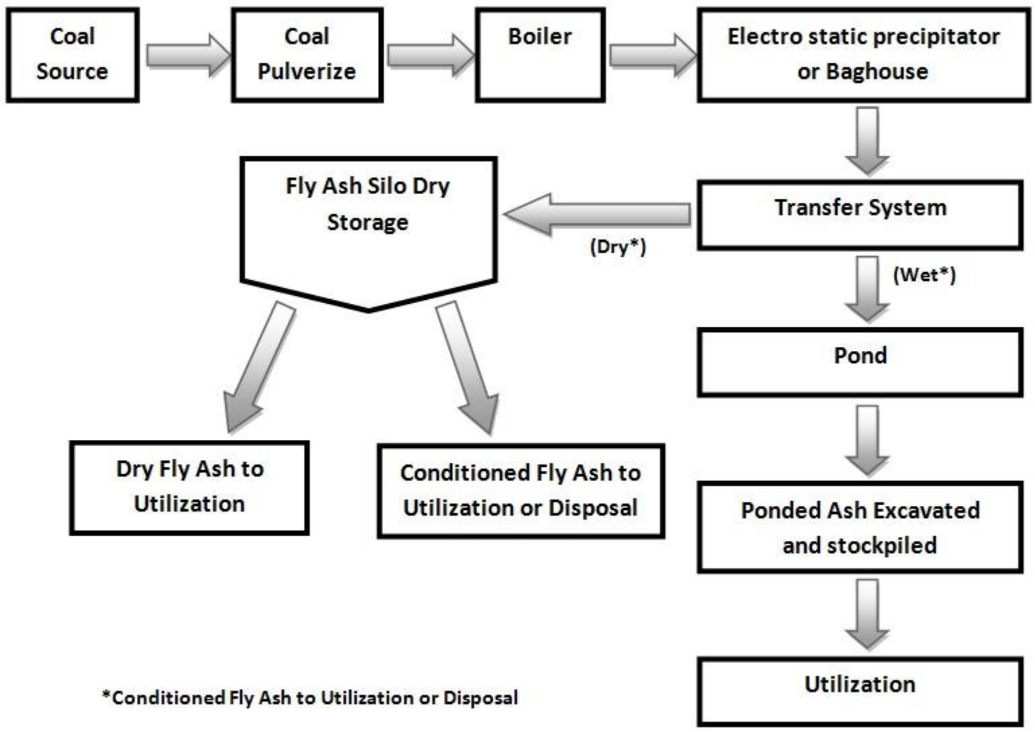

Figure 2.1 Method of fly ash transfer (wet, dry or both) [15]

2.1.1.1 Minerological Characteristics of Fly Ash

Fly ash particles are fine powders, heterogeneous in nature and mostly spherical in shape. Also angular and irregular fly ash particles found that contain both mineral particles and remnants of unburned coal. The fly ash particle is very tiny that its size range from less than 1 to 100 micrometer.

Variability of fly ash compositions, mainly comes from; the combustion systems, the coal composition, the rate of cooling and the ash collection methods. Generally, glassy particles form about (50-90 %) of mineral matter and small part of from remnant occurs in crystals form [16, 17].

2.1.1.2 Chemical Properties

Fly ash particles harden while suspended in the exhaust gases and during cooling periods, they are collected from the chimney by electrostatic filters. The particle size of the fly ash usually ranged from less than 1 μm to 100 μm (Figure 2.2) and they comprise of silicon dioxide (SiO_2), which has two forms; crystalline, which is sharp, hazardous and pointed, and amorphous, which is smooth and rounded; aluminium dioxide (Al_2O_3) and iron oxide (Fe_2O_3). In general, fly ashes are heterogeneous and comprise of a glassy particles mixture with different crystalline phases such as mullite, quartz and other iron oxides [18-20]. Class C and F fly ash are the two main classes defined by ASTM C618 [21]. This classification based on the amount of chemical composition included, for instance, the content of calcium, silica, alumina and iron in the ash. Class F fly ash normally obtained from burning bituminous coal or anthracite and usually has little or no cementitious value because of the small amount of lime CaO (less than 10%) that it has. While, Class C fly ash usually produced from the burning of sub-bituminous coal and lignite that is contain more than 20% lime. This class categorized as cementitious and pozzolanic material, which with the presence of water can react and obtain strength with time.

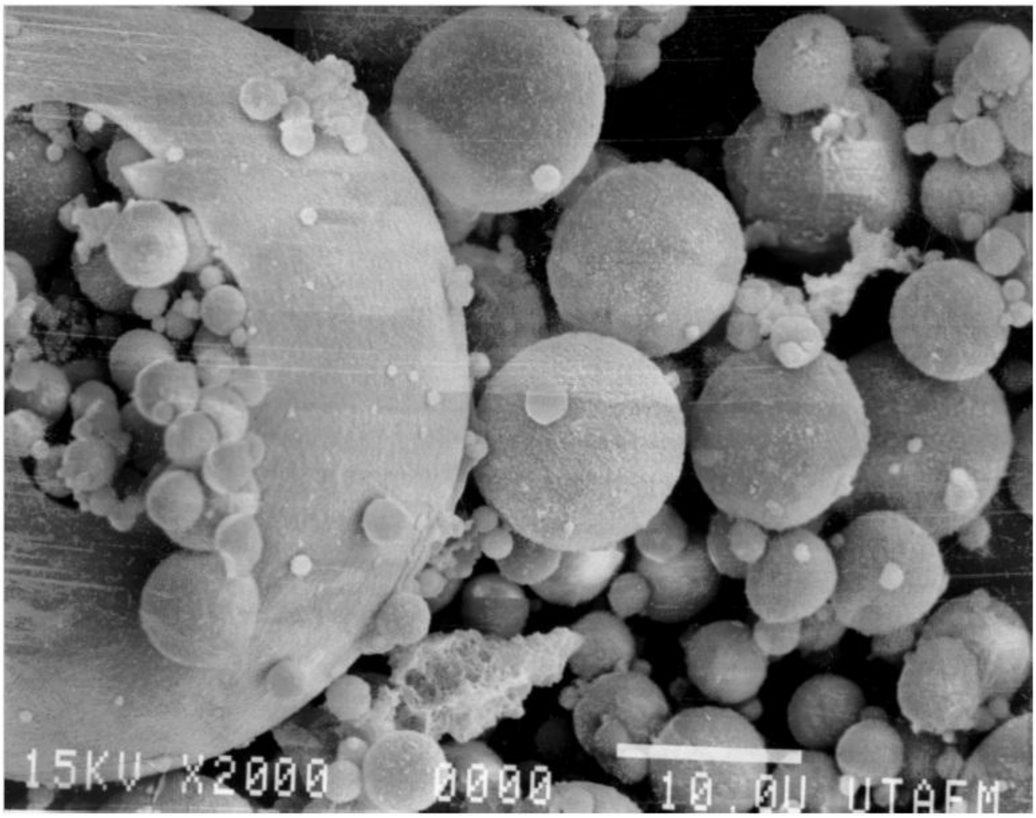

Figure 2.2 SEM image of fly ash particles [22]

2.1.1.3 Physical Properties

The shape, particle size distribution, density, fineness and the constituents of fly ash particles, usually affects the characteristics of the concrete and the artificial lightweight aggregate made by. One of the most important physical properties for fly ash is fineness that defined as the percent by weight of the material retained on the 0.044mm sieve. The finer particles have higher specific surface area. By using the Blaine apparatus the fineness of fly ash can be measured which is usually varies from 2500 to 5500 cm^2/g. Fly ash contains high amounts of hollow spherical particles and unburned coal, called cenospheres, which in turn result the low specific gravity. The bulk density of dry fly ash and the specific gravity range from 7.9 to 9.5 kN/m^3 and from 1.90 to 2.55 g/cm^3, respectively.

The colour of fly ash varies from light cream to dark brown, dark gray or black. This is due to the carbon content, the iron-rich particles and moisture. The black or gray colour usually comes from the carbon content while the brown color comes from the Fe_2O_3 content at which variation in their amounts is responsible of the color changing [15, 17, 23].

2.1.2 Silica Fume

Silica fume is a by-product material resulting from the production of silicon metal or ferrosilicon. Silicon metal usually produced in electric furnaces. Coal, quartz, and woodchips are the raw materials. Silica fume, which is condensed and collected from the escaping smoke from the furnaces, consists mainly of a very high content of amorphous silicon dioxide with very tiny spherical particles (Figure 2.3). Ferrosilicon alloys are usually produced with nominal silicon content range from 61 to 98 percent. The product is called silicon metal rather than ferrosilicon when the silicon content reaches 98 percent. As the silicon content increases in alloys, the SiO_2 content will increase in the silica (Table 2.1).

Most of published information and field use, have been from production of alloys of 75 percent ferrosilicon or higher while, limited application have been made using silica fume from production of 50 percent ferrosilicon alloys [24].

The colour of silica fume differs from light to dark grey. SiO_2 is colourless component so that the non-silica components are responsible for the change in colour such as carbon and iron dioxide. For instance, the darker the colour of silica fume means the higher carbon content. The carbon content in silica fume generally is influenced by the factors associated with production process such as: furnace temperature, wood chip composition, furnace exhaust temperature, and the type of products being manufactured. However, sometimes the degree of compaction may affect the changing in colour.

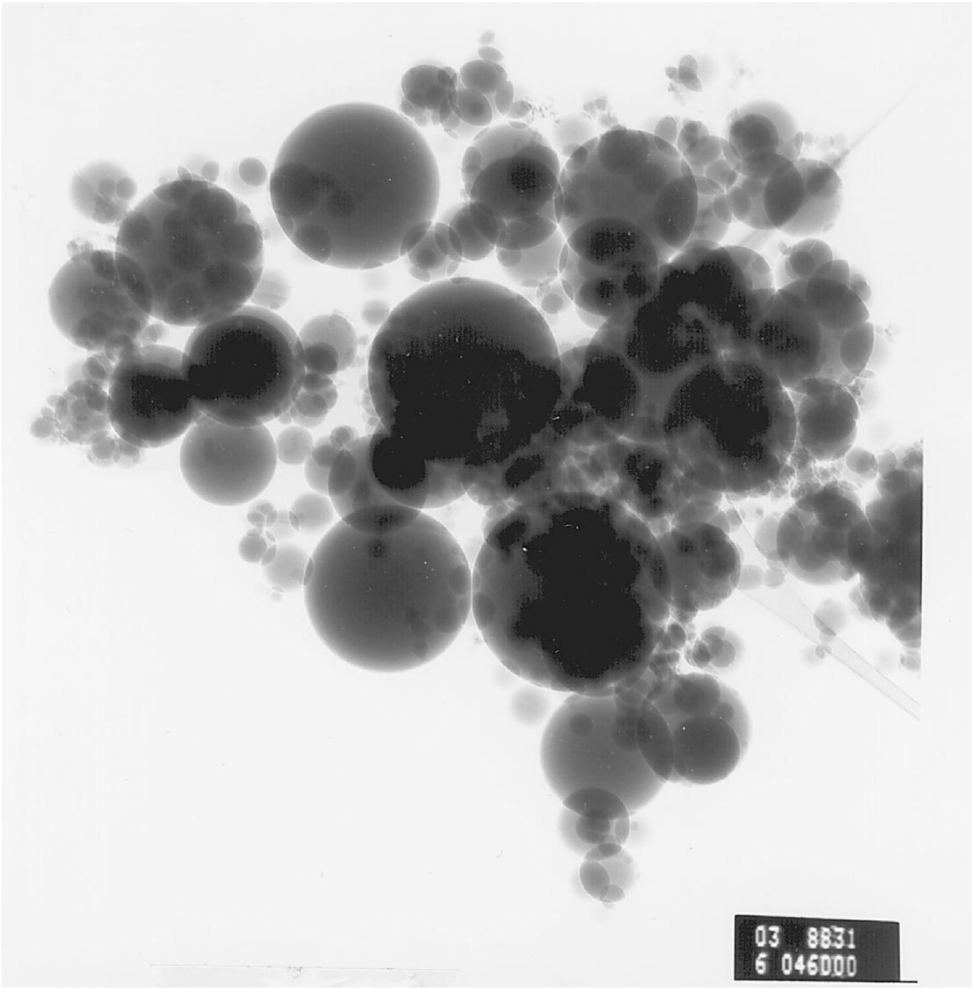

Figure 2.3 TEM micrograph of silica fume [24]

Table 2.1 Alloy types and their silica fume contents [24]

Alloy type	SiO_2 content of silica fume
50 percent ferrosilicon	61 to 84 percent
75 percent ferrosilicon	84 to 91 percent
Silicon metal (98 percent)	87 to 98 percent

Generally, the chemical composition of the silica fume is constant because of using two main raw materials in the process (quartz and coal) which they are very pure. The particle size of silica fume is about 0.1 μm as an average diameter, while the specific surface area is approximately 20000 m^2/kg, which is about 40 to 80 times more than ordinary Portland cement. The carbon content in silica fume is less than 2% [25].

2.2 Lightweight Aggregates (LWA)

Lightweight aggregate (LWA) is a material that has bulk density not exceeding 1200 kg/m^3 or having a particle density not more than 2000 kg/m^3 [26] and can be found naturally or artificially obtained. It is granular material and has many advantages [27, 28] such as: decreasing in the dead load that in turn result having smaller structural sections and footing sizes, longer spans, reduction in the sizes of slabs and columns, greater flexibility in design, improved fire resistance and more thermal isolation. Eventually, the most significant advantage of using the lightweight aggregate for concrete is the environmental impact when the raw toxics by product materials are utilized in the production of lightweight aggregates

2.2.1 Natural Lightweight Aggregate

The natural lightweight aggregate can be found in some places in the world because most of it has a volcanic origin. Pumice, scoria, tuff, volcanic cinders, and diatomite are the best known lightweight aggregates while the most generally utilized natural lightweight aggregates in the construction applications are scoria and pumice. Although they have variable properties, they are light strong enough to be used in their natural state. These types of aggregates are manufactured by mechanical treatment of lava (crushing, sieving, and grading). For instance, Pumice is a type of extrusive volcanic rock, obtained when the molten SiO_2 which lava forms the explosive eruption of a volcano cools. Quick cooling freezes the material existing in the molten state. The gas bubbles that occur in the molten lava are responsible for the low density of the pumice when trapped on cooling (Figure 2.4). The bulk density of pumice usually ranges from 5 to 9 kN/m^3 [29]. Similar to pumice aggregates the scoria, which is a extrusive rock not formed by the crystallization of volcanic magma and slow cooling. Its main difference from pumice is that it has darker colour, distinct connected broken and large bubbles [30, 31]. Another famous natural lightweight aggregate is diatomite, which is siliceous sedimentary rock consist mainly fossilized skeletal remains of diatoms. It is usually found in volcanic areas accompanied by the deposits shaping in lakes volcanically active places. It also has very low density and very tiny porous [32].

Figure 2.4 Pumice stone [35]

2.2.2 Artificial Aggregate from Industrial by Products

2.2.2.1 Furnace Clinker

Clinker aggregate is a by-product of combustion of the coal in industrial or domestic firing system. After crushing and screening, they are used as a lightweight aggregate that is dark coloured, solid and with a sintered form. Because of its high contain of sulphate and chlorides, it is not recommended to be used in the production of concrete mixtures only used fabrication of concrete blocks [33].

2.2.2.2 Bottom Ash Lightweight Aggregate

In electricity generation plant when coal is used for combustion process and with presence of turbulent air flow, it produces fly ash. A small amount of the ashes stay at the bottom and thus is called bottom ash aggregate. It usually includes an unburned coal or slag and it is a granular porous material. Its bulk density varies from 45 to 75 Ib/ft^3 [34].

2.2.3 Industrially Produced Artificial Lightweight Aggregate

Because of increasing demand and non-availability of natural LWA, some researchers developed new methods for manufacturing of artificial LWAs in factories from industrial by product like fly ash, blast furnace slag, and bed ash as well as from natural raw materials such as shale, slate, and expanded clay.

2.2.3.1 Fibo and Leca

Both Leca and Fibo are expanded clay aggregates produced in UK and Scandinavia, respectively. The expanded clay is the widely produced lightweight aggregate in the world which is primarily prepared either by wet or dry process of the raw materials before burning.

The dry process established on the reduction of clay into a tiny dry powder and then particularizing with water in an inclined steel cylinder kiln rotating at known speed is introduced while the wet process consists of mixing the clay and water into a paste. This paste is provided to the rotating kiln from above where it is broken to smaller granules by chains. Afterwards, the final product is screened, sieved and graded [18, 35].

2.2.3.2 Perlite

Perlite is a type of a volcanic glass which is can be expanded 4 to 20 % more than its first volume when it is heated to its melting point. This growth and increase in volume is caused by the occupancy of 2 to 6 % merged water in the crude perlite rock. When it is heated rapidly to more than 871ºC, the crude rock pops in a way like to popcorn as the merged water vaporizes and formulates endless little bubbles that result in a wonderful lightweight and remarkable physical characteristics [37]. Figure 2.5 exhibits a photographic view of different sizes of perlite.

Figure 2.5 Different sizes of perlite [37]

2.2.3.3 Slag Pellets

The process of manufacturing slag pellets was developed firstly in Canada that is produced from the molten slag coming from furnaces by various injections of water followed by a mechanical dispersion with a rotary drum. An internal expansion is provided by the injected water, which gives a steam vapour. Then, the shaped pellets are cooled soon in the air and vitreous shell is created. The pellets fall back on an inclined ground with grates in a way that the greater particles are projected far away while the smaller ones fall nearer [38].

2.2.4 Lightweight Aggregate Production with Fly Ash

The production of lightweight aggregate by using fly ash is a way to recycle the waste materials since million tons of fly ash is produced annually and only a few amount of it is utilized. Three methods are generally used for the hardening of fly ash pellets namely, sintering, autoclaving, and cold bonding [39,40].

2.2.4.1 Sintering Method

The manufacturing of sintered fly ash aggregates consists of two principle processes. First one is the pellitization of the fly ash when sprayed water mixed with fly ash in an inclined rotating disc of particularization. While the second process is subjecting the pellets to a temperature of about 1100ºC where 5 to 8% coal in the fly ash is ignited. Afterwards, the manufactured aggregate is separated, sieved and graded [39].

2.2.4.2 Autoclaving Method

This method uses pressurized saturated steam curing for hardening of fly ash pellets.

The manufacture of autoclaved fly ash aggregates typically involves using 47% fly ash, 45% quartz, 4.5%lime, 2.0% additives and 1.5% water by weight. All of the mixture is pelletized and then heated in a high humidity environment and then heated for 6.5 hours at 200ºC to produce lightweight aggregate that finds its primary use in masonry units [40].

2.2.4.3 Cold Bonding Method

This method is a type of bonding that depends on the capacity of fly ash to react with calcium hydroxide at the temperature of ambient to result in a material having water resistivity bonding material that depend on the pozzolanic reactivity of fly ash. The manufacturing process includes pelletizing or extruding the fly ash with Portland cement and water. After that the fresh pellets are cured for several days to produce aggregates [38].

2.3 Pelletization Theory

The technique in which the particle size enlarged is called agglomeration where fine particles like powders and dusts are gathered into larger masses such as pellets [41]. Through pelletization, the mixture is agglomerated where fine particles dispersed in either gas or liquid are enlarged by tumbling, without any need for external forces for compaction [41,42]. For this, usually a pelletizing revolving disc or drum is employed and the result from this process is a ball like shape called “the fresh pellet”. Several factors are affecting the quality and strength of the produced pellets such as: the amount of the moisture in the medium, the characteristics of the used particles, and mechanical process parameters like the speed of rotation and the tilting angle of revolving disc. The crushing strength of the pellets should be enough for storing and hauling purposes. The range of the size of the manufactured pellets usually between 3 to 40 mm and the colour vary from light to dark brown depend on the amount of iron and carbon in the mixes. Finer fly ash does not need any binder for achieving maximum pelletization efficiency [43].

Observations and analysis performed on the aforementioned parameters with regard to the kinetic and mechanic laws formed the theory of pelletization process. The essentials of theory are as follows [44];

When the fine-grained materials got moistened, a thin liquid layer is formed on the grain surface that appearances meniscus or crescent in the middle of grains, shapes such as ties (Figure 2.6 a). In condition when the particles revolved in balling disc, they develop a ball shaped structures accompanied by improved bonding forces among the grains caused by gravitational and centrifugal forces (Figure 2.6 b and c). During pelletization process, the air that fills the free spaces among the particles expelled because of the developed force on the pellets and leaving the gaps for water and the particles. A denser structure formed means a closer packed particles that enhance the structure coherence and creates sufficient strength for the pellets to be stored or handled [45].

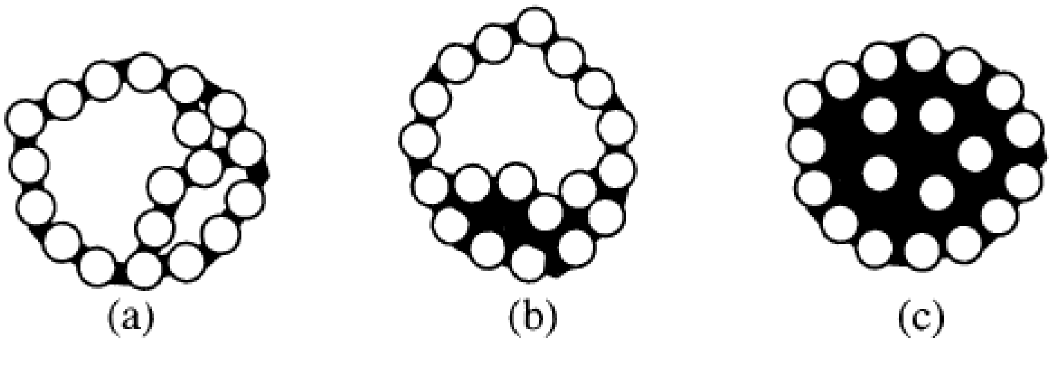

Figure 2.6 Mechanism of pellet formation [44]

The pelletization process parameters govern the strength of the pellets and also the resultant of pressure applied on the pellets. The capillary forces (surface tension generated by the height of liquid column) represent an important role in the magnitude of the coherence of pellets. The coherence of the structure is proportional with capillary and mechanical forces applied on the pellets. Previous experimental works have concluded that the maximum strength of pellets may be achieved when all the water fills the capillaries at the time of production unless the entrapped air inside the structures which cause restriction in capillary action. The desired water content for the fly ash is range between 20 and 25% as an optimum.

At the time of pelletization process, three stages affect the measure to which inter-granular spaces filled with water [38, 17];

- The pendular state, the water exists only at the contact points of the grains,
- The funicular state, in addition to aforementioned for the pendular state, water completely fills some of the pores; and
- The capillary state, where water fills all the inter-granular spaces fully without existing of a water film on the pellets surface.

The granulometric distribution of pelletized material is as well as excessive significance. The granulometric distribution of pellets may be regulated at the time of pelletization procedure through controlling the water content and the feeding rate of the binder. Figure 2.7 shows the mechanism of ball creation when the moisture content is less than optimum state. For this, the moistened particles move closer as well as come to be joined with water ties. While Figure 2.8 shows the mechanism of ball creation when the moisture content is more than optimum state. In this case, because of the excessive wetting, the formation is weaker and capillary forces are diminished. Consequently, the formations are different sized and can easily be demolished by the affect of the mechanical forces of the balling disc [46].

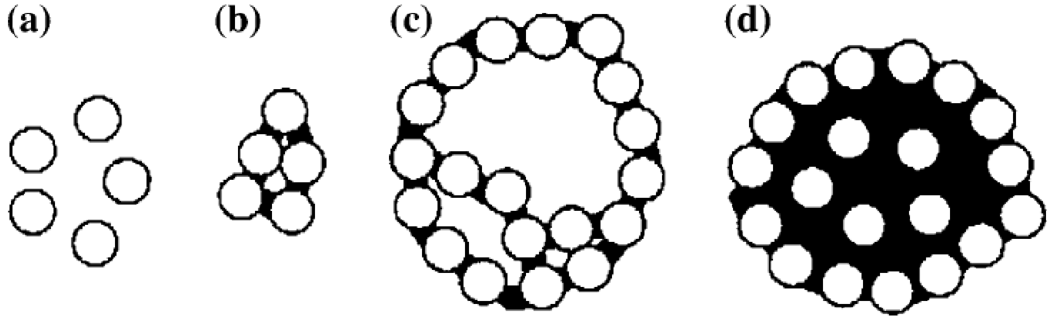

Figure 2.7 Mechanism of ball nuclei formation (Water content below optimum state) [46]

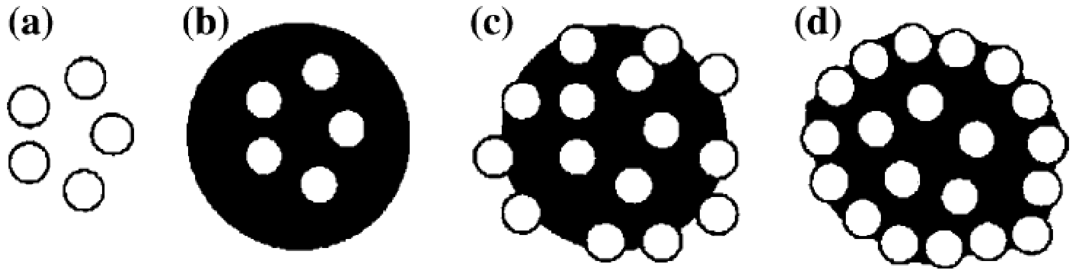

Figure 2.8 Mechanism of ball nuclei formation (Water content above optimum state) [46]

2.4 Lightweight Aggregate Concrete (LWC)

2.4.1 Production of lightweight concretes

One of the methods for the production of the structural lightweight aggregate concretes (LWCs) consists of totally or partially replacement of natural aggregates in concrete with aggregates having large voids proportions [47] such concrete usually classified as a lightweight aggregate concrete. The use of various raw materials and different methods for the production cause changing in characteristics of lightweight aggregates so that the aggregates obtained from clay, fly ash, blast furnace slag, shale and slate posses enough strength characteristics to be used in structural concrete applications.

Kayali [27] investigated the performance of concrete made from lightweight aggregates and compared with ordinary natural sand and gravel. For this study, the aggregates used was manufactured using the sintering method but without pelletizing where in a kiln fired briquettes were crushed and replaced with the normal aggregates. The used lightweight aggregates were suitable for high performance and high strength concrete. The produced concretes with these aggregates showed that they are 22% lighter and 20% stronger than the concretes made with the normal weight aggregates. The results also demonstrated a reduction of about 33% in the drying shrinkage of the concretes made with the lightweight concretes. In addition, the lightweight concrete made from crushed and sintered fly ash aggregates showed the higher strength, lower chloride penetration, the lower carbonation and contribution in the powerful bonding characteristics between the paste and the aggregates.

Joseph and Ramamurthy [48] examined the strength and sorption behavior of concrete produced by fly ash aggregate using cold bonding method with partial replacement of cement and as a material replaced with sand. The cold-bonded coarse aggregates manufactured through pelletization, by utilizing a class C fly ash. The optimum water content used was 30% by the weight of fly ash and the angle of pelletizing disc was 55º with a speed of 55 rpm to achieve extreme pelletization efficiency. The pelletization period was 13 minutes and then the aggregates sieved and only the portion passing 12.5 mm and retain on sieve 4.75mm water cured for

28-days at 27±2ºC. For the control mixture, the cement content was 450 kg/m^3 and 175 kg/m^3 was the amount of water. The replacement of the cold bonded aggregates was 50% and 65% by volume of the total aggregates and for the fly ash powder replacement with cement. In addition, three levels of 10%, 30%, and 50% by weight of cement were adopted. For the sand replacement with fly ash, three cement contents of 250, 350, and 450 kg/m^3, and two water contents of 175 and 220 kg/m^3 used.

The results from this study showed that the replacement of sand with fly ash is very effective in the reduction of water absorption and sorptivity attributable to the densification of both matrix and matrix-aggregate interfacial bond. The compressive strength of cold-bonded fly ash aggregate concrete was 45 MPa, for a mixture contains 250 kg/m^3 cement and with total inclusion of approximately 0.6 m^3 of fly ash in unit volume of concrete.

In the literature, artificial lightweight fly ash aggregates were also produced by employing the same method of pelletization described above. The studies showed that the angle and the revolution speed of the pelletization disc might be 43 degrees and 45 rpm, respectively, to give the optimum efficient production with moisture content of 24%. In addition, the pelletization disc used had a diameter of 40 cm and a depth of 15 cm. The formation of pellets occurred between 6 and 9 minutes, with a measured over all time for the pelletization process of about 20 minutes [17, 38, 49, 50, 51, 52].

Gesoglu et al.[50] favoured stiffening the pellets of lightweight fly ash aggregates rather than removing the old cement mortar adhered to the aggregates by producing artificial aggregates made from fly ash with a cement/fly ash ratio of 0.1 by weight.

For strengthening the old cement mortars and the strength of light weight aggregates, the lightweight fly ash aggregates were submerged in water glass – sodium silicate (Na_2O $nSiO_2$) solution for 30 minutes. After that, the aggregates are held in suspension for 10 minutes to remove the excess water from the aggregates which are taken out of the solution and after that they were put in oven for 1 hour to dry and preventing bonding between the contacted aggregates particles.

Manikandan and Ramamurthy [43] studied the effect of the fly ash fineness on the efficiency of pelletization process. For this, two types of fly ash employed from different thermal power plants. The finer fly ash reported the higher efficiency as compared with coarser one. However, the pelletization efficiency of coarser fly ash was enhanced with the addition of clay binders such as kalonite and bentonite.

Zhang and Gjorv [53] examined the pozzolanic reactivity of different lightweight aggregate types like sintered fly ash and expanded clay. Although the pozzolanic effect wasn't too much observed, but they concluded that there might be a low degree of reaction between the cement paste and aggregate grains due to re-crystallization of mineral compounds at the time of manufacturing process of the aggregates.

2.4.2 Engineering Properties of Lightweight Aggregate Concretes

The engineering properties of the lightweight concrete are determined by type of aggregate used. The density of lightweight usually varies from 300 to 2000 kg/m^3, corresponding to cube strengths from about 1 to over 60 N/mm^2 and 0.2 to 1 W/mK for thermal conductivities. RILEM/CEB proposed a classification depends on the relationship between strength and density [18] as shown in Table 2.2.

Table 2.2 Classification of lightweight concretes according to compressive strength-density relationship [18]

Property	Class and type		
	Structural	Structural/Insulating	Insulating
Compressive Strength (MPa)	>15	>3.5	>0.5
Density Range (kg/m^3)	1600-2000	<1600	≤1450

Compressive strength of 50-63 MPa can be obtained although the high porosity and inherent weakness of the lightweight aggregate concrete. To achieve high strengths in LWC, low w/c ratios might be adopted. Nevertheless, it is very hard to calculate the w/c accurately for the paste because the lightweight aggregates usually have high absorption capacity. So that the lightweight aggregate concretes consume more cement and mineral admixtures in contrast with the normal weight concretes at the same strength [18, 54].

Shannag [55] studied the properties of fresh and hardened concretes consisting of natural lightweight aggregates available locally (volcanic tuffs and scoria origin) and mineral admixtures. The air dry densities of the mixtures varied from 1935 to 1995 kg/m^3 and had a compressive strength of 22.5-43 MPa. He reported an increase of 57% and 14% in compressive strength when the cement partially replaced with silica fume blends of 5-15% by weight, respectively. However, partial replacement of cement with fly ash blends of 10% by weight, showed a reduction in compressive strength of about 18%.

Mouli and Khelafi [56] experimented six concrete mixtures; control mixture with only Portland cement and the remaining mixtures with 10%, 20%, 30%, 40%, and 50% replacement level of cement by pozzolan. Crushed natural pozzolan was used as lightweight aggregates (LWA). The reported results showed that the mixture containing 20% pozzolan replacement level had the higher compressive, flexural, and splitting strengths than the control concrete at all testing ages.

2.4.3 Physical Properties and Durability

The coefficient of thermal expansion of lightweight concrete is significantly lower than that of conventional concrete, because of the high amounts of void space. The density of the concrete obviously governs the thermal conductivity coefficients and the low coefficients of thermal conductivity will ensure better fire resistance of the structures.

Henikensiefken et al. [57] investigated the absorption behaviour of mortars made with saturated lightweight aggregate (SLWA). The results showed that when using LWA as an internal curing agent, increased the degree of hydration by creating denser microstructure. In addition, electrical conductivity, water absorption and sorptivity were reduced because of formation of a dense microstructure. Eventually, better result is attained with a mixture of 23.7% LWA and w/c ratio of 0.3, in contrast with conventional mortar mixture.

Liu et al. [58,59] made a study on the coarse and fine lightweight aggregates, at which the separated the LWA (expanded glass and expanded clay) into four groups of <1.18 mm, 1.18-2.36 mm, 2.36-4.75 mm, and 4.75-9.5 mm so as to examine the transport characteristics like resistivity to chloride penetration, water absorption and permeability. From the experimental results obtained, demonstrated that using size fraction <1.18 mm fine LWA decreased the resistance of all-LWC to water and chloride-ion penetration in contrast to the sand-LWC that has the same coarse LWA. In addition, the pre-soaked LWA caused an increase in water permeability and sorptivity of LWC in contrast to the NWC at the same water cementitious material.

2.5 Self Compacting Concrete (SCC)

2.5.1 Definitions

Enhancement the working environment and maximized productivity have had precedence in the development of concrete technology over the last years. For this, a material developed that can be placed without compaction or vibration named self compacting concrete. Self compacting concrete has met the challenge successfully and it is used more and more in routine practices [60]. SCC is also defined according to EFNARC [61], as the concrete that has ability of flowing under its own weight and fills the formwork totally, even in the existence of packed steel reinforcements. According to Okamura, SCC is modern type of high performance concrete (HPC) that has excellent segregation resistance and deformability. In addition, it can flow through and fill the gaps between the reinforcements and corners of moulds by itself without the need of compaction or vibration [62].

2.5.2 Workability Requirements of Fresh SCC

Fresh Properties of SCC is important because through them, the ability of concrete placing can be assessed so that the practical requirements needed are obviously different from those of conventional fresh concrete. EFNARC and RILEM [60, 61] recommended some important characteristics that are required for the workability performance of SCC as described in the following:

- *Filling ability* is the ability of concrete to fill the formworks and enclosed areas that include reinforcements completely with maintaining homogeneity,
- *Segregation resistance* is the ability of concrete to maintain the homogeneity during mixing and transportation. The risk of segregation in SCC is very high due to its high fluidity thus preventing segregation in SCC is an important aspect, and
- *Passing ability* is the ability of concrete to pass between narrow openings and enclosed spaces such as the areas of packed reinforcements without blockage caused by the interlock of aggregate particles.

In case the workability requirements have been attained from the produced concretes, the following important advantages can be acquired [62]:

- Quicker construction,
- Improved surface finishes (more fair faces),
- Enhanced durability,
- Lessening in place manpower,
- Easier placing,
- Thinner concrete sections,
- Superior freedom in design,
- Safer working environment, and
- Decreased noise levels (lack of vibration).

2.5.3 Rheology of SCC

Rheology is defined as the study of material deformation, or flow under stress. The fresh state properties of cementitious materials can be characterized utilizing rheological parameters. These parameters in cementitious materials, aid in describing the ease at which it can be used in the fresh state, comprising workability, compacting ability, flowability, placing ability, finishing ability, pumping ability and extruding ability. Different rheological properties are needed for different applications. Mixture designs can be styled to the required applications when understanding the rheology of cementitious materials [63].

The fluids flow behaviour, generally categorized into two groups; Newtonian and non-Newtonian [64]. For a well ordered flow (laminar) whereby fluid particles move in straight, parallel lines (parallel flow) Newton states that the shear stress on an interface tangent to the direction of flow is proportional to the distance rate of change of velocity, wherein the differentiation is taken in a direction normal to the interface [65]. Mathematically this is stated as:

$$\tau \propto \frac{\partial V}{\partial n} \tag{2.1}$$

Inserting the coefficient of proportionality into Newton's viscosity law leads to the results:

$$\tau = \mu \frac{\partial V}{\partial n} \tag{2.2}$$

Where μ is called the coefficient of viscosity and the unit of which being the poise corresponding to 1g/cm*s.

Newtonian fluid in this context is a viscous material. Non-Newtonian fluids are also viscous materials wherein the shear stress is related to the shear rate, $\partial V/\partial n$, in a more complicated way. The power law may be used to describe the behaviour of a viscous material. This can be formulized as follows:

$$\tau = k\left(\frac{dV}{dy}\right)^n \qquad (2.3)$$

For a Newtonian fluid, $k = \mu$, and n =1. The other values of n, however, lead to a non-Newtonian fluid. A non-Newtonian fluid whose behaviour is described by equation (2.3) with $n < 1$ is called a pseudoplastic. This name obtains because with increasing shear rate,$\left(\frac{dV}{dy}\right)$, there is curiously decrease in effective viscosity. That is, on increasing shear rate is “thinning”. This stress, shear-rate curve is given in Figure 2.9. Many non-Newtonian slurries are pseudoplastic. If, on the other hand, $n > 1$, the fluid is called dilatants. This time, the fluid “thickens” with increasing shear rate [65].

Paste, mortar and concrete, are often considered as non-Newtonian fluids [66]. The rheological behaviour of a fluid such as cement paste, mortar or concrete is most often characterized by at least two parameters, τ_0 and μ, as defined by Bingham equation [67].

$$\tau = \tau_0 + \mu\gamma \qquad (2.4)$$

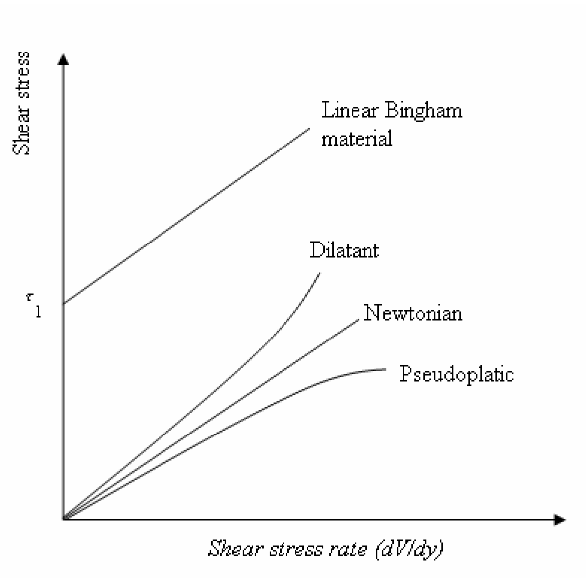

Figure 2.9 Rheological behaviors of some viscous materials [65]

Where τ is the shear stress applied to the material (in Pa), τ_0 is the yield stress (in Pa), μ is the plastic viscosity (in Pa*s), and γ is the shear strain rate (also is called the strain gradient) (in s^{-1}). The yield stress and plastic viscosity are the Bingham parameters that characterize the flow properties of materials. For self-compacting concrete, a fluid parameter may be necessary for representing the shear rate- shear stress relationship [66].

2.6 Basic Mix Design for SCC

For mix designing of SCC, there is no certain specification, so that so many educational institutions, ready mixed, admixture, precast and contracting companies have made their own mix design methods.

The mix designs generally use volume as a key parameter, due to the significance to the need for filling the voids in the middle of aggregate particles. Some methods try out fitting the available ingredients, by optimising the grading envelope. However, other methods try to evaluate and optimise the stability and flow of the paste and mortars fractions, and then the addition of coarse aggregates is introduced and the SCC mix examined [61].

For many years ago, different mix design methods are developed at academic institutions and other associations as published [61]. These publication gave guidelines for the designing but these godliness are not aimed to supply particular instructions about the mix design but in Table 2.3 gives an indication of the typical range of constituents in SCC by weight and by volume. However, many SCC mixes may fall outside these ranges therefore they are in no way restrictive.

Table 1.3 Typical range of SCC mix composition [61]

Constituent	Typical Range by mass (kg/m^3)	Typical Range by volume (litres/m^3)
Powder	380 – 600	
Paste		300 – 380
Water	150 – 210	150 – 210
Coarse aggregate	750 – 1000	270 – 360
Fine aggregate (sand)	Content balances the volume of the other constituents, typically 48-55% of total aggregate	
Water/Powder ratio by Vol.		0.85 – 1.10

2.7 Influence of Mineral Admixtures on Fresh Properties of Concretes

2.7.1 Influence of fly ash on Fresh Properties of Concretes

The concretes that contain fly ash and cement usually have absolute volume exceeds the ones that contain only cement. This is because fly ash has normally lower density and the mass of fly ash used is usually equal or greater than the reduced mass of cement. While it counts on the used proportions, this result in increasing the volume of cement paste produces a concrete with enhanced plasticity and better cohesiveness. Fly ash changes the behavior of flowing of the cement paste and generally, fly ash addition results in reduction of water demand in a concrete for a given workability [22].

Bouzoubaa et al. [68] studied the self-compacting concrete with addition of fly ash. The cement replacements were 40%, 50%, and 60% by class F fly ash. They showed that the incorporation of fly ash enhanced the slump flow diameter and decreased the V-funnel flow time of SCCs. In addition, the setting times of SCCs were 3 and 4 hours longer those of the control concrete.

It was reported in the study of Sonebi [69] that incorporation of pulverized fuel ash and limestone powder lessened the requirement of superplasticizer necessary to obtain the desired slump. And also the usage of these mineral materials enhanced the rheological properties and decreased the risk of cracking of concrete due to heat hydration, thus led to more durable concrete.

Sekino et al. [70] carried out a study to recommend the mix design method for SCCs comprising high volume of fly ash, and to assess the effects of replacing cement by fly ash on the strength and durability of SCCs. From the results obtained they made a conclusion that is at 50% replacement level of FA had excellent workability and filling ability at the construction site.

2.7.2 Influence of Silica Fume on Fresh Properties of Concretes

When increasing the amounts of silica fume, the water demand of concrete will increase, due to its high surface area [71,72]. The fresh concretes that containing silica fume blends, are usually have less tendency of segregation and more cohesive than the concrete without silica fume. However, increasing the portion of silica fume will result in a sticky fresh concrete and shows significantly reduced bleeding. This effect caused by high surface area of silica fume to be wetted; there is very little free water left in the mixture for bleeding. In addition, the blocking of the pores physically by the silica fume blends result in the reduction of bleeding [24].

Silica fume concrete usually includes chemical admixtures that may affect the time of setting of the concrete. Previous studies stated that the setting time is not significantly affected by the use of silica fume alone. Practical control of the setting time may be achieved by using appropriate chemical admixtures. In the literature, there is a general agreement on the retardation of initial and final setting times of the concretes containing FA and GGBFS. The behavior seen in the SF concretes was different from those with FA and GGBFS in that the addition of SF generally reduced the initial and final setting times of the concretes, especially at 10 and 15% replacement levels. No general agreement could be found in the literature considering the effect of SF content on the setting times of concretes [73]. Some researchers [74,75,76] stated that SF has retarding effect while some others reported its accelerating effect on the setting times.

The properties of self-compacting concrete with binary, ternary and quaternary cementious blends of different mineral admixtures were also studied in the litrature. From the study results, it was concluded that incorporation of mineral admixture enhanced the L-box height ratio and improved the passing and filling ability of SCCs. The addition of silica fume increased the slump flow time irrespective to its portion. However, this bad effect of silica fume repaired when FA blends incorporated with SF blends together in the ternary system [77].

2.8 Influence of Mineral Admixtures on Hardened and Durability Properties of Concretes

2.8.1 Influence of Fly Ash on Hardened and Durability Properties of Concretes

The addition of fly ash blends in concrete generally has lower early strength due to the slow pozzolanic reaction of fly ash. The content and the properties of the used fly ash are the main factors in the reduction of strength. A type of concrete so called high-volume fly ash concrete (HVFA) designed by CANMET in which 55-60% of Portland cement is replaced by class F fly ash and such concrete showed very good mechanical and durability properties [78,79,80].

In order to investigate the effects of including high volume FA replacement ratio on the properties of SCCs, Yazici [81] performed a study in which cement replaced by class C fly ash in deferent amounts from 30 to 60%. Similar tests carried out with incorporating 10% SF to the same mixtures. The results reported that with increasing FA content, the compressive strength decreased at all ages. At 28 days testing age, the compressive strength of control (0% FA) and 60% FA mixtures were 61.8 MPa and 28.4 MPa, respectively. All mixtures showed strength gain after 28 days and the control mixture reached to 72.5 MPa at 90 days while for 60% FA mixture was 38 MPa. However, it was possible to obtain a SCC having strength value of about 50 MPa with 30 to 40% FA replacement. Addition of SF blends with 10% to the system affected the compressive strength positively and contributed to the production of SCC mixtures that develop high mechanical properties incorporating high FA volume.

Saraswathy et al. [82] performed a study on concrete specimens with 10%, 20%, 30%, and 40% of activated fly ash replacement levels to evaluate the compressive strength at different ages of 7, 14, 28, and 90 days and contrasted the results with that concrete made by ordinary Portland cement only. They also measured the electrical resistivity and ultrasonic pulse velocity of the concretes to get an idea about the quality of concrete. Their results reported that the compressive strength of concrete increased with curing time, irrespective to the amount of FA replaced. A reduction in compressive strength observed, for instance; replacing cement by 10 to 40% FA caused a reduction in strength of about 1.5 times. For ultrasonic pulse velocity, the results showed that the measured values for ordinary Portland cement found to be 4.35 km/s while that for activated fly ash system ranged between 4.36 and 4.00 km/s.

McCarthy et al. [83] examined the use of high levels of low-lime fly ash as cement in concrete. Tests covering water permeability, carbonation rates, water absorption and chloride diffusion carried out to check the durability on the produced concrete. From the experimental results, they observed that water permeability, water absorption, and chloride diffusion tests improved with high FA levels, whereas for the carbonation rates close performance to Portland cement concrete was generally reported.

Malhotra [84] prepared a report on the resistance of concrete to the chloride ion penetration measured according to the ASTM C 1202 on 10-year-old concretes to investigate the long-term performance of concretes including pozzolans. The results showed that the charged passed through the concrete mixtures were less than 1000 Coulombs at 10 years indicating very low chloride-ion penetrability. However, for the mixtures comprising high volume of FA, the charged passed was zero which indicates a negligible rating of these concretes [85].

2.8.2 Influence of Silica fume on Hardened and Durability Properties of Concretes

The presence of silica fume in concretes enhances the bond between the paste and aggregates thus the influence of the impact of the quality of the used aggregate on mechanical characteristics of concrete becomes more critical in silica fume concrete.

Bhanja et al. [86] performed a comprehensive experimental study over the water-binder ratios ranging from 0.26 to 0.42 and silica fume-binder ratios from 0.0 to 0.3. The compressive, split-tensile and flexural strengths were investigated at the age of 28 days. The results showed that with incorporation of the silica fume, the compressive and the tensile strengths increased, and additionally, the results reveled that the optimum content depends on the water-cementitious material ratio (w/cm) of the mixture and it is not constant.

Mazloom et al. [87] stated that after the age of 90 days, the compressive strength of the concrete mixtures containing silica fume was negligible; however, there were increase in strength of about 26% and 14% in the control concrete after one year compared to its 28 and 90 days strength, respectively. The results marked 21% strength increase for the mixture comprising 15% silica fume, at the testing age of 28 days. Thus, incorporation of silica fume in the concrete mixture, chiefly affect the short-term strength of concrete. The difference in strength development in ordinary Portland cement concrete and silica fume concrete can be ascribed [88] to the rapid formation of an inhabiting layer of the reaction products preventing further reaction of SF with calcium hydroxide after 90 days. In the case of the control concrete, hydration is at less advanced stage and strength still show significant enhancement.

In order to investigate the durability performance of concretes containing condensed silica fume (CSF) in comparison to Portland cement (PC) and PC/GGBFS controls, Alexndar et al. [89] stated that durability performance was significantly improved when using CSF in the tests of oxygen permeability index, chloride conductivity and water sorptivity.

The sulphate resistance of concrete containing silica fume is good, partly because of lower permeability, and partly in consequence of a lower content of calcium hydroxide and of alumina, which has incorporated in C-S-H. Tests on mortars have reported the good impact of silica fume upon resistance to solutions magnesium, sodium and calcium chlorides [90].

In the literature, an intensive experimental study carried out to examine the properties of SCCs with different mineral admixtures. From the results, it was reported that when silica fume blends partially replaced with the cement binder in the concrete mixtures, very good improvement achieved in chloride permeability, sorptivity index and water permeability tests in comparison with the control mixture. However, the mixtures containing SF and FA blends together in the ternary system with different replacements showed behaviour comparably similar to the mixtures containing only SF blends [77].

2.9 Self-compacting Lightweight Concretes

There is limited information in the literature related to the use of lightweight aggregate in the production of self-compacting concretes. Most of the studies in this area focused on mix design method and fresh properties. However, some researchers designed self-compacting light weight concrete mixtures by the most popular method introduced by Okamura. His method consist of examining the properties of the cement paste and mortar prior to evaluate the properties of cement, fine aggregates, superplasticizer and pozzolanic material for saving the process from redundancy of needless testing, even if it is complicated technique makes it hard to apply to companies which produce the ready-mixed concrete. Other researchers advised applying the mixture proportioning of high performance self-compacting concrete for the lightweight concrete to keep the material away from segregation as well as reduction in strength caused by the decreasing in weight of the aggregate. When employing this method, the viscosity of high-performance self-compacting concrete increases in its fresh state and the segregation is prevented [91].

Topcu and Uygunoglu [92,93] examined the effects of aggregate type on the physical and mechanical properties of hardened self consolidating concrete made with coarse lightweight aggregate like pumice, volcanic tuff, and diatomite. The mixtures were designed by preparing different combinations of water to binder ratio with the total constant powder content and superplasticizer dosage levels. Experimental results revealed that unit weight of the mixtures was decreased in ratio of 30-35%, 22-31% and 34-38% by replacing of the crushed limestone with pumice, tuff and diatomite, respectively.

Lastly, concretes have been easily produced with comprising cold-bonded fly ash aggregates but, its usage in the production of self-compacting concretes has not obtained enough attention in the literature especially when binary and ternary blends of FA and SF are incorporated as mineral admixtures with different replacement levels. From what already mentioned above, lies the importance of this research to participate in enriching and adding new information to the literatures related to the modern and advanced concrete technologies.

CHAPTER 3

EXPERIEMNTAL STUDY

3.1 Materials

3.1.1 Cement

The cement employed for manufacturing both cold-bonded lightweight fly ash aggregates and SCLWC mixes was CEM-I 42.5 (PC) ordinary Portland cement which coincide to ASTM Type I grade and having a specific gravity and specific surface of 3.15 g/cm^3 and 3260 cm^2/g, respectively. Table 3.1 shows the physical characteristics and chemical composition of cement and mineral admixtures.

Table 3.1 Physical characteristics and chemical composition of cement and mineral admixtures

Chemical analysis [%]	Portland cement	Silica Fume	Fly Ash
CaO	62.58	0.45	4.24
SiO_2	20.25	90.36	56.2
Al_2O_3	5.31	0.71	20.17
Fe_2O_3	4.04	1.31	6.69
MgO	2.82	-	1.92
SO_3	2.73	0.41	0.49
K_2O	0.92	1.52	1.89
Na_2O	0.22	0.45	0.58
Loss of ignition	3.02	3.11	1.78
Specific gravity (g/cm^3)	3.15	2.2	2.25
Specific surface(cm^2/g)	3,260	210,800	2,870

3.1.2 Fly ash

A class F fly ash (FA) was used in this study which conform to ASTM C 618 [21] was utilized in the manufacturing both cold-bonded lightweight fly ash aggregates and SCLWC mixtures. It was provided by Ceyhan Sugözü thermal power plant and it had a specific gravity of 2.25 g/cm^3 and specific surface of 2870 cm^2/g. Table 3.1 presents the chemical and physical characteristics of the fly ash used.

3.1.3 Silica fume

Silica fume (SF) obtained from Norway was used. From the information provided by the supplier, it had a specific surface of 210800 cm^2/g and specific gravity of 2.2 g/cm^3. Chemical analysis and physical properties of SF is given in Table 3.1.

3.1.4 Superplasticizer

A polycarboxylic-ether type superplasticizer (SP) having a specific gravity of 1.07 was used in all mixtures to obtain the required workability. The properties of superplasticizer are listed in Table 3.2 as provided by the supplier.

Table 3.2 Properties of superplasticizer

Properties	Superplasticizer
Name	Glenium 51
Color tone	Dark brown
State	Liquid
Specific gravity (kg/l)	1.07
Chemical description	Modified polycarboxylic type plymer
Recommended dosage	%1-2 (% binder content)

3.1.5 Aggregates

3.1.5.1 Fine Aggregates

For the fine aggregates, a mixture of crushed limestone and natural river sand with a maximum size of 5 mm was employed. The particle size distributions and physical properties of the fine aggregates are presented in Table 3.3.

Table 3.3 Sieve analysis and physical properties of the fine aggregates

Sieve size (mm)	Fine aggregate	
	River sand	Crushed sand
16	100	100
8	100	100
4	86.6	95.4
2	56.7	63.3
1	37.7	39.1
0.5	25.7	28.4
0.25	6.7	16.4
Fineness modulus	2.87	2.57
Specific gravity (g/cm^3)	2.66	2.45
Absorption (%)	0.55	0.92

3.1.5.2 Lightweight Aggregates (LWAs)

Coarse cold-bonded fly ash lightweight aggregates were produced via a special manufacturing procedure called pelletization (particularization). For this, a dry mixture of 10% Portland cement and 90% fly ash by weight was prepared and put together in a rotating and 45º angle tilted pan (Figure 3.1 and Figure 3.2). Afterward, water sprayed continuously for 10 minutes to act as a banding material in the pelletization procedure. To get stiffener fresh pellets, the particularization process was extended for additional 10 minutes (Figure 3.3). Then, they were placed in closed plastic bags and kept for hardening in curing room having 70% relative humidity and temperature of 20 °C for 28 days as shown in Figure 3.4. After curing period of 28 days, the aggregates were separated. For instance, the portion passing a 16 mm sieve and retaining on 4 mm sieve were chosen as a lightweight coarse aggregates (Figure 3.5).

Figure 3.1 The general view of the pelletization disc

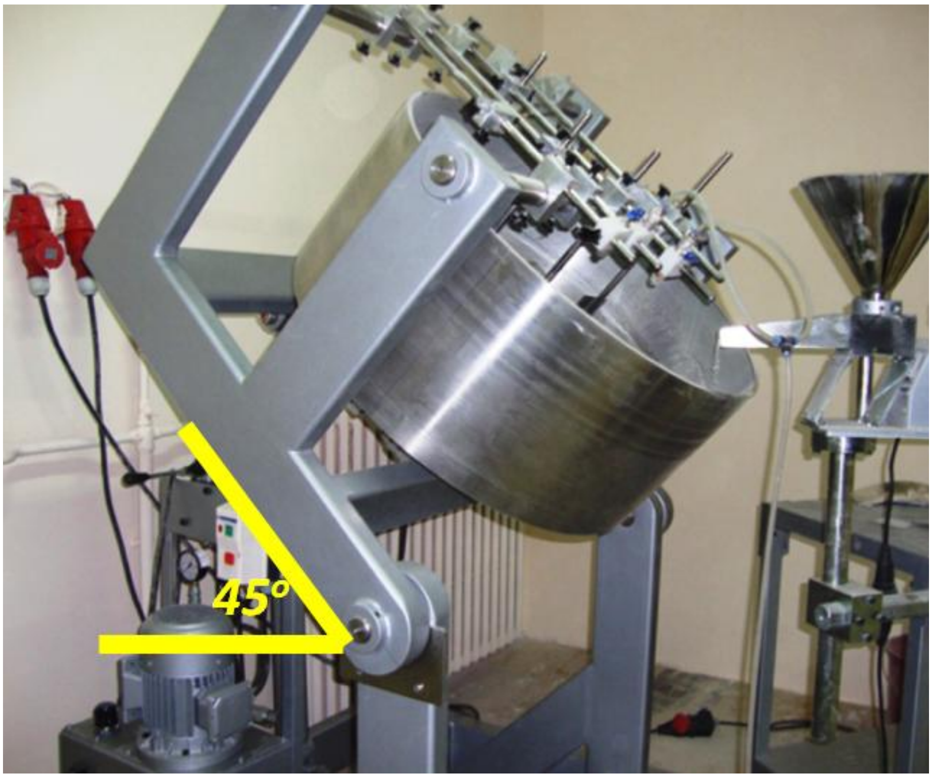

Figure 3.2 Photographic view of 45° angle tilted pan

Figure 3.3 Formation of fresh artificial lightweight aggregates

Figure 3.4 Aggregates placed in plastic closed bags

Figure 3.5 Photographic view of a stack of produced aggregates

3.1.6 Tests on lightweight aggregates

3.1.6.1 Aggregates Crushing Value Test

In order to investigate the crushing strength values of the produced aggregates, different aggregates sizes selected and put in the aggregate crushing value machine (ACV) to obtain the failure load. The crushing strength test performed as per BS 812, part 110 [94]. About 10 LWA pellet from each size of 6, 8, 10, 12, and 14, chosen to be loaded diametrically as illustrated in Figure 3.6. Moreover, Figure 3.7 presents the crushing strength values of different LWA sizes.

3.1.6.2 Specific gravity and water absorption test

ASTM C 127 [95] standards were followed for measuring the specific gravity and water absorption of the LWA. The absorption capacity of the LWA was 12.7% after 24 hours of immersion in water and the specific gravity for bulk; apparent and saturated surface dry conditions were 1.67, 2.24 and 1.92 g/cm^3, respectively. Figure 3.8 exhibits the absorption rate profiles measured up to 15 days.

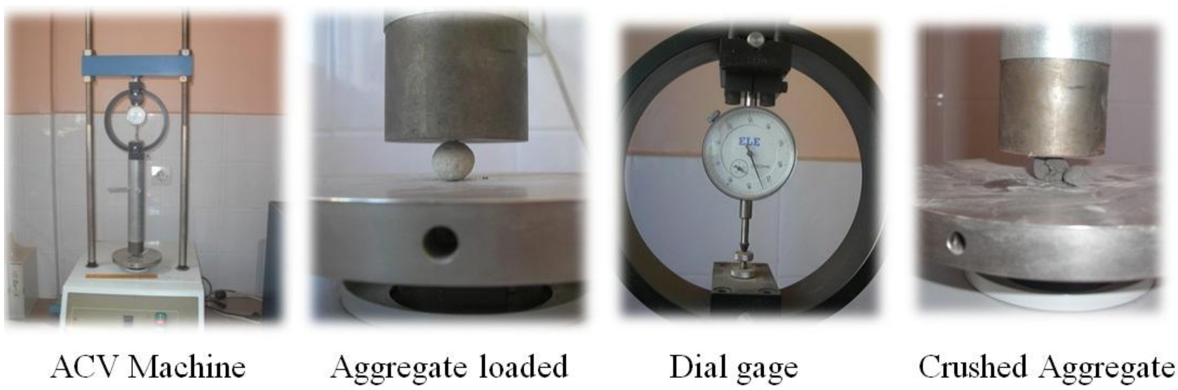

Figure 3.6 Measuring the crushing strength of the LWA pellets

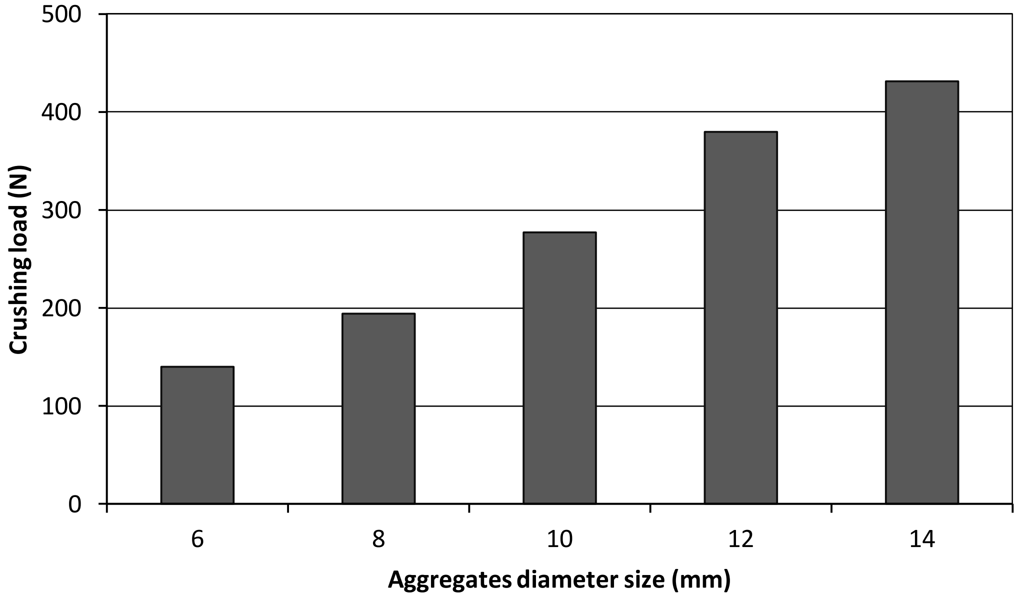

Figure 3.7 Crushing strength values of LWA

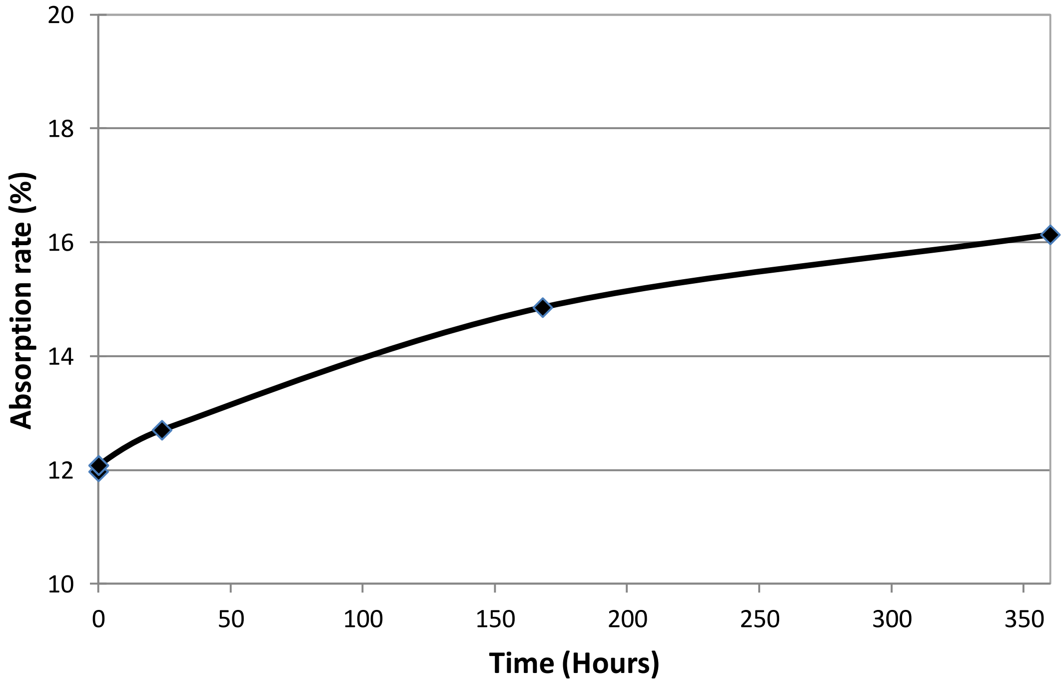

Figure 3.8 Absorption rate profile of the LWA

3.2 Concrete Mixture Details

A total of nine mixtures were designed having a constant water-binder ratio of 0.35 with total cementitious materials content of 550 kg/m^3. Cold-bonded lightweight coarse aggregates volume was 50% of the total aggregates in the mixture while the natural and crushed sand aggregates occupied the remaining 50% of the total aggregates volume. Portland cement included in the control mixture as the only binder, whereas the other mixtures incorporated binary (PC+FA, PC+SF); and ternary (PC+FA+SF) cementitious blends in which a proportion of PC was replaced with the mineral admixtures. The replacement ratios for FA were 15 and 30%, while the replacements of SF were 5 and 10% by weight of the total binder content. Table 3.4 shows the details of the concrete mixture proportions.

Table 3.4 Mixture proportioning of the concretes

Mixture ID	Mixture description	w/b	Water (kg/m^3)	Binder (kg/m^3)	PC (kg/m^3)	FA (kg/m^3)	SF (kg/m^3)	Natural Sand (kg/m^3)	Crushed Sand (kg/m^3)	LW aggregates (kg/m^3)	Super plasticizer (kg/m^3)	Unit weight (kg/m^3)
M1	Control-PC	0.35	192.5	550	550	0	0	509	179	688	5.5	2124
M2	15FA	0.35	192.5	550	467.5	82.5	0	501	176	677	5.3	2101
M3	30FA	0.35	192.5	550	385	165	0	492	173	665	5.3	2078
M4	5SF	0.35	192.5	550	522.5	0	27.5	506	178	684	6.4	2117
M5	10SF	0.35	192.5	550	495	0	55	503	177	680	6.4	2109
M6	15FA5SF	0.35	192.5	550	440	82.5	27.5	496	174	670	6.2	2090
M7	15FA10SF	0.35	192.5	550	412.5	82.5	55	495	174	668	6.2	2085
M8	30FA5SF	0.35	192.5	550	357.5	165	27.5	489	172	661	5.6	2070
M9	30FA10SF	0.35	192.5	550	330	165	55	486	171	657	5.6	2062

3.3 Concrete Casting, Test specimens, and Curing

Due to high absorption capacity of the artificial lightweight aggregates and to eliminate the early slump loss, a special method was used. This consisted of immersing the artificial lightweight aggregates in water for 30 minutes, and afterward placed on a dry trowel for drying the aggregates manually by hands to a saturated surface dry (SSD) condition. Laboratory mixing pan was used in concrete mixing. First of all the binder was mixed with SSD lightweight aggregate and then the crushed sand and natural sand was added to the mixer. After homogenizing of the binder and the aggregates after 30 seconds of mixing, roughly one third of the mixing water was supplied gradually in the mixer with continuous mixing for one more minute. Lastly, the remaining water with superplasticizer was introduced, with resuming the mixing for another 3 minutes and after that left for 2 minutes to rest. After all, additional 2 minutes of mixing adopted to accomplish the sequence of the mixing. The SCLWCs were designed to have a slump flow class SF2 (660-750 mm) according to EFNARC [61]. For this, varying amounts of superplasticizer utilized to obtain the already mentioned slump flow class.

After the mixing procedure ended, the fresh concrete mixtures were investigated for workability, passing ability, and viscosity. At the same time, they were examined for bleeding and segregation visually. When the SCLWCs are at the hardened state, they were tested for ultrasonic pulse velocity (UPV), compressive strength, chloride ion permeability, gas permeability, sorpitivity, and water absorption at 28 and 56 days.

From each concrete mixture, four Ø100 x 200 mm cylinders, two Ø150 x 300 mm cylinders and six 150 mm cubes were cast without any vibration or compaction. Demolding of the specimens done after 24 hours of casting and then they were immersed in water for curing up to the time of testing.

3.4 Tests for Fresh Properties

3.4.1 Slump Flow Test (T_{500})

The slump flow experiment employed for checking the flow rate and flowability of self-compacting concrete in unconfined positions. It can easily be specified for all SCCs, as the main inspect at which the designed concrete match the specifications.

To measure the slump flow, the slump flow cone is fully filled with SCLWCs without compaction and the upper surface is leveled. The cone is raised upward slowly and an average diameter is determined from the spread concrete as illustrated in Figure 3.9. Moreover, the time at which the cone is raised and when the moving concrete attaches the 500 mm diameter circle is measured. This is known as T_{500} time according to EFNARC [61], thus a shorter time means higher flowability. There are three flow classes for different application areas of these classes are given in Table 3.5. Eventually, visual observations during the measurement of the T_{500} time provide information about uniformity and tendency of segregations.

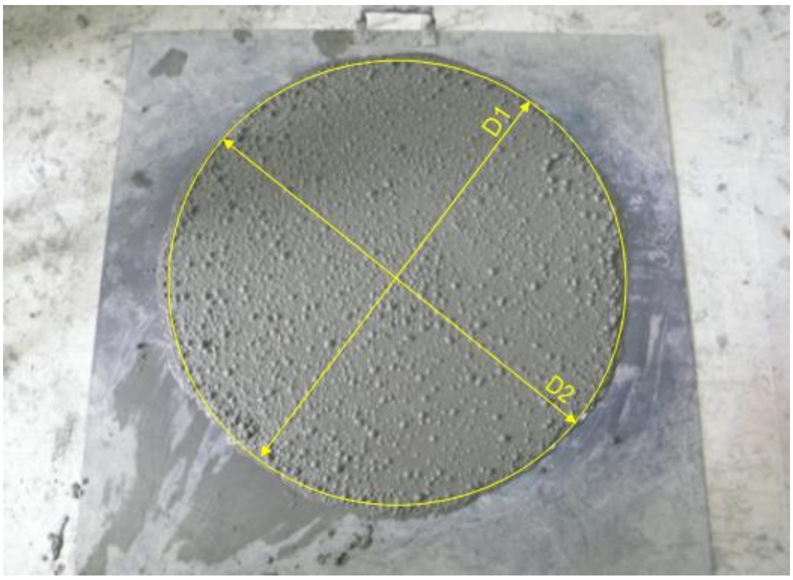

Figure 3.9 Typical illustration of slump flow diameter

Table 3.5 Slump flow, viscosity, and passing ability classes according to EFNARC [61]

Class		Slump flow diameter (mm)
Slump flow classes		
SF1		550-650
SF2		660-750
SF3		760-850
Class	T_{500} (s)	V-funnel time (s)
Viscosity classes		
VS1/VF1	≤2	≤8
VS2/VF2	>2	9-25
Passing ability classes		
PA1	≥0.8 with two rebar	
PA2	≥0.8 with three rebar	

3.4.2 V-funnel Flow Test

V-funnel flow time test usually adopted for determination of viscosity and passing ability of SCCs (Figure 3.10). The procedure of computing the flow time is; filling the V-shaped funnel with fresh concrete and let it to rest for some seconds. Afterward, the hinged trapdoor is released and the time is measured till it completely becomes empty as seen in Figure 3.11. Shorter time of flowing indicates better passing ability of a concrete. Khayat et al. [96] stated that for a concrete to be qualified for self compatibility, it is recommended to have less than 6 sec for V-funnel flow time. In EFNARC [61] specifications (Table 3.5), the V-funnel flow time and T_{500} time values together evaluate the viscosity of a concrete by two designated classes.

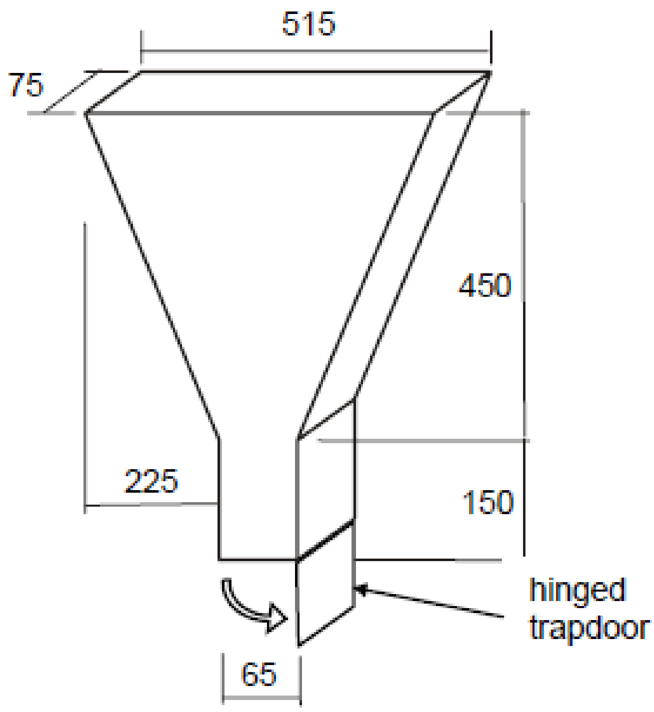

Figure 3.10 Schematic representation of V-funnel [61]

Figure 3.11 Measurement of V-funnel flow time

3.4.3 L-box Test

L-box test investigate the ability of concrete to pass between narrow openings and enclosed spaces such as packed reinforcement sections without having uniformity loss, segregation, or blockage. As shown in Figure 3.12, L-box is "L" shaped apparatus, having vertical and horizontal parts with a moving gate. Two or three steel reinforcing bars put in front of the gate to represent an obstruction for the concrete to move.

The test procedure is pouring the fresh concrete in the vertical section and let it to rest for a couple of seconds. After, the gate is opened and let the concrete flows to the horizontal section through the gaps between the obstructing bars. The horizontal section of the box can be marked at 200 mm and 400 mm from the gate and the times taken to reach these points measured. These are known as T_{200} and T_{400} times and are an indication for the filling ability. When the movement stopped, the depths of concrete that are directly behind the gate (H_1) and at the end of the horizontal section of L-box (H_2) are measured and the ratio of H_2/H_1 is computed. Passing ability classes according to the L-box height ratio values are given in Table 3.5, whereas, Figure 3.13 exhibits photographic view of L-box test.

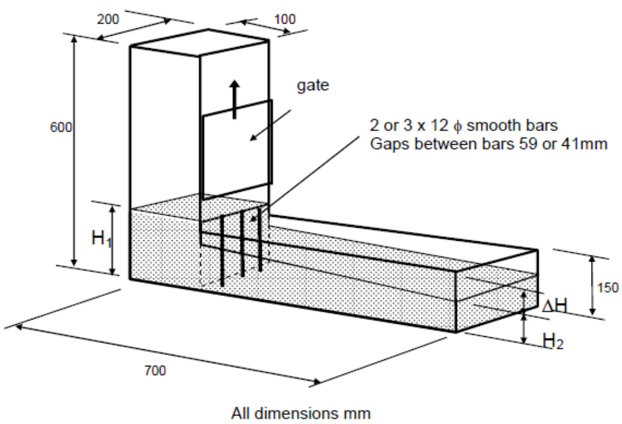

Figure 3.12 Schematic representation of L-box [61]

Figure 3.13 Photographic view of L-box test

3.5 Tests for Hardened Properties

3.5.1 Compressive Strength

Compressive strength test was performed on 150x150x150 mm cube specimens at 28 and 56 days coinciding with ASTM C39 [97] for all SCLWCs. Three cubes for each mixture investigated with a machine having 3000 kN capacity and loading rate of 4.5 kN/sec.

3.5.2 Ultrasonic Pulse Velocity (UPV)

Earlier to the compression test, the ultrasonic pulse velocity (UPV) test was carried out as per ASTM C597 [98] for SCLWCs at 28 and 56 days.

3.5.3 Rapid Chloride Permeability

AASHTO T277-89 [99] specifications were followed to measure the resistance of

SCLWCs to the chloride ion penetration by knowing the amount of the charge passed through the concrete. Two specimens of Ø100 x 200 mm dimensions were tested simultaneously for each concrete at the end of 28 and 56 day curing periods. After curing, two 50 mm thick disc samples were cut from the middle of each cylinder and were conditioned as mentioned in AASHTO T277-89 [99]. Then, the disc specimens were transferred to the test cell in which one face of the specimen was in touch with 0.30 N NaOH solutions and the other was with 3% NaCl solution. A direct voltage of 60 $\pm$ 0.1 V was applied across the faces (Figure 3.14 and 3.15). A data logger registered the current passing through concrete over 6 hour period. Terminating the test after 6 hours, current (in amperes) versus time (in seconds) were plotted for each concrete and the area under the curve was integrated to obtain the charge passed (in coulombs). Five classes from "high" to "negligible" were categorized according to AASHTO T277-89 as listed in Table 3.6.

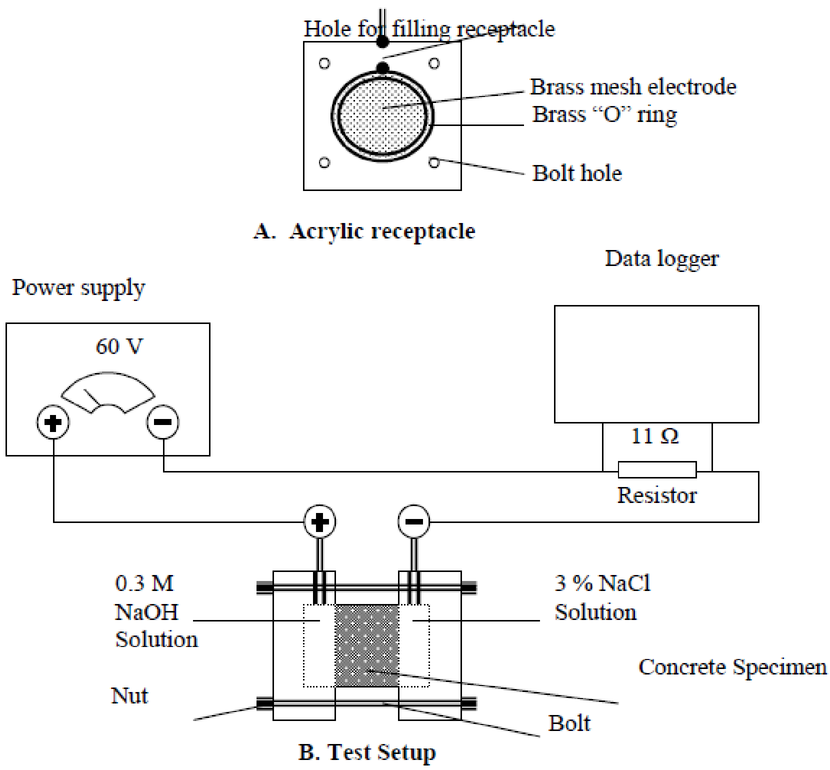

Figure 3.14 Experimental set-up for RCPT

Figure 3.15 Photographic view of the RCPT set up

Table 3.6 Interpretation of results obtained using RCPT [99]

Charge passed (Coulombs)	Chloride Permeability	Typical of-
>4000	High	High w/c ratio (<0.6) conventional Portland cement concrete
2000 – 4000	Moderate	Moderate w/c ratio (0.4 – 0.5) conventional Portland cement concrete
1000 – 2000	Low	Low w/c ratio (< 0.4) conventional Portland cement concrete
100 -1000	Very Low	Latex-modified concrete, Internally sealed concrete
< 100	Negligible	Polymer-impregnated concrete, Polymer concrete

3.5.4 Gas Permeability

A RILEM TC 116-PCD [100] recommendation, the CEMBUREAU method was conducted for measuring the gas permeability coefficients of the concrete mixtures. The gas permeability was measured on 50 mm height and 150 mm diameter concrete disk specimens cut from the mid portion of Ø 150x300 mm cylinders. Oxygen gas was used as the permeating medium. Differential pressures varying from 150 to 500 kPa were applied to the specimens that build up a minimum lateral pressure of 0.7 MPa on the rubber tube. When curing periods of 28 and 56 days were ended, the specimens dried at 100 $\pm$5 ^{o}C in oven to make sure each specimen weight change was less than 1%. Then, they were kept in a sealed box till test began. At each testing age, two specimens were investigated and the average of them was recorded. The photographic view and the schematic layout of the apparatus as well as the detail of the testing cell are shown in Figures 3.16 to 3.18.

For each differential pressure from 150 to 500 kPa, Hagen-Poiseuille relationship [105] for laminar flow of a compressible fluid through a porous media with small capillaries under steady-state condition was used to determine the apparent gas permeability coefficient K_g, which can be calculated using the modified Darcy's equation:

$$K_g = \frac{2P_2QL\mu}{A(P_1^2 - P_2^2)} \qquad (3.1)$$

Where;

K_g is the gas permeability coefficient (m^2)

Q is the volume flow rate (m^3/s)

A is the cross-sectional area of the sample (m^2)

μ is the viscosity of oxygen ($2.02x10^{-5}$ Ns/m^2)

L is the height of sample (m)

P_1 is the inlet gas pressure (N/m^2)

P_2 is the outlet gas pressure (N/m^2)

Figure 3.16 Photographic view of the gas permeability test set up

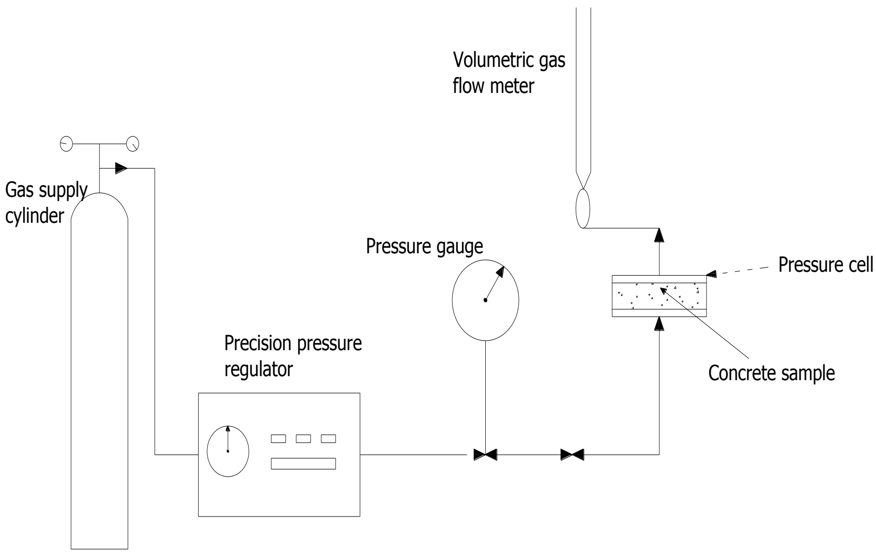

Figure 3.17 Illustration of the gas permeability test set up

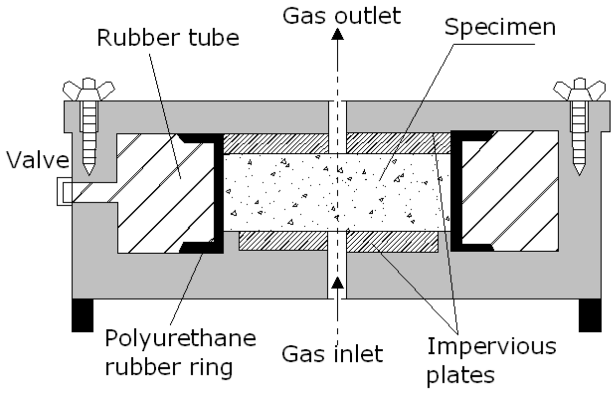

Figure 3.18 Schematic presentation of the pressure cell and test specimen

3.5.5 Sorptivity

ASTM C1585 [101] standard was followed to examine the sorptivity index of the SCLWCs. Water sorptivity experiment measures the rate at which water is drawn into the pores of concrete. For this, two test specimens with dimensions of Ø100 x 50 mm cut from Ø100 x 200 mm cylinder specimens were used. The specimens were dried in an oven at approximately 100 $\pm$ 5°C until the constant mass was obtained; thereafter the specimens were allowed to cool to the ambient temperature in a sealed container. Afterward, the sides of the specimens were coated with paraffin wax; the sorptivity test was carried out by placing the specimens on glass rods in a tray so that their bottom surface up to a height of 3 mm were in contact with water, as illustrated in Figure 3.19. This procedure was considered to allow free water movement through the bottom surface [102]. The specimen were removed from tray and weighted at different time intervals up to 1 hour to evaluate mass gain. The volume of water absorbed was calculated by dividing the mass gained by the nominal surface area of the specimen and the density of water. These values were plotted against the square root of time. The slope of the line of the best fit was defined as the sorptivity coefficient of concrete [103]. The test performed in 28 and 56 days.

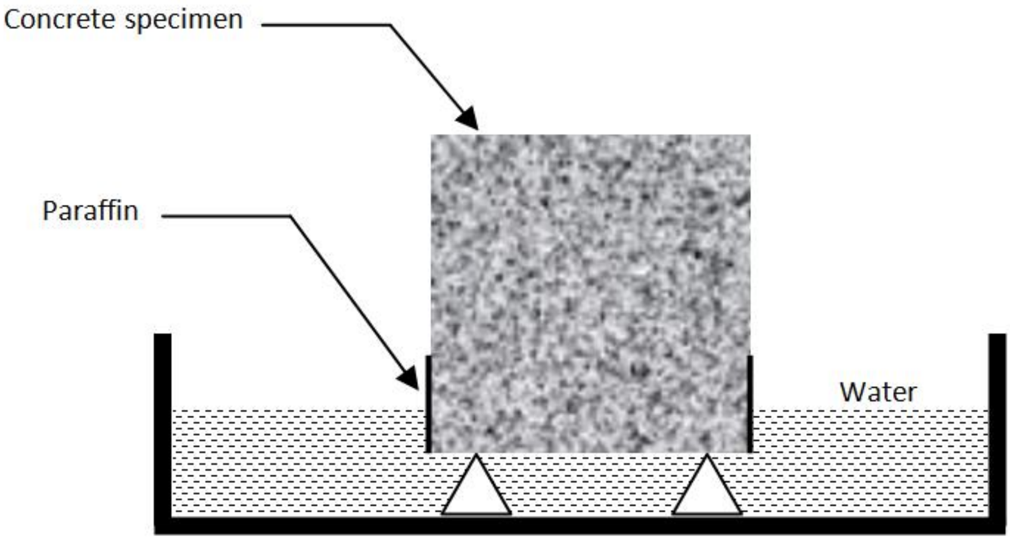

Figure 3.19 Sorptivity measurements of SCLWCs

3.5.6 Water Absorption

The water absorption test carried out for SCLWCs according to ASTM C642 [104] standard. For this, two 50 mm height and 100 mm diameter concrete specimens were cut from Ø100 x 200 mm cylinder specimens were employed. In the determination of water absorption by total immersion, firstly, the concrete specimens were put in an oven to dry at 100 ± 5°C for 24 hours to have a constant weight, and then they allowed cooling to the ambient temperature. Thereafter, they were totally submerged in the water at 20°C and the mass of each specimen was recorded after 7 days of immersion into the water. The 7 day water absorption percentage of each specimen was then evaluated for comparison purposes. At the ages of 28 and 56 days, two specimens from each mixture were tested and the average values were reported.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Fresh Concrete Properties

4.1.1 Fresh Concrete Density

The fresh density of the self-compacting lightweight concretes (SCLWCs), varied from 2124 to 2062 kg/m^3 as presented before in Chapter 3, Table 3.4. The aforementioned values of the fresh density seem to be slightly high. The reasons behind this rise in densities may be due to, first, high binder content and low w/b ratio. Second, slightly high specific gravity of the cold-bonded aggregate used (1.92 g/cm^3) because of the source fly ash that already had relatively high specific gravity. Lastly, the usage of crushed and natural fine aggregates and this is considered as a principal reason which results in having concretes exceed the limitations given by ACI. Nevertheless, the previous studies mentioned similar results [106-109].

4.1.2 Slump Flow Diameter and Slump Flow Time

The SCLWCs produced in this study had slump flow diameters ranging from 700 to 750 mm that was obtained by using different volume of superplasticizer, as shown in Table 4.1.

According to Table 3.4 (Chapter 3), the required superplasticizer content was varying according to the mineral used (i.e. at control concrete 5.5 kg/m^3 superplasticizer was used while the mixture with 10% silica fume had 6.4 kg/m^3 superplasticizer content). Slump flow classes of the produced SCLWCs were defined and illustrated in Figure 4.1. Generally, SF2 type slump classes' self-compacting lightweight concretes were produced. According to EFNARC [61], SCC guide, SF2 class self compacting concretes (660-750) can be applied to many normal structural members (e.g. walls, columns). Despite the high superplasticizer amount in M5 (10SF), the slump flow diameter recorded was the lowest one, as obviously seen in Figure 4.1. However, this adverse effect of SF appeared to be amended and relatively reduced with adding FA as a ternary blend.

T_{500} slump flow times of the produced self-compacting lightweight concretes are presented in Figure 4.2. The T_{500} slump flow time was generally less than 2.16 s (control mixture) except for the 10SF mixture (M5) indicating that the SF blends remarkably increased the slump flow time of the SCLWC, particularly when higher replacement levels are used. Using FA blends noticeably seemed to be the most efficient in lessening the slump flow time.

Table 4.1 Slump flow, V-funnel and L-box properties of SCLWCs

Mix ID	Mixture description	Slump flow		L-box			V-funnel flow time(s)
		T_{500} *(s)*	*D (mm)*	T_{200}*(s)*	T_{400}*(s)*	H_2/H_1	
M1	Control	2.2	720	2.8	9.5	0.888	15.4
M2	15FA	2.0	720	2.8	7.7	0.894	11.8
M3	30FA	1.9	750	1.1	2.1	0.975	7.7
M4	5SF	2.1	750	1.2	2.7	0.934	16.1
M5	10SF	4.1	700	4.9	10.7	0.851	17.5
M6	15FA5SF	1.8	750	1.3	3.3	0.950	8.1
M7	15FA10SF	2.1	720	2.6	5.7	0.937	10.1
M8	30FA5SF	0.8	750	0.8	2.2	0.975	6.3
M9	30FA10SF	1.9	750	0.9	2.4	0.961	8.0

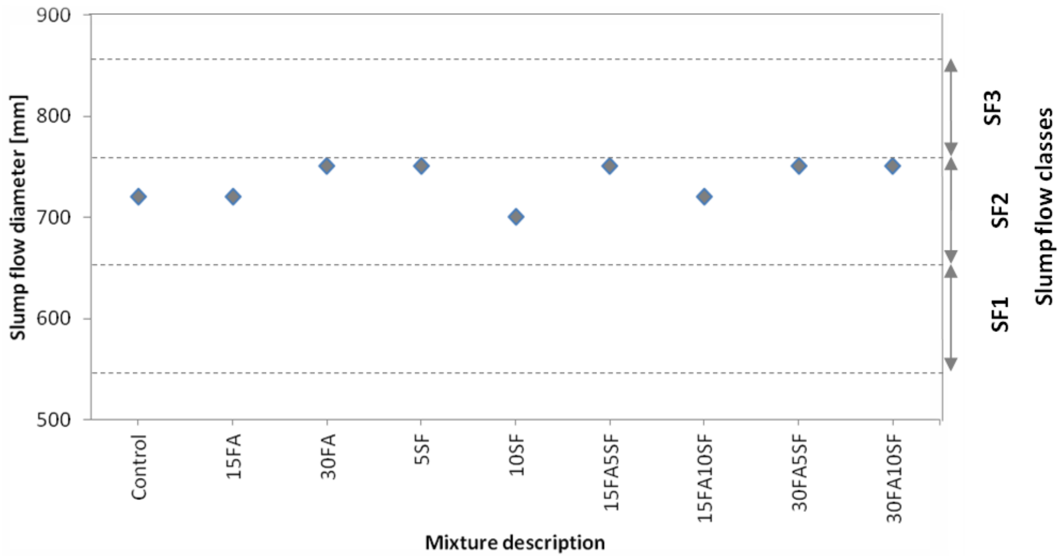

Figure 4.1 Variation of slump flow diameter and slump classes

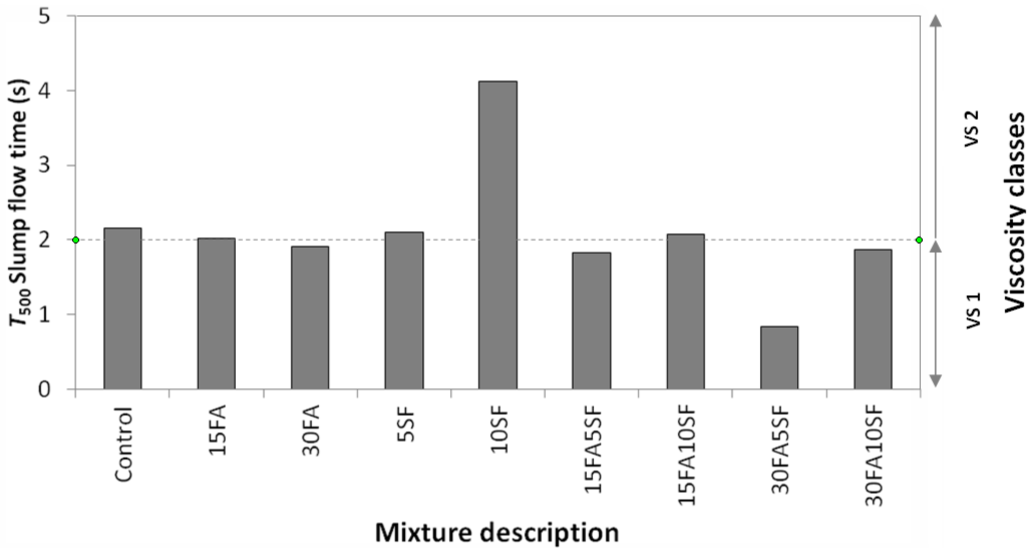

Figure 4.2 Variations of slump flow time and viscosity classes

4.1.3 V-funnel Flow Time

The variation of V-funnel flow time of the SCLWCs is given in Table 4.1 and Figure 4.3. The range of the time measured by using the V-funnel was between 6.3 and 17.5, counting primarily on the types of the mineral admixtures employed. Concrete mixture M8 with 30%FA and 5%SF had V-funnel flow time value of 6.3 which is the lowest time reported for the V-funnel flow times of the SCLWCs while the highest flow time of 17.5 was measured for Mixture M5 containing 10% replacement level of SF blends and this may be attributed to the high water absorption capacity of the silica fume blends due to its high surface area. In general, more viscous concretes produced when SF blends incorporated in binary system. However, the usage of FA reduced the viscosity which in turn caused lowering in the V-funnel flow time of the SCLWCs. Mineral admixtures were utilized in ternary blends so as to decrease the V-funnel flow time of the SCLWCs, as the V-funnel flow times of the concretes increase with SF and decreased with FA.

Figure 4.4 demonstrates the viscosity classes of the produced SCLWC. According to EFNARC [61] recommendation, viscosity should be specified only in special conditions such as best surface finish and in limiting the formwork pressure or improving the segregation resistance. As obviously seen in Figure 4.4, most the produced SCLWC can be classified as VS2/VF2. This type of concretes may be applied at ramps and walls/columns with SF1 and SF2 class slump flow diameter, respectively. With the addition of 30% FA blends in binary or ternary systems, the viscosity classes of the produced SCLWC turn into the VS1/VF1.

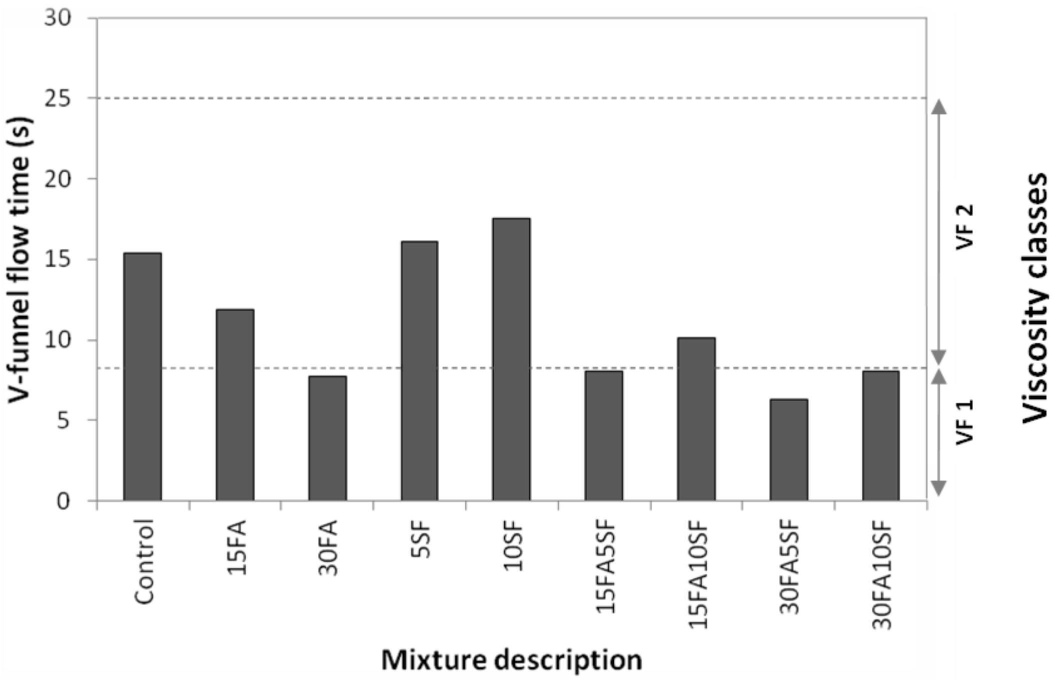

Figure 4.3 Variation of V-funnel flow time (s) and viscosity classes

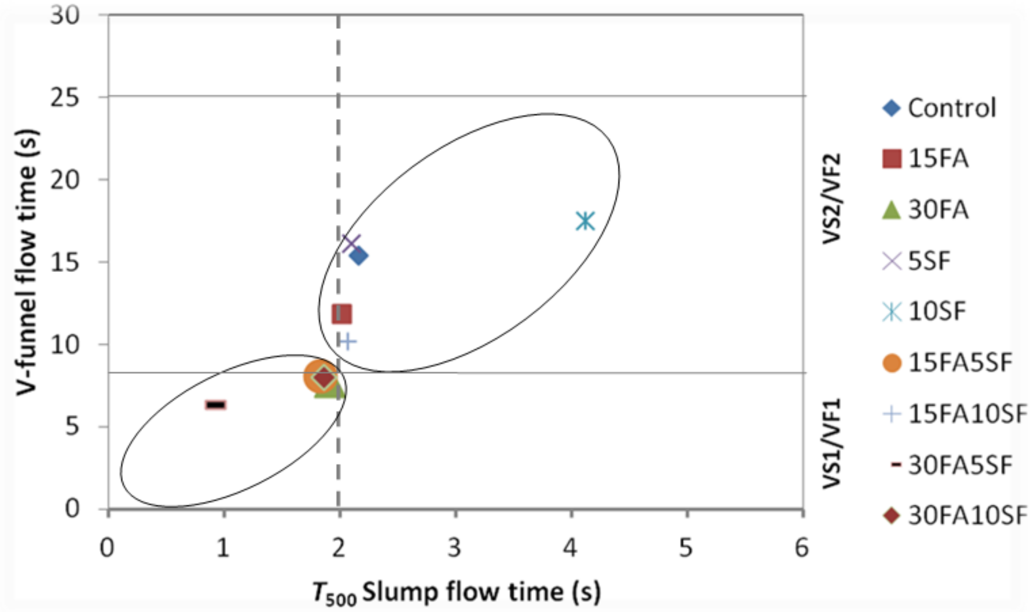

Figure 4.4 Variation of viscosity classes with T_{500} slump flow and V-funnel times

4.1.2 L-box Height Ratio, T_{200} and T_{400} Times

To identify the passing ability of the produced SCLWC, L-box test was used. There are two variations of this test, namely the three bar test and the two bar test. More congested reinforcements is simulated in the three bar test [61]. In the current study, three bar L-box height was utilized. The test provided H_2/H_1 ratio as a measure of the flowability among reinforcing bars. The variation in the three bar L-box height ratio is illustrated in Figure 4.5. To affirm that a self-compacting concrete has the passing ability, L-box height ratio must be equal to or greater 0.8. According to the Table 4.1, all mixtures satisfied the EFNARC [61] limitation given for the L-box height ratio. As clearly seen in Figure 4.5, the mixture M5 with 10%SF (binary use of PC+SF) has the lowest H_2/H_1 ratio of 0.851. While the SCLWC mixtures containing ternary blends of mineral admixtures had H_2/H_1 ratios of 0.950 - 0.975. Thus, the usage of mineral admixtures combined in ternary blends significantly enhanced the passing ability and filling ability of SLWCs.

T_{200} and T_{400} times as mentioned before, to be taken for the mixture to reach a distance of 200 and 400 mm along the horizontal section from the sliding door of the L-box. The test results of L-box are presented in Figure 4.6 and Table 4.1. These results gave some indication about the easy flow of the concrete mixtures with mineral admixtures in comparison with the control mixture. The measured T_{400} of the control concrete was about 9.5 s which lessened to as low as 2.1 and 2.7 s as the FA and SF partially replaced the PC. Moreover, further reduction in these values marked when mineral admixtures in ternary blends put together, counting mainly on the amount and the type of the mineral admixtures used.

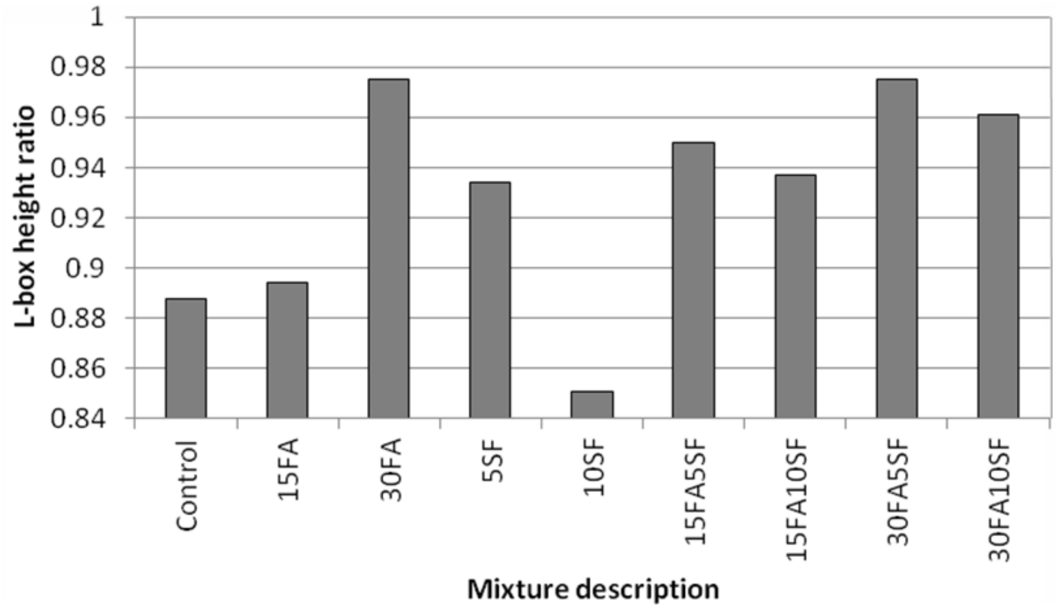

Figure 4.5 Variation of L-box height ratio values

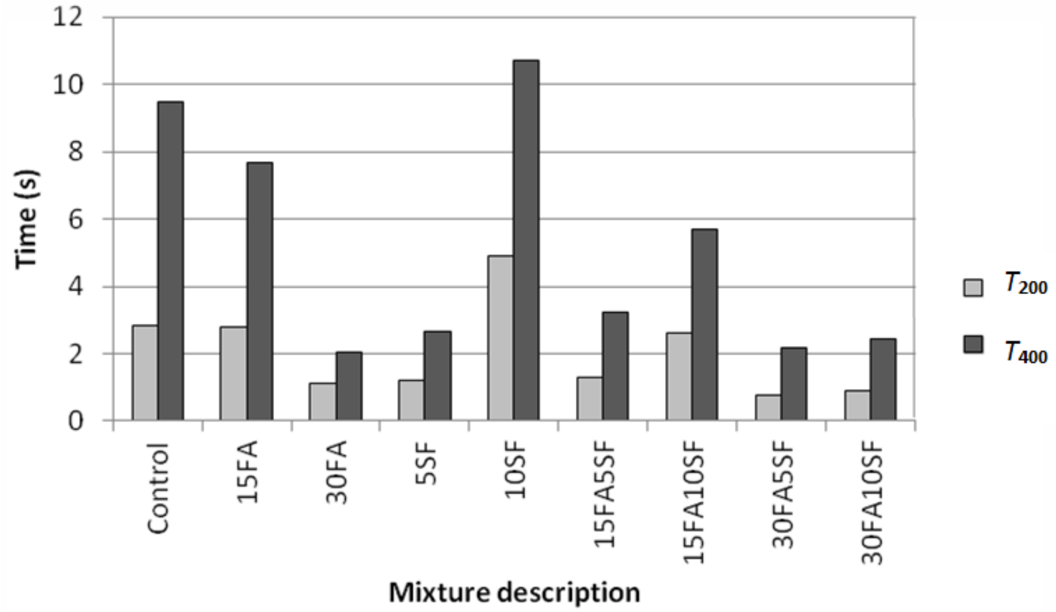

Figure 4.6 Variation of T_{200} and T_{400} time

4.2 Hardened Properties of SCLWCs

4.2.1 Compressive Strength

The variation in the compressive strength of SCLWCs is presented in Table 4.2 and Figure 4.7. Also, Figure 4.8 shows the normalized compressive strength of the SCLWCs with respect to the control specimen. The control concrete specimens had compressive strengths of 48 and 52 MPa at the 28 and 56 days, respectively. The binary use of FA blends caused a reduction in the compressive strength of SCLWCs when the replacement level increased. 30% replacement of FA led to a decrease in the compressive strength approximately 13% at 28 and 56 days. Previous researchers also indicated similar negative effects of FA [73,110,111]. Nevertheless, this negative impact of FA blends marked improvement by the combination utilize of the mineral admixture. The mixtures with ternary use of FA and SF, (15FA5SF) and (15FA10SF) had a compressive strength equal or/and slightly higher than that of the control specimens. As demonstrated in Figure 4.7, the highest compressive strengths of the concretes achieved when SF blends partially replaced with PC blends in binary system with different replacement levels. This incorporation led to a change of approximately 7 to 12% greater than that of the control concrete. The highest strength of as high as 58.3 MPa was measured at 56 days for mixture with binary blends of 10% SF.

4.2.2 Ultrasonic Pulse Velocity

The UPV test is carried out for the assessment of the concrete quality and its integrity by passing the ultrasound waves through the specimen being tested. This test also gives a good indication about the existence of voids, honeycombs or/and cracks, the variation in UPV values is given in Table 4.2 and Figure 4.9.

Furthermore, Figure 4.10 exhibits the normalized UPV values of the SCLWCs with respect to the control specimen. It was found that the control concrete had UPV of 4310 and 4477 m/s for 28 and 56 days, respectively. The UPV values reported for SCLWCs with mineral admixtures ranged from 3962 to 4470 m/s and 4110 to 4630 m/s for 28 and 56 days, respectively, primarily counting on the amount and type of the supplementary mineral materials employed. SCLWC mixtures with binary blends of 5 and 10 % SF demonstrated the highest UPV values, regardless of testing age, while the mixture with ternary blends of 30% FA and 10% SF reported the lowest UPV value. The concrete is categorized as “excellent,” “good,” “doubtful,” “poor,” and “very poor” for UPV values of 4500 m/s and above; 3500 to 4500; 3000 to 3500; 2000 to 3000; and 2000 m/s, respectively [112]. All the produced SCLWCs in this study had UPV values between 3500 to 4500 m/s exception from aforementioned, concretes with binary blends of SF at 56 days had UPV values above 4500 m/s, so the rating of concretes were found to be good and excellent, respectively.

Table 4.2 Compressive strength and UPV values of SCLWCs

Mix No.	Mixture description	Compressive Strength [MPa]		UPV [m/s]	
		28 days	56 days	28 days	56 days
M1	Control-PC	48.0	52.0	4310	4477
M2	15FA	44.6	50.9	4190	4400
M3	30FA	41.7	45.6	4110	4424
M4	5SF	53.0	55.8	4404	4609
M5	10SF	54.0	58.3	4470	4630
M6	15FA5SF	48.2	53.0	4088	4403
M7	15FA10SF	47.9	55.0	3962	4214
M8	30FA5SF	42.5	45.3	4104	4268
M9	30FA10SF	42.9	46.9	3937	4110

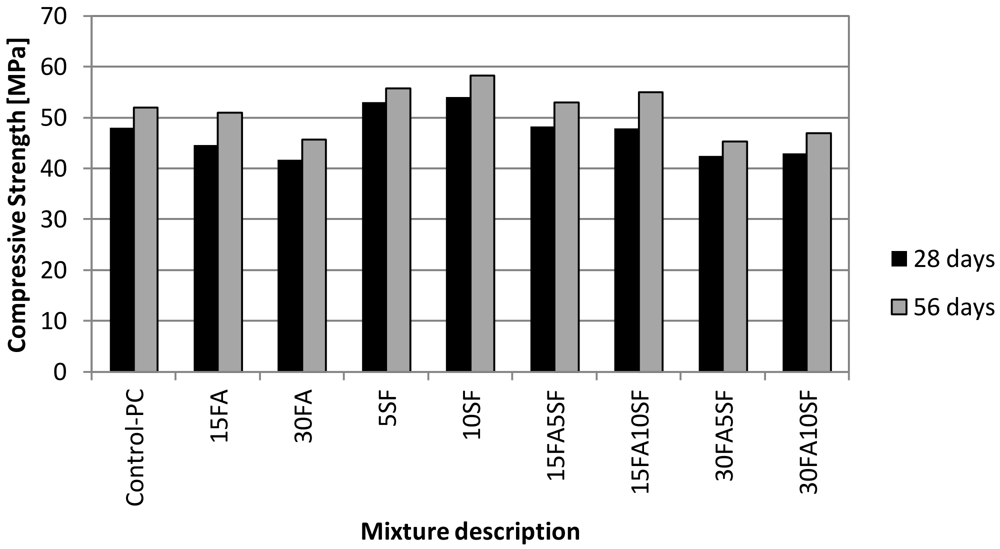

Figure 4.7 Variation in compressive strength of SCLWCs

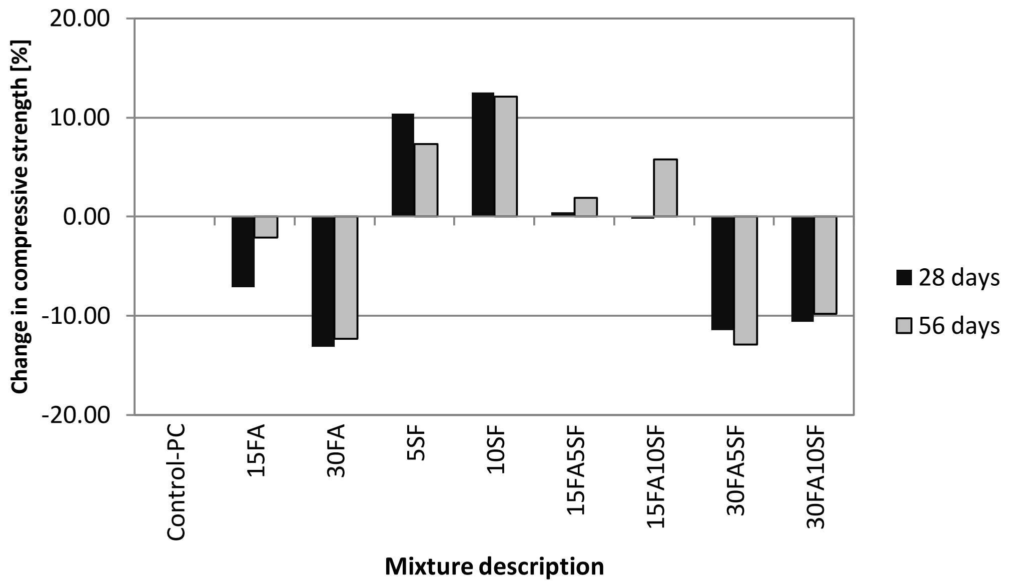

Figure 4.8 Normalized compressive strength of SCLWCs with respect to control specimen

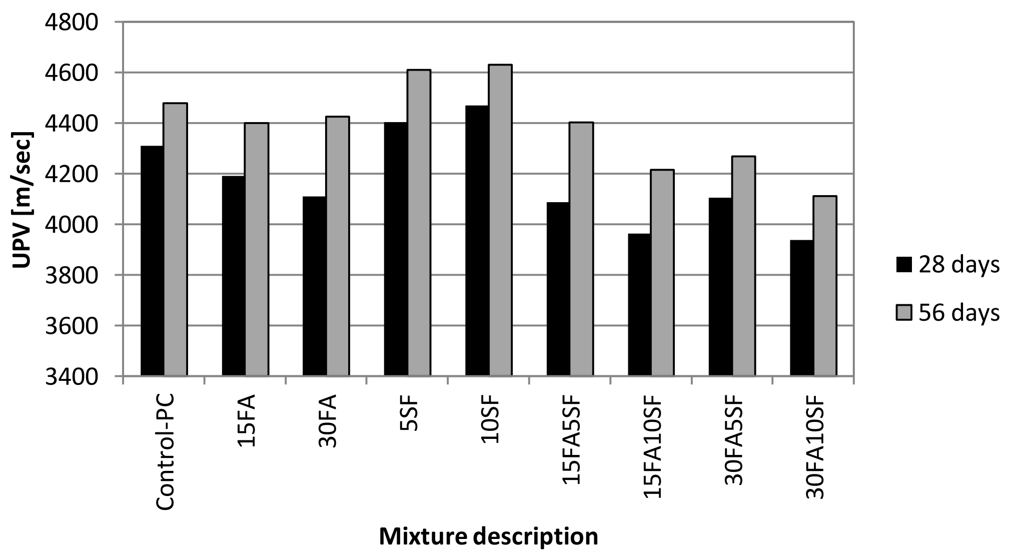

Figure 4.9 Variations in UPV values of SCLWCs

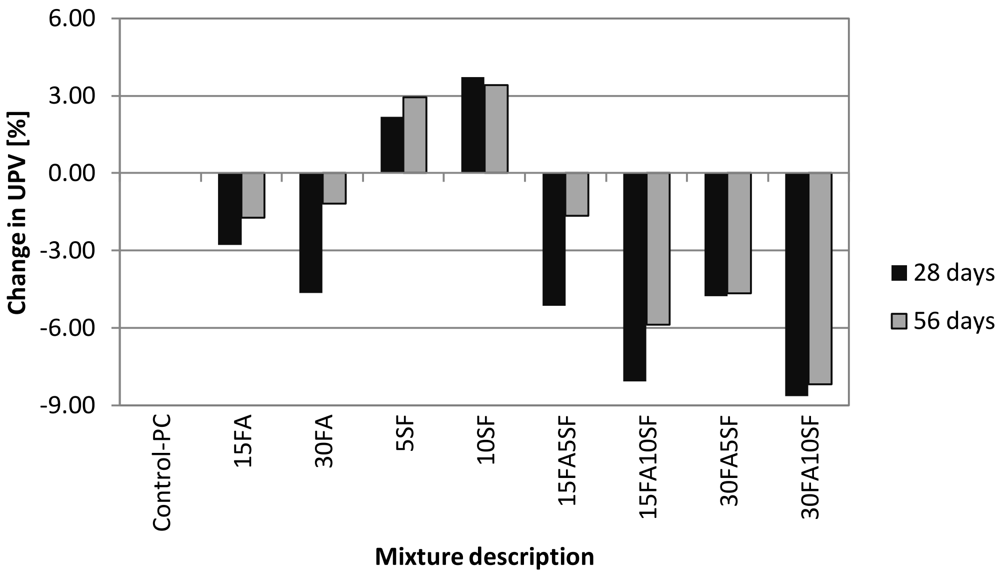

Figure 4.10 Normalized UPV values of SCLWCs with respect to control specimen

4.2.3 Rapid Chloride Permeability

Rapid chloride ion permeability test results of SCLWCs are given in Table 4.3. Figure 4.11 presents the variation in chloride ion permeability of SCLWCs. Also Figure 4.12 shows normalized chloride ion permeability of SCLWCs with respect to concrete specimen. The total charged passed through the control specimens were 3580 and 3005 Columbus at 28 and 56 days, respectively. Nevertheless, they are the lowest resistance to the chloride permeability among the other SCLWC mixtures and being rated as moderate. The incorporation of the mineral admixtures clearly reported a decreasing in the chloride ions permeability of the SCLWCs. Regardless to the testing age, the use of binary blends of FA and SF with different replacement percentages reduced the total charge passed to about (9% to 25%) and (15% to 46%), respectively. From Table 4.3 and Figure 4.12, the mixture with ternary blends of 15% FA and 10% SF at testing age of 56 days marked the highest reduction in chloride ion permeability with a total charge passed of 1336 Columbus which is rated as low. Intriguingly, the total charges passed through the mixture with ternary blends of 30%FA and 5% SF (M8) in both ages were approximately the same as the control specimen. The low permeability of the concretes with mineral admixtures may be attributed to transformation large pores to fine pores or pore refinement [113-116].

Table 4.3 Chloride ion permeability of SCLWCs at 28 day and 56 days

Mix No.	Mixture description	Chloride ion permeability at 28 days		Chloride ion permeability at 56 days	
		Charged passed, coulombs	Rating	Charged passed, coulombs	Rating
M1	Control-PC	3580	Moderate	3005	Moderate
M2	15FA	3271	Moderate	2664	Moderate
M3	30FA	3135	Moderate	2247	Moderate
M4	5SF	3043	Moderate	2083	Moderate
M5	10SF	1923	Low	1753	Low
M6	15FA5SF	2423	Moderate	1933	Low
M7	15FA10SF	1633	Low	1336	Low
M8	30FA5SF	3449	Moderate	3000	Moderate
M9	30FA10SF	2725	Moderate	2347	Moderate

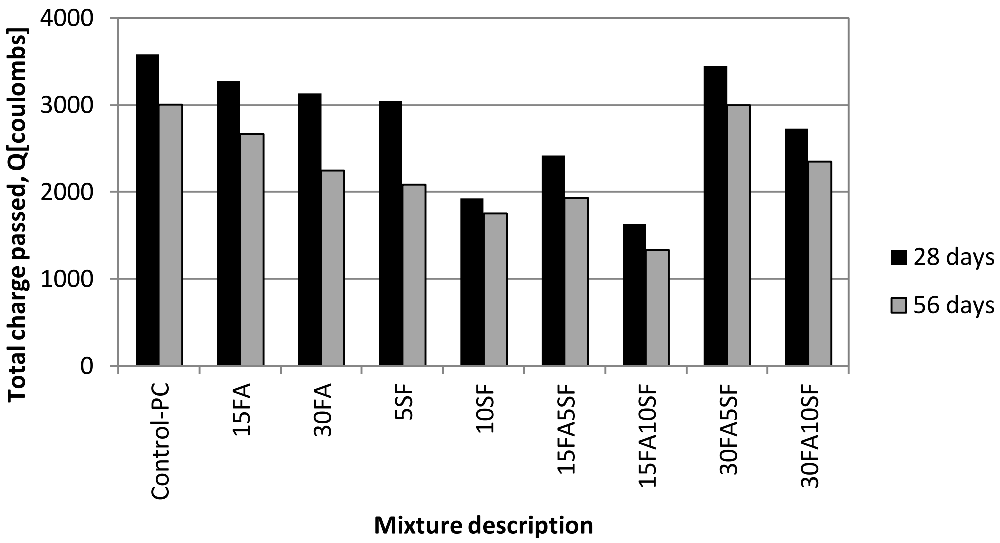

Figure 4.11 Variation in chloride ion permeability of SCLWCs

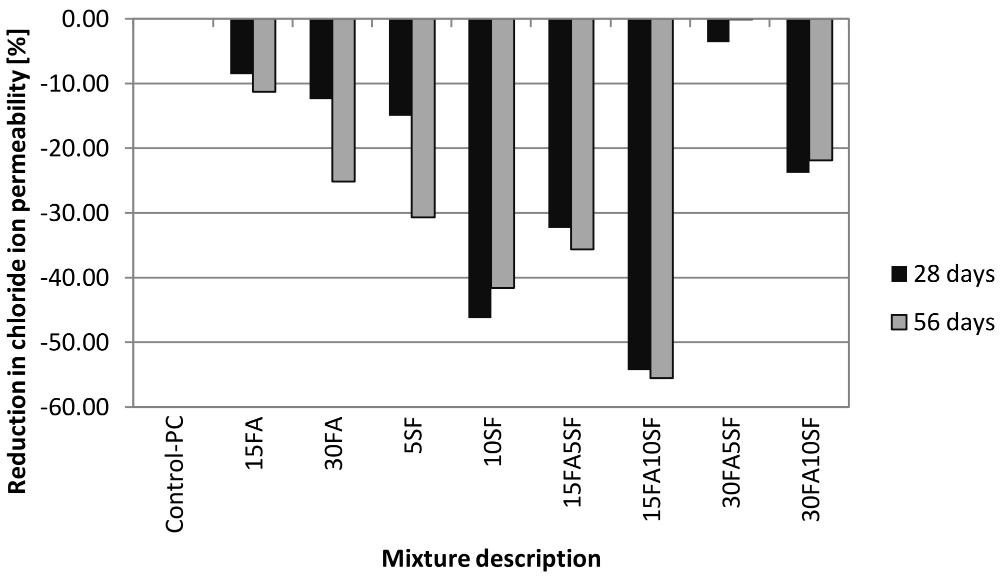

Figure 4.12 Normalized chloride ion permeability of SCLWCs with respect to control specimen

4.2.4 Gas Permeability

The apparent gas permeability calculation was carried out on the basis of the Hagen-Poiseuille relationship for laminar flow of a compressible fluid through a porous body with small capillaries under steady-state conditions [117]. RILEM [100] recommends the use of 150, 200 and 300 kPa inlet pressures for determination of the average gas permeability coefficient. Thus, the coefficients of apparent gas permeability determined at the ages of 28 and 56 days according to RILEM on SCLWC specimens are presented in Tables 4.4 and 4.5 respectively. Figure 4.13 shows the variation in apparent gas permeability. Moreover, the normalized apparent gas permeability of SCLWCs with respect to control specimen is exhibited in Figure 4.14. It was observed that the permeability coefficients for the control specimens were found to be 15.3-13.5 ($x10^{-16}$) m^2 at 28 and 56 days, respectively. The use of SF blends in the binary system with both 5% and 10% percentage of replacement seemed to be very effective in the reduction of the apparent gas permeability coefficients and this positive effect noticed even in the early age of 28 days. However, SCLWC mixture with 15% FA replacement level of blends marked a lowest reduction among the SCLWCs. In general, the combination use of FA and SF together in the ternary system enhanced the quality of SCLWCs in term of apparent gas permeability. For instance, the SCLWC mixture comprising 30% FA and 10% SF marked a highest decrease as high as approximately 85% at testing age of 56 days.

To evaluate the behavior of concrete according to the inlet pressure head (P1), Figure 4.15 and 4.16 are plotted for both testing ages of 28 and 56 days. In this figures, the coefficients of apparent gas permeability of the concretes incorporated with mineral admixture were varied with the inlet pressure of 150 to 500 kPa. The apparent gas permeability calculation was carried out on the basis of the previously mentioned equation. It was observed from the figures that the gas permeability coefficient had a tendency to diminish up to 350 kPa and then began to be stable with slight drop and increase after the inlet pressure of 350 kPa depending on the type of the mineral admixture used. However, the profile drawn for 56 days showed more stability and steadiness for the behavior of gas permeability coefficients after pressure level of 300 kPa.

Table 4.4 Gas permeability values of SCLWCs at 28 days

Pressure level (KPa)	Gas permeability, K_a x10^{-16} [m^2]								
	Control	15FA	30FA	5SF	10SF	15FA5SF	15FA10SF	30FA5SF	30FA10SF
150	22.01E-16	21.60E-16	13.5E-16	6.39E-16	3.63E-16	13.4E-16	3.66E-16	5.82E-16	4.27E-16
200	16.03E-16	11.91E-16	9.91E-16	2.26E-16	2.08E-16	9.44E-16	2.26E-16	3.11E-16	2.13E-16
250	10.04E-16	9.23E-16	8.19E-16	1.51E-16	1.66E-16	8.10E-16	1.73E-16	2.24E-16	1.70E-16
300	7.84E-16	8.71E-16	6.49E-16	1.34E-16	1.47E-16	6.87E-16	1.47E-16	1.78E-16	1.56E-16
350	6.34E-16	7.82E-16	4.75E-16	1.36E-16	1.37E-16	5.87E-16	1.26E-16	2.05E-16	1.45E-16
400	5.57E-16	7.62E-16	3.57E-16	1.26E-16	1.37E-16	5.37E-16	1.43E-16	2.49E-16	1.411E-16
450	5.44E-16	6.75E-16	3.08E-16	1.15E-16	2.92E-16	5.07E-16	1.23E-16	2.41E-16	1.37E-16
500	5.22E-16	7.27E-16	3.45E-16	1.32E-16	3.33E-16	4.97E-16	1.16E-16	2.35E-16	1.37E-16
Average	15.30E-16	14.10E-16	9.96E-16	3.33E-16	2.39E-16	9.91E-16	2.47E-16	3.57E-16	2.66E-16

Table 4.5 Gas permeability values of SCLWCs at 56 days

Pressure level (KPa)	Gas permeability, K_a x10^{-16} [m^2]								
	Control	15FA	30FA	5SF	10SF	15FA5SF	15FA10SF	30FA5SF	30FA10SF
150	20.6E-16	18.6E-16	7.01E-16	4.18E-16	3.39E-16	13.4E-16	3.42472E-16	4.38E-16	2.99E-16
200	12.0E-16	11.3E-16	4.72E-16	2.77E-16	2.09E-16	9.44E-16	2.00526E-16	2.47E-16	1.80E-16
250	9.68E-16	9.08E-16	4.12E-16	1.35E-16	1.51E-16	7.10E-16	1.51717E-16	1.87E-16	1.18E-16
300	8.07E-16	7.70E-16	3.47E-16	1.73E-16	1.34E-16	5.63E-16	1.26215E-16	1.59E-16	1.14E-16
350	7.76E-16	7.26E-16	3.28E-16	1.25E-16	1.36E-16	5.57E-16	1.14157E-16	1.51E-16	1.00E-16
400	6.86E-16	6.46E-16	3.12E-16	1.36E-16	1.26E-16	5.37E-16	1.06425E-16	1.38538E-16	1.28E-16
450	7.15E-16	7.05E-16	3.23E-16	9.70E-17	1.15E-16	5.07E-16	1.05278E-16	1.3751E-16	1.25E-16
500	6.90E-16	6.30E-16	3.55E-16	2.41E-16	1.32E-16	4.97E-16	0.964069E-16	1.44962E-16	2.00E-16
Average	13.5E-16	12.5E-16	5.07E-16	2.90E-16	2.28E-16	9.50E-16	2.23E-16	2.81E-16	1.98E-16

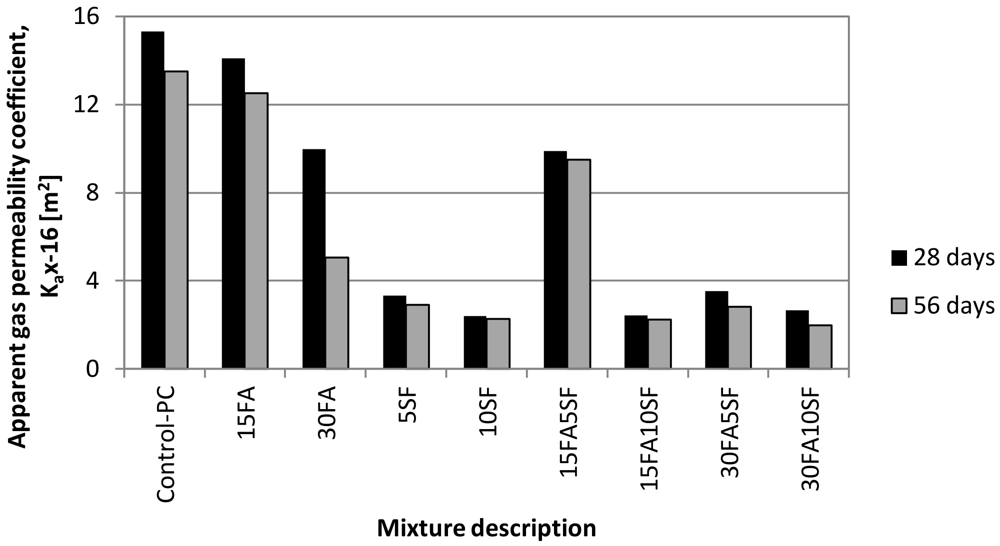

Figure 4.13 Variation in apparent gas permeability of SCLWCs

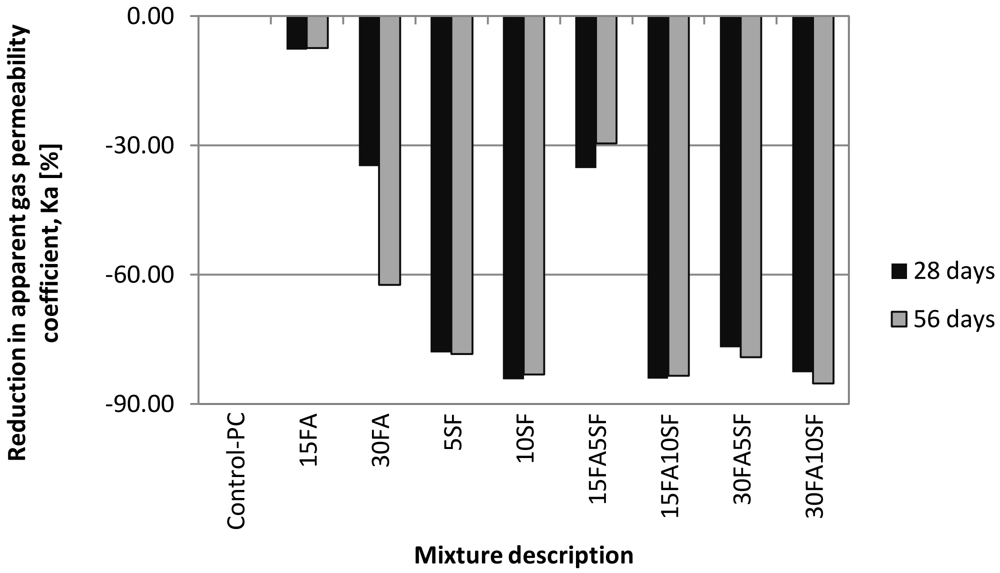

Figure 4.14 Normalized gas permeability of SCLWCs with respect to control specimen

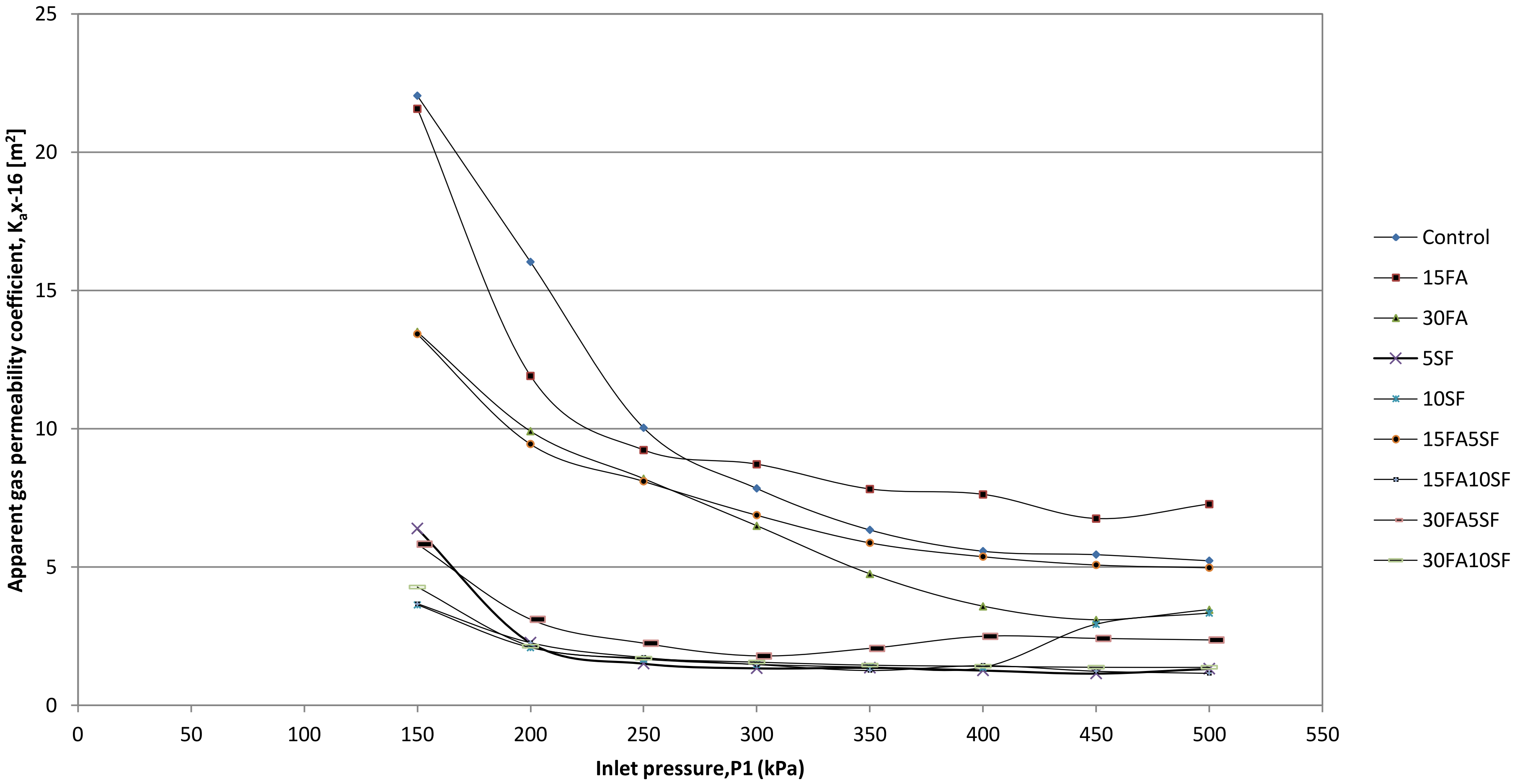

Figure 4.15 Variation in apparent gas permeability of SCLWCs concretes with inlet pressure at 28 days

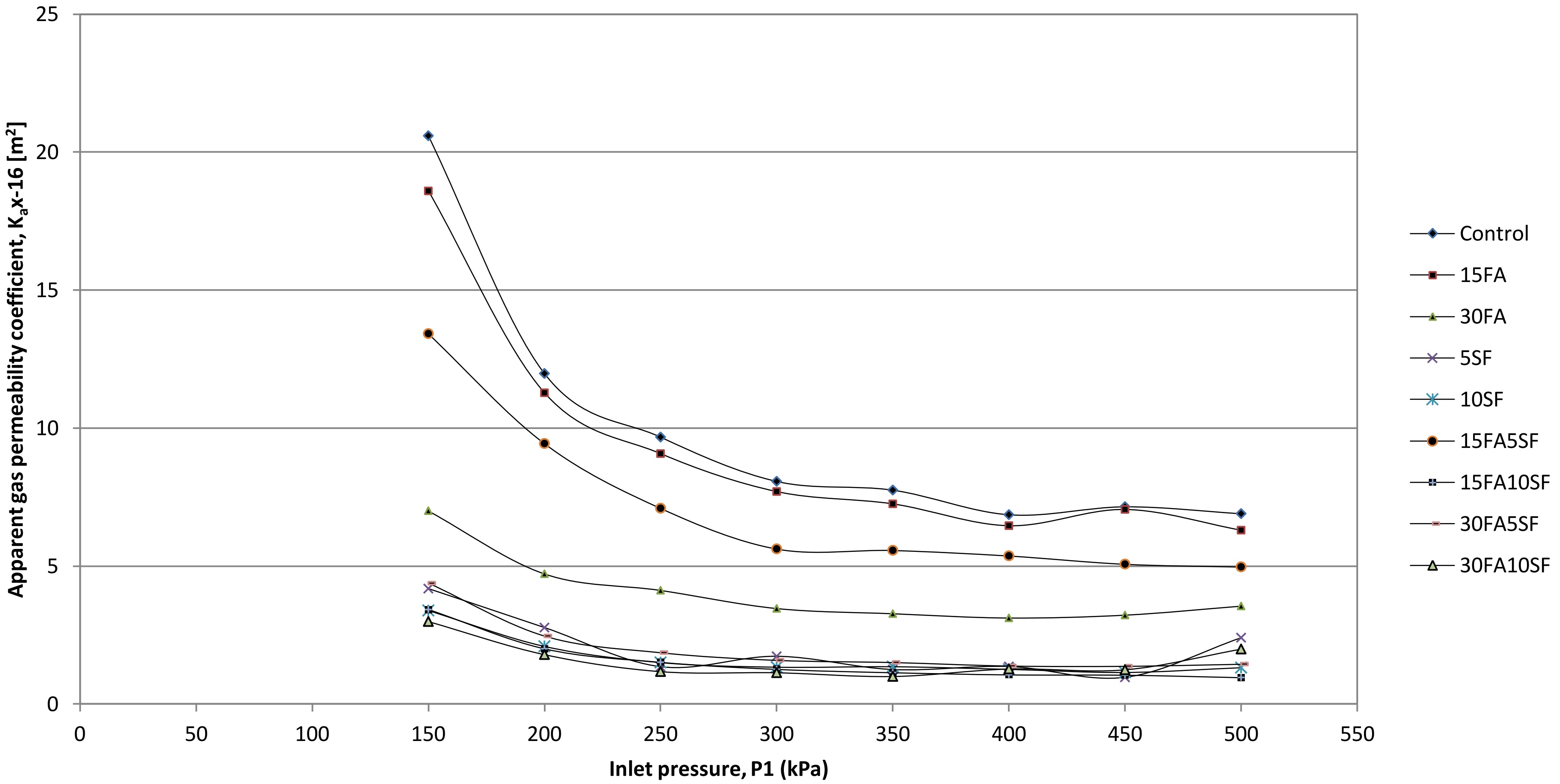

Figure 4.16 Variation in apparent gas permeability of SCLWCs with inlet pressure at 56 days

4.2.5 Sorptivity

The sorptivity test depends on the moving water into the concrete across big joined pores [116]. Table 4.6 Figure 4.17 presents the results of water sorptivity of SCLWCs. In addition, the normalized water sorptivity of SCLWCs with respect to the control specimen displayed in Figure 4.18. Sorptivity of the concretes comprising mineral admixtures was lower than that of control concrete, though, consecutively lessened the sorptivity of SCLWCs. The use of FA and SF blends together in the ternary system seemed to be the most effective in the reduction of sorptivity index. For example, the lowest sorptivity index was measured for concretes with the ternary blends of 30% FA and 5% SF at the testing age of 56 days. As seen in the Figure 4.17 and Figure 4.18, there is a drop in the sorptivity index even in the age of 28 days; however, it is more visible and much greater in the age of 56 days.

The reduction in sorptivity mirrors a tiny pore structure that would, for example, inhibit ingress of aggressive elements into the pore system [90]. For this reason, minimizing sorptivity is important in order to reduce the ingress of chloride-containing or sulphate-containing water into concrete, which can cause serious damage [118].

Table 4.6 Water sorptivity and water absorption values of SCLWCs

Mix No.	Mixture description	Water Sorptivity [mm/min$^{0.5}$]		Water Absorption [%]	
		28 days	56 days	28 days	56 days
M1	Control-PC	0.182	0.169	6.0	5.6
M2	15FA	0.179	0.147	5.8	4.6
M3	30FA	0.146	0.143	5.6	4.8
M4	5SF	0.176	0.138	5.6	4.9
M5	10SF	0.145	0.133	5.4	4.3
M6	15FA5SF	0.154	0.134	5.6	3.5
M7	15FA10SF	0.140	0.124	5.2	3.4
M8	30FA5SF	0.168	0.119	5.3	4.6
M9	30FA10SF	0.152	0.130	5.1	4.2

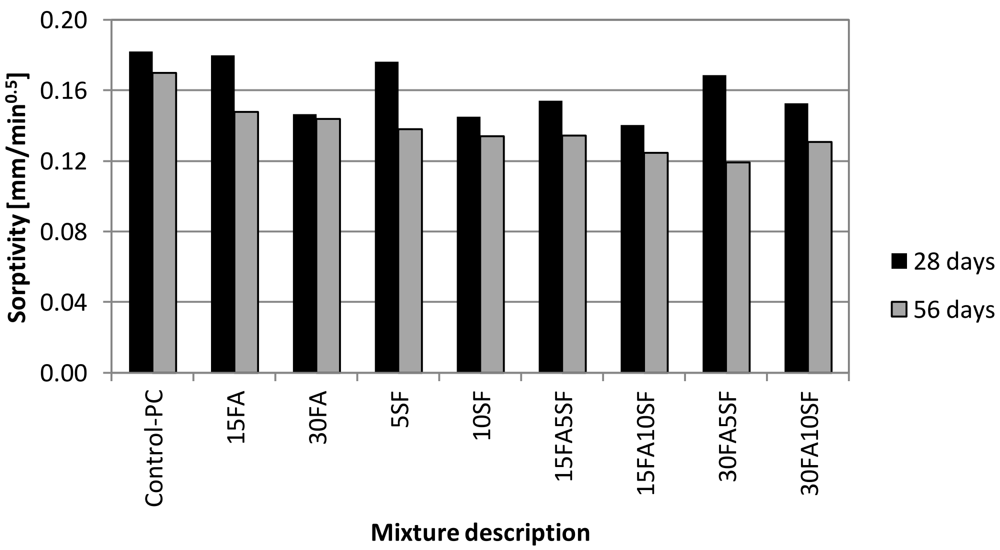

Figure 4.17 Variation in water sorptivity of SCLWCs

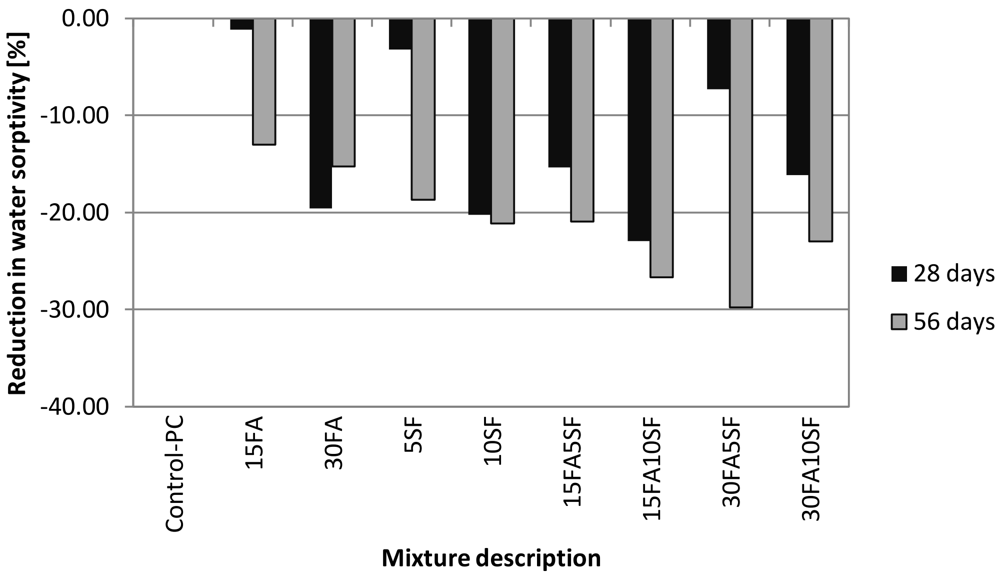

Figure 4.18 Normalized water sorptivity of SCLWCs with respect to control specimen

4.2.6 Water Absorption

The variations in water absorption of SCLWCs are depicted in Table 4.6 and Figure 4.19 and also the normalized values with respect to the control specimen given in Figure 4.20. It is clear that the rate of water absorption decreases systematically with an increase in curing period (from 28 to 56), and there is a tendency of reduction when mineral admixtures are incorporated. The water absorption values for the control specimens were 6% and 5.6% at 28 and 56 days, respectively. However, noticeable decline marked with the existence of FA and SF blends in binary system. SCLWC mixture with 15% FA replacement level (M2) at 56 days had water absorption rate less than that in control specimen by 1.2 times, while for SCLWC mixture with 10 SF replacement level (M4) at 56 days was 1.3 times less than the control specimen. The aforementioned figures also illuminate the benefit of combing FA and SF in ternary system, which reported the lowest absorption rates. For example, SCLWC with 15%FA and 10%SF (Mixture M7) at the age of 56 days had absorption rate 1.6 times less than that of the control specimen.

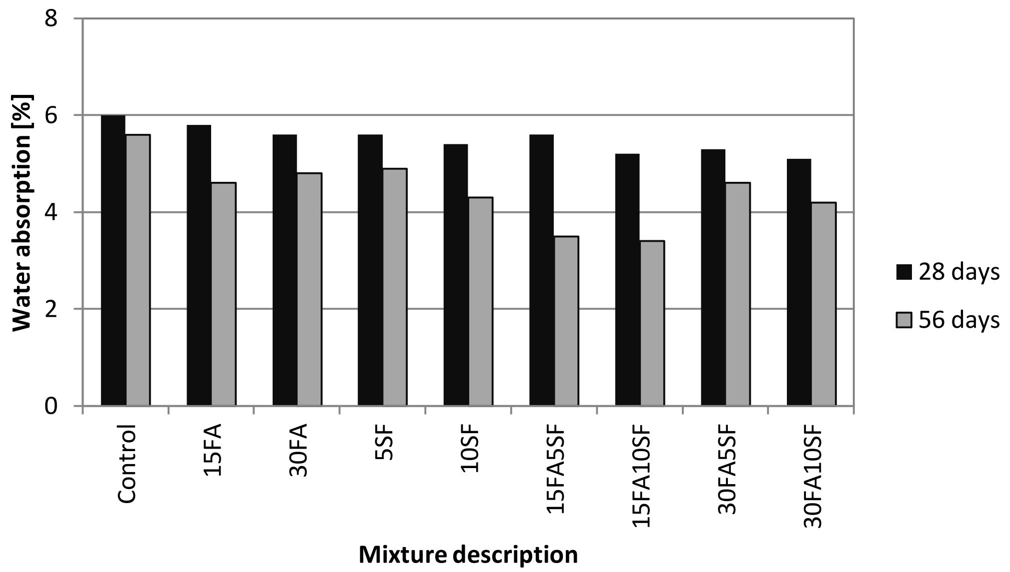

Figure 4.19 Variation in water absorption of SCLWCs

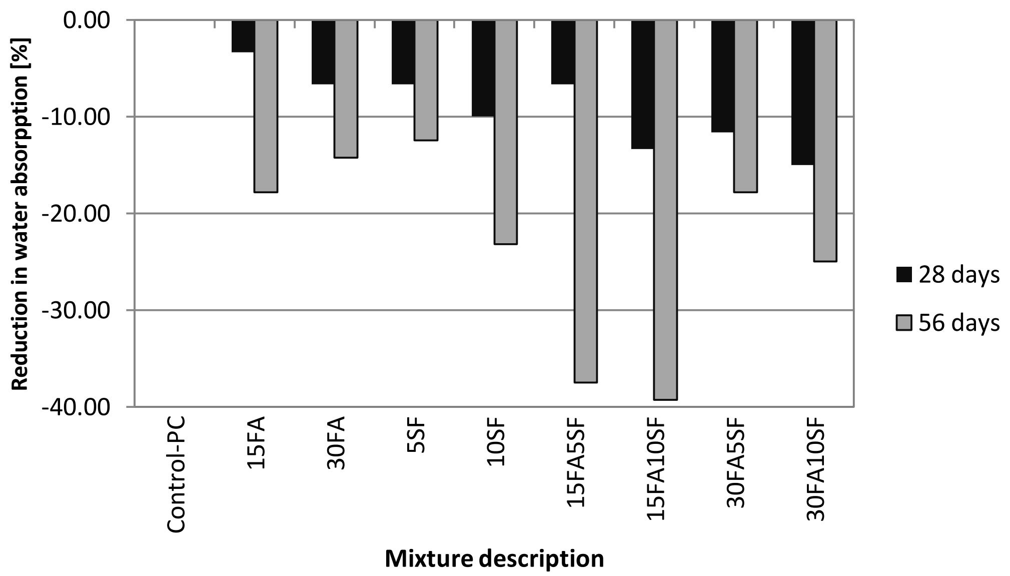

Figure 4.20 Normalized water absorption of SCLWCs with respect to control specimen

CHAPTER 5

CONCLUSIONS

Depending on the experimental results obtained from this study, the following may be concluded:

- All the concrete mixtures designed to have a slump flow diameter between 660 and 750 mm which was acquired by using different dosage of superplasticizer. Using SF in the binary blends apparently increased the need of superplasticizer of the mixtures whereas with the use of FA, a slight fall was observed in the amount of superplasticizer used.
- Incorporating the mineral admixtures improved fresh properties of SCLWCs. Slump flow time of the concretes except mixture M5 (10SF) containing any of the mineral admixtures was shorter than that of the control mixture with only PC.
- Using SF with 10% replacement shows a visible increase in the V-funnel flow times in the produced concretes. However, this negative effect is reduced in the combined usage of ternary blends of FA and SF.
- All the mixtures with ternary blends showed increased L-box height ratios which led to improve the passing and filling ability of SCLWCs. likewise, the T_{200} and T_{400} times were less than that of the control mixture.
- In general, all SCLWCs containing FA blends had lower compressive strength, whereas SCLWCs with SF blends had comparable and higher strength amount than those of the control concrete, respectively. The ternary use of FA and SF blends in mixtures 15%FA and 5%SF (Mixture M6) and

15%FA and 10%SF (Mixture M7) enhanced the compressive strength and gives the SCLWCs an equal or slightly higher compressive strength than those containing binary blends of FA and the control concretes, respectively.

- All the produced SCLWCs in this study had UPV values between 3500 to 4500 m/s exception from aforementioned, concretes with binary blends of SF at 56 days had UPV values above 4500 m/s, so the rating of concretes were found to be good and excellent, respectively. Using binary blends of 5 and 10 % SF in SCLWC mixtures, showed the highest UPV values, irrespective to the testing age.
- It was observed in chloride ion permeability that the control specimens at both testing ages, marked the lowest resistant to the chloride ion permeability with "medium" rating. Though, the addition of minerals clearly showed an effective decrease in the chloride ion permeability. SCLWC mixture with 15% FA and 10% SF at 56 days demonstrated the highest drop in chloride ion permeability with "low" rating. In contrast to the SCLWC mixture 30%FA and 5% SF blends in both ages had a passing charge approximately the same as the control specimen.
- It is proved that incorporation of mineral admixtures is efficient in the reduction of apparent gas permeability. For instance, the use of SF blends in the binary system with both 5% and 10% replacement level reported sharp decreasing in both testing ages of 28 and 56 days compared with the control specimens. However, SCLWC mixture with 15% FA replacement level of blends marked a lowest reduction among the SCLWCs. Combination of blends in ternary system improved the quality of SCLWCs in term of apparent gas permeability at which, the comprising 30% FA and 10% SF

marked a highest decrease as high as approximately 85% at testing age of 56 days.

- Utilizing any of the mineral admixtures in the production of SCLWCs reduced the sorptivity index. Accordingly, enhanced the durability of the concretes. Results proved that there is a drop in the sorptivity index even in the age of 28 days; however, it is more visible and much greater in the age of 56 days. The lowest sorptivity index was measured for SCLWCs containing ternary blends of 30% FA and 5% SF at 56 days.
- It is clear that the rate of water absorption decreases systematically with an increase in curing period (from 28 to 56), and there is a tendency of reduction when mineral admixtures are incorporated. The ternary use of FA and SF showed more reduction in the water absorption compared with binary use of FA, at the age of 56 days. Like SCLWC with 15%FA and 10%SF (Mixture M7) at the age of 56 days had absorption rate 1.6 times less than that of the control specimen.

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