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INITIAL AND FINAL SETTING TIME OF SELF-COMPACTING MORTARS WITH COLD BONDED FLY ASH FINE AGGREGATE

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Hussein Ghanim HASAN

ABSTRACT

INITIAL AND FINAL SETTING TIME OF SELF-COMPACTING MORTARS WITH COLD BONDED FLY ASH FINE AGGREGATE

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The current study experimentally investigated the effect of the artificial lightweight aggregate and the water-to-binder ratio on the initial and final setting times of self-compacting mortars. The artificial lightweight aggregates used in this study were manufactured through cold bonding pelletization of 90% of class-F fly ash and 10% of Portland cement in a tilted pan with an ambient temperature and moisture content. The self-compacting mortars were designed at four binder contents of 540 kg/m³, 520 kg/m³, 500 kg/m³, and 480 kg/m³ at four different water-to-binder ratios of 0.33, 0.37, 0.40, and 0.44, respectively. In each water-to-binder ratio, the natural aggregate was substituted with the artificial lightweight aggregate at the replacement levels of 0%, 20%, 40%, and 60%. Totally, 16 self-compacting mortar mixtures were designed and produced. Slump flow diameter, V-funnel flow time, initial and final setting times were experimentally investigated as fresh properties while the compressive strength of the mortar mixtures were measured at 5 different ages of 3-day, 7-day, 28-day, 56-day, and 90-day. Test results showed that both initial and final setting times of the self-compacting mortars were significantly affected by the water-to binder ratio. Addition to the setting times, the slump flow diameter and V funnel flow time was influenced by both the water-to-binder ratio and the artificial lightweight aggregate content. Moreover, the compressive strength results indicated that increasing the artificial lightweight aggregate content systematically decreased the compressive strength of the mortar mixtures at aforementioned testing ages whereas decreasing the water-to-binder ratio increased the compressive strength.

Keywords: Cold bonding pelletization; Fly ash; Fresh properties; Self-compacting mortar; Setting time.

ÖZET

SOĞUK BAĞLAMA YÖNTEMİ İLE ÜRETİLMİŞ UÇUCU KÜL İNCE AGREGALI KENDİLİĞİNDEN YERLEŞEN HARÇLARIN PRİZ BAŞLAMA VE BİTİŞ SÜRELERİNİN İNCELENMESİ

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Mevcut çalışma yapay hafif agreganın ve su bağlayıcı oranının kendiliğinden yerleşen harçların priz başlangıç ve bitiş süreleri üzerine etkisini deneysel olarak incelemektedir. Bu çalışmada kullanılan yapay hafif agregaları %90 uçucu kül ile %10 Portland çimentosunun eğimli bir tamburda uygun sıcaklık ve nem oranında soğuk bağlama yöntemiyle üretildi. Kendiliğinden yerleşen harçlar 540 kg/m³, 520 kg/m³, 500 kg/m³ ve 480 kg/m³ olmak üzere dört bağlayıcı miktarında sırasıyla 0.33, 0.37, 0.40 ve 0.44 olmak üzere dört farklı su bağlayıcı oranında tasarlandı. Her bir su bağlayıcı oranında, doğal agrega %0, %20, %40 ve %60'lık oranlarda yapay hafif agrega ile yer değiştirildi. Toplamda 16 kendiliğinden yerleşen harç karışımı tasarlandı ve üretildi. Yayılma çapı, V hunisi akma zamanı ve priz başlangıç ve bitiş süreleri taze özellik olarak incelenirken harçların basınç dayanımı 3 günlük, 7 günlük, 28 günlük, 56 günlük ve 90 günlük olmak üzere 5 farklı yaşta ölçüldü. Deney sonuçları kendiliğinden yerleşen harçların hem priz başlangıç hem de bitiş sürelerinin su bağlayıcı oranından önemli bir şekilde etkilendiğini gösterdi. Priz sürelerine ek olarak, yayılma çapı ve V hunisi akma süreleri de hem yapay hafif agrega miktarından hem de su bağlayıcı oranından etkilendi. Basınç dayanımı sonuçları da yapay hafif agrega miktarının arttırılmasının sistemli bir şekilde harç karışımlarının yukarıda bahsedilen yaşlardaki basınç dayanımını düşürdüğünü, su bağlayıcı oranın azaltılmasının ise basınç dayanımını arttırdığını gösterdi.

Anahtar kelimeler: Soğuk bağlamayla peletleme; Uçucu kül; Taze özellikler; Kendiliğinden yerleşen harç; Priz süresi.

To precious spirits of my mother and father

They were cared and supported me in all condition…

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LIST OF SYMBOLS/ ABREVIATIONS

AAs	Artificial Aggregate
AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
AFA	Artificial Fly Ash Aggregate
ASA	Artificial Slag Aggregate
ASTM	American Standard for Testing Material
BSI	British Standards Institution
C-S-H	Calcium-Silica-Hydrated (Gel)
EDX	Energy-dispersive X-ray spectroscopy
FA	Fly Ash
FM	Fineness Modulus
HPC	High Performance Concrete
HSC	High Strength Concrete
IN	Internal Curing
ITZ	Interfacial Transition Zone
LWA	Lightweight Aggregate
LWCA	Lightweight Coarse Aggregate
NCA	Natural Coarse Aggregate
NFA	Natural Fine Aggregate
NA	Natural Aggregate

NSC	Normal Strength Concrete
NWA	Normal Weight Aggregate
PC	Ordinary Portland Cement
SEM	Scanning Electron Microscopy
SP	Superplasticizer
SSD	Saturated Surface Dry Aggregate
W/B	Water/Binder Ratio
W/C	Water/Cement Ratio

CHAPTER 1

INTRODUCTION

1.1 General

In the last decades, the investigating of self-compacting concrete (SCC) with cold bonded fly ash properties has attracted the interests of the researchers. Self-compatibility mortar (SCM), as an integral part of SCC, may serve as an essential for the design of concrete (EFNARC, 2005). The properties of mortars in the fresh state can be pointedly influenced by the specific gravity, shape, particle size distribution, and surface texture of the aggregates used. For this, aggregates have remarkable effect on both fresh and mechanical properties of mortar. Hence, more investigation is needed to better understand the effect of using different type of aggregate (Gonçalves et al., 2007). Aggregate is considering the main occupants of concrete (occupied about 65%-75% of concrete volume); so the use of such waste materials as artificial aggregates (AAs) in concrete deemed as an effective solution to preserve the environment.

AAs are manufacture through processing of different materials and production methods like cold bonding pelletization and sintering (Güneyisi et al., 2012; Arslan and Baykal, 2006; Gesoğlu, 2004; Dongxu et al., 2002, Cheeseman and Virdi, 2005; Joseph and Ramamurthy, 2009; Güneyisi et al., 2012). Cold bonding is a kind of bonding technique that activates the ability of pozzolanic powder material to react with Portland cement to form a bonding material at normal temperatures.

Pelletized aggregates are left for several days to cure in order to gain proper strength (Koçkal, 2008). On the other hand, method of sintering, which is mainly based on atomic diffusion, is a diffuse application for mass production of lightweight aggregates (LWA). Immediately after pelletization process, aggregate particles are treated with high temperatures (higher than 1200C^{o}), then, it become ready for use in concrete without spends a long term curing periods.

In Turkey, although huge amount of fly ash (FA) exist as a result of industrial process (up to 15 million tons per year), only a small portion is utilized in the construction field (Turkish Standard Institute, 2010). Therefore, using FA in the production of AAs can be considered as an effective way for recycling and reserving the environmental. Although general trend for production of AAs is governed by sintering method, the energy saving aspects led the researchers to employ the cold-bonding pelletization process rather than others.

In the manufacturing process of cold bonded aggregate, the quantity and type of binder has an essential effect on the characteristics of final products (Cheeseman and Vindi, 2005; Güneyisi et al., 2012; Koçkal, 2008; Koçkal et al., 2011; Geetha and Ramamurthy, 2011; Ramamurthy and Harikrishnan, 2006). In the study of Koçkal (2008), it was reported that through the production of sintered fly ash aggregate, the using of 10% bentonite at 1200 C^{o} produced high strength and low specific gravity aggregate. Also, Geetha and Ramamurthy (2006) proposed that 10% bentonite provided optimum properties for aggregate at sintering temperature of 1000 C^{o} and duration of about 95 min by using different types of clay binders for sintering process.

Moreover, the natural and crushed fine aggregate had a great influence on the water demand, workability and rheology of the mortar (Westerholm et al., 2008). Furthermore, the experimental results clearly showed that the particle shape of the fine aggregate considerably contributed to the plastic viscosity. However, for the same water content and/or volume of cement past, the angular shape of fine aggregate produced lower workability concrete than spherical sands (Menikov, 1970; Westerholm, 2006). Hence, the use of AAs in the production of SCM did not find an adequate attention yet. Since artificial light weight aggregates (LWA) has relatively lower strength than natural aggregates (NA). Moreover, the concretes containing LWA may have less mechanical properties than equivalent NA (Koçkal and Özturan, 2011).

1.2 Research Objectives

The main objective of the present study was to investigate the initial and final setting time of self-compacting mortar (SCM) incorporated lightweight fly ash fine aggregates (LWFA) which was produced via cold bonding palletization method. For this, totally sixteen mortar mixtures were designed through partially replaced the natural fine aggregate (NFA) by LWFA with varied percentage (0, 20, 40 and 60%). Then, the fresh properties of SCM was tested through initial and final setting time, mini-slump flow, mini V-funnel. Moreover, the hardened properties of SCM was evaluated in the terms of compressive strength.

1.3 Outline of the Thesis

Chapter 1 - presents the introduction as well as the aim and objectives of the thesis are introduced.

Chapter 2 - presents a literature review and general background information about

properties of FA, NA and AAs. The production of AAs as well as definition, theory of pelletization and the product of palletization lightweight aggregates are briefly introduced. Moreover, general information about the mix design, properties and advantages of SCC is presented in this chapter. Effect of AAs on mortar and/or concrete are discussed as well as advantages and disadvantages of it.

Chapter 3 - The properties of the materials used to produce SCM in this chapter are described. Mixture proportions, preparation and casting of test specimens and test methods also present in this chapter as well as sintering and cold bonding process of AAs.

Chapter 4 - Presents the results of fresh and hardened tests for SCM produced in this study.

Chapter 5 - Conclusion of the thesis is given in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Fly Ash (FA)

Pozzolans, alumina or siliceous materials, keep little or not any cementitious effect. At any temperature, the particles shape, existence of humidity and the reaction of calcium hydroxide evaluate the cementitious features of this material. However, FA deemed as one of the most useful pozzolans material around the world. Actually, it is inorganic waste product manufactured during the firing of coal pieces at nearly 1200C^{o} in thermal power stations. The reacting between FA and $Ca(OH)_2$ at room temperature will form the cementitious composites. Therefore, the presence of SiO_2 and Al_2O_3 as amorphous form will effects on the pozzolanic activity of FA (Baker, 1984; Naik and Singh, 1995; Baykal et al., 1997). Moreover, the characteristics of FA depend on many factors such as the composition of feed coal, the type of power plant, chemical composition of the coal and burning system and conditions of deposition of FA.

2.1.1 Mineralogical Properties of FA

Mainly, FA contains rounded or spherical glassy shape particles of dissimilar iron oxide content such as alumina, and silica. The microscopy analysis revealed that FA particles contained not only irregular and angular particles but also metal particles and unburned coal remnants. Hence, the mineral compositions of FA are strongly

dependent on the coal composition, the cooling system, burning conditions and ash collection systems. The essential minerals in FA comes from bituminous coal are magnetite, hematite, quartz, mullite and free CaO. The most of minerals available in A (about 50-90%) are formed as crystals or glassy shape. While, the other minerals like goethite, pyrite, calcite, and anhydrite particles represent about 2.5% (Ramadan, 1995; Döven, 1996; Gesoğlu, 2004).

2.1.2 Chemical Properties of FA

The main components of FA are silica (SiO_2), alumina (Al_2O_3) and iron oxide (Fe_2O_3). The silica and alumina are forms as amorphous spherical and crystalline shape, respectively. Basically, FA consist of a blend of glassy particles with crystalline phases such as quartz, mullite as well as alkali oxides such as MgO and SO_3, which are considerably heterogeneous. However, the chemical structure of FA varies according to the coal source. Consequently, silica and alumina may be considered the main components of FA (Satapathy, 2000; Matsunaga et al., 2002).

Depending on its chemical compositions including calcium, silica, alumina, and iron content, fly ash is classified into two class; Class F and Class C with respect to ASTM C 618 ((2000). Class F fly ash involved only in pozzolanic reaction because it need a cementing agent such as Portland cement, quicklime and hydrated lime. This type of FA is also known as low calcareous ash because it has less than 10% of CaO. However, Class C fly ash generated from the igniting of younger lignite or sub bituminous coal includes more than 20% lime (CaO). This type of FA is classified as pozzolanic cementitious material and it can be strengthen in the presence of water. In general, Class C has higher $CaO+MgO+SO_3$ and lower $Al_2O_3+SiO_2$ compared to Class F. Owing to higher CaO content, Class C participates in both cementitious and pozzolanic

reactions; whereas Class F involve only in the pozzolanic reactions during the hydration process (Döven, 1996; Gesoğlu, 2004).

2.1.3 Physical Properties

The properties of concrete are affected by the fineness, shape, particle size distribution, thicknesses, and chemical composition of FA particles. The physical properties of FA depend on the source of coal, gradation of powder before burning, the circumference and consistency of combustion and the procedure of collection. Indeed, the collection process such as container sieves and mechanical or electrostatic precipitators strongly effect on the properties of produced FA. Hence, FA particles are differs in shape and size; angular, rounded, irregular and spherical can be formed and observed via optical tools and scanning electron microscopy.

The most popular particles shapes are the angular and irregular particles. Also, spherical and rounded particles can be find in diameter of about (0.5 – 200) μm (Bradbury, 1982; Alonso and Wesche, 1991; Erdoğan, 1993). Because of agglomeration of fly ash molecules in liquefied phase, the allocation of the grain size distribution for the fly ash and the pulverized coal differs during the combustion method.

Fineness, one of the physical properties of FA that relates to its pozzolanic activity, is defined as the percentage by weight of the material recollected on the 0.044 mm (No. 325) sieve. Very fine particles have high specific surface area. The superficial section for FA is able to be measured using the Blaine apparatus. Moreover, the Blaine fineness of FA varies from 2500 to 5500 cm^2/g. The specific gravity of solid FA particles ranges starting 1.9 to 2.9. FA has low specific gravity due to containing high

quantities of unburned coal and hollow spherical particles called cenospheres. Also, because FA has a high percentage of iron, it tends to have higher specific gravity. The bulk density of dry FA is about 7.9-9.5 kN/m³ (Raask, 1968; Myers et al., 1976; Bradbury, 1982; Wesche and Alonso, 1991). Likewise, FA diversifies in color from light cream to dark brown, dark gray and black. The color of FA is affected by the quantity of carbon capacity and the iron-rich particles and moisture. The carbon content in FA is responsible of gray or black appearance, which is ranging from 0.5% to 12%. In effect, the presence of Fe_2O_3 is responsible of giving brown color to FA.

2.1.4 Application and Uses of FA

FA can be use as construction material due to it′s pozzolanic reaction and regular shape of particles. Actually, FA is used as by-products materials in the construction fields such as road sub base for subgrade stabilization, landfill shelter, land renewal, waste stabilization and solidification, mineral reclamation, productions of bricks, blocks and paving stones, mineral filler in asphaltic concrete. Moreover, it can be used in the multiple applications such as LWA and concrete production as well as roller compacted concrete and autoclaved cellular concrete. Fillers for polymer matrix compounds, metal matrix compounds, and other filler applications are alternative uses for FA (Döven, 1996; Gaarder, 2010; Josephson, 2010).

2.1.5 Utilization Areas of FA

Around the world, manufacturing of FA amount was around 600 million tons per year. Less than 25% of the total produced FA is recycled in other applications. More than 95% of the total produced FA is utilized in the Netherlands, Germany and Belgium, while about 50% of FA is used in the United Kingdom. In the United States and China, the percentage of recycling FA was 32 and 40%, respectively. In various publications,

however, it is emphasized that the utilization of FA, in cement and concrete production, is approximately 5% and it is being used in place of aggregate or as a mineral admixture (Kutahya, 2012). The remedies for the utilizations of FA wastes based on the properties of fly ash are presented in Figure 2.1 for the producers of thermal electricity (Wang and Wu, 2006).

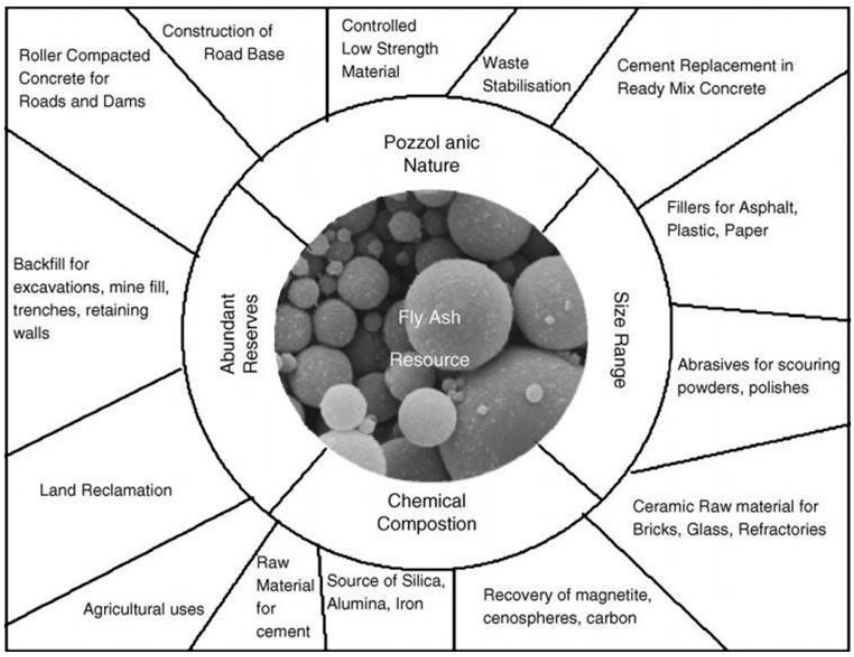

Figure 2.1 Possible fly ash utilization areas reproduced (Wang and Wu, 2006)

2.1.6 Influence of FA on the Fresh Properties of Concretes

Concretes contain FA and other cementitious materials usually have lower density compare with equivalent concrete which is containing only cement because FA has lower density and mass. In effect, incorporating FA in concrete enhanced the plasticity and cohesiveness, it follows that they are enhance the flowability. For a given workability, it was reported that the addition of FA cause a reduction in the demand of mixing water (Bouzoubaa and Lachemi, 2001).

Studied conducted on SCC revealed that the addition of 40%, 50%, and 60% (class F) FA enhanced the slump flow diameter and decreased the V-funnel flow time of SCC. Moreover, the setting times of SCC was 3 and 4 hours longer those of the control concrete. In the study Sonebi (2004), it was reported that the incorporation of pulverized fuel ash and limestone powder decrease the superplasticizer demand which is necessary to obtain the desired slump. Moreover, the usage of these mineral materials enhanced the rheological properties and decreased the risk of cracking of concrete due to heat hydration, which is lead to more durable concrete (Sekino and Narita, 2003). Thus, from the previous studies it can be claimed that 50% replacement level of FA had a good effect on the workability and filling ability of concrete.

2.1.7 Micro-Structural Properties of LWFAs

The mechanical features and durability of concrete affect by its compounds and the interfacial transition zone (ITZ) between aggregate and cement paste. In NWC, the interface between the aggregate/cement pastes is the weakest part of the micro-structural system and the area where cracks start (Hong and Gjorv, 1990). However, in LWACs the particles are able of absorbing water, which produced near matrix; this kind of aggregate is permeable in nature. The porosity can change from 25 to 75% of Lytag aggregate relying on the production procedure utilized (Swamy and Lambert, 1981). Moreover, cement-matrix and aggregate interface performed on many further studies that work to recognize the inner and surface construction of LWA (Shondeep et al., 1992).

The micro-mechanical system has ultimate bonding between the aggregate and cement matrix (Chia and Ran, 1998). In general, sintered fly ash LWA was manufactured at polymer and temperature handling to enhance the strength, pozzolanic reaction and

absorption of aggregate as per to their characteristics of aggregate by variation to the micro-structure. Scanning election microscopy (SEM) is examination to observe further suit dispensation of low pore dimension, and to notice the huge expansion in the sintered LWFAs at the heat-treated (about 1200 – 1300 C°) (Weasserman and Bentur, 1997). The utilizing of LWA, as dry and saturated condition, influence on the interior ITZ microstructure. Moreover, the thickness of ITZ surrounding of NA is about 35 μ. While, it is about 10 μ and 15 μ for dry and saturated LWA, respectively (Amir et al., 2005).

2.2 Lightweight Aggregate

2.2.1 Background

In general, about 30% of FA production is used in minor technical programs such as fills and earthworks, backfills, walkway base and sub base layer. However, FA waste production start using in middle technical programs recently such as blended cement, concrete tubes, pre-cast and pre-stressed product's substances, LWC bricks and blocks, autoclaved aerated concrete and LWA for concrete productions. Presently, in India, the power zone relies on coal established thermal power stations, which produce a massive amount of FA and assessed to be about 110 million tones yearly (Baykal and Döven, 2000).

In effect, the utilization of LWA in concrete is lead to produce lighter weight concrete than of NA. Hence, this lightness in weight benefit to reduced substantially the dead-load of construction elements and permits greater pre-cast elements to be held. Autoclaved cellular concrete (ACC), is a LWC material that can be produced through utilizing 60 - 75% of FA by mass of cement. With increasing interest over the extreme utilization of natural aggregates, artificial LWA manufactured as of environmental

waste is a usable recent representative of constructional aggregate substance (Ahmaruzzaman, 2010). Agglomeration system is one of the coarse systems periods manufacturing the LWA. In agglomeration system the pellets are created in two paths either by compaction and agitation granulation. The agitation system is not needed to any exterior power rather than revolving power. Increase the amount of water in the binder causes an increase in the cohesive strength of the pieces. To strengthen the green pellet sintering, autoclaving and cold bonding are three unlike procedures utilizes (Bijen, 1986). The partial replacement of NWC is 20% - 40% by the volume of LWA was calculated by (Behera et al. 2004) with the difference of the compressive strength just 1%.

2.2.2 Lightweight Aggregate in Nature

LWA can be found as natural form in some places around the world because most of it has a volcanic origin. Pumice, scoria, tuff, volcanic cinders, and diatomite are the most LWA known. Actually, scoria and pumice are the most generally utilized natural lightweight aggregates in the construction applications (Venuat, 2005).

Although they have variable properties, they are strong enough to be used in the 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 2.2).

The bulk density of pumice usually ranges from 5 to 9 kN/m^3 (Venuat, 2005). Similar to pumice aggregates the scoria, which is an extrusive rock not formed by the crystallization of volcanic magma and slow cooling. Its main difference from pumice is that it has darker color, distinct connected broken and large bubbles. 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 (Topcu and Uygunoglu, 2007).

Figure 2.2 Pumice stone (Booya, 2012)

2.2.3 Artificial Aggregate from Industrial by Products

2.2.3.1 Furnace Clinker

Clinker aggregate is a by-product materials result from combustion of coal in industrial or domestic furnace system. After crushing and screening, products are used as LWA. In usual, clinkers are a dark in color and sintered as a solid form. Due to high contain of sulphate and chlorides, clinkers not recommended to be used in the production of concrete mixtures but it can be used in the fabrication of concrete blocks.

2.2.3.2 Bottom Ash Lightweight Aggregate

When coal is used for combustion process in electricity generation plant, it produces ashes. Thus, a small amount of the ashes stay at the bottom and thus is called bottom ash aggregate. It usually contains unburned coal or slag which is granular porous material. The bulk density of these ashes varies from 45 to 75 Ib/ft^3 (Phillips et al., 2005).

2.2.4 Industrially Produced of Artificial Lightweight Aggregate

Due to increasing demand and non-availability of natural LWA, some researchers developed new methods for manufacturing of artificial LWA in factories from industrial by product like FA, granulated ground blast furnace slag (GGBFS) and bed ash as well as from natural raw materials such as shale, slate, and expanded clay.

2.2.4.1 Fibo and Leca

In general, Leca and Fibo are expanded clay aggregates produced in UK and Scandinavia, respectively. The expanded clay is the widely use in the production of LWA around 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 (Clarke, 1993).

2.2.4.2 Perlite

Perlite is a type of a volcanic glass which it can be expanded by 4 to 20 % of its original volume when it is heated to melting point. This growth and increase in volume occurs by the occupancy of 2 to 6 % merged water in the crude perlite rock. In effect, when Perlite rapidly heated to greater 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 (Booya, 2012). Figure 2.3 exhibits a photographic view of different sizes of perlite.

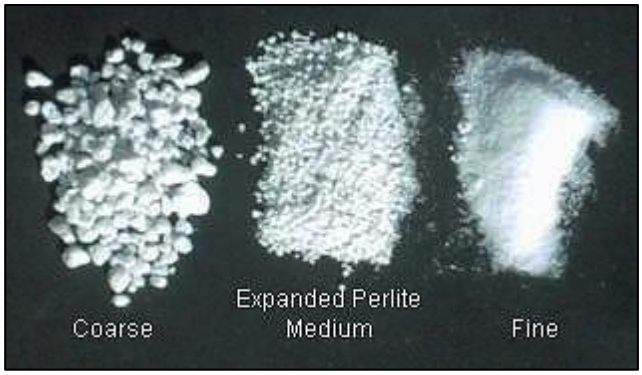

Figure 2.3 Different sizes of perlite (Booya, 2012)

2.2.4.3 Slag Pellets

The process of manufacturing slag pellets was firstly developed in Canada, which 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 and then gives a steam vapor. Then, the pellets are cooled in the air and vitreous shell is created. Actually, the pellets fall back on inclined ground with grates in a way that the greater particles are projected far away while the smaller ones fall nearer (Gesoğlu, 2004).

2.2.5 Production of LWFAs

The production of LWA by using FA deemed as an the most effective way to recycle the waste materials since million tons of FA is produced annually and only a few amount of it is utilized. In effect, there are three major methods used for the hardening of FA pellets namely, sintering, autoclaving, and cold bonding (Ramamurthy and Harikrishnan, 2006; Bremner and Thomas, 2004).

2.2.5.1 Sintering Method

The manufacturing of sintered FA aggregates consists of two principle processes, first one is the pellitization of the FA through it mixed with the sprayed water in inclined rotating disc of particularization. While the second process is subjecting the pellets to a temperature of about 1100 Cº where 5 to 8% coal in the FA is ignited. Afterwards, the manufactured aggregate is separated, sieved and graded (Ramamurthy and Harikrishnan, 2006).

2.2.5.2 Autoclaving Method

This method based on pressurized saturated steam curing for hardening of FA pellets. The manufacture of autoclaved FA aggregates typically involves using 47% FA, 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 200 Cº to produce lightweight aggregate that finds its primary use in masonry units (Bremner and Thomas, 2004).

2.2.5.3 Cold Bonding Method

This method is a type of bonding that depends on the capacity of FA to react with calcium hydroxide at the ambient temperature to produce material owning water

resistivity. The bonding of material basically depend on the pozzolanic reactivity of FA. Likewise, the manufacturing process includes pelletizing or extruding the FA with Portland cement and water. After that the fresh pellets are cured for several days to produce aggregates (Gesoğlu, 2004).

The method of cold bonding (CB) is more than only one simple method. A mix of lime, ash, and water following the mixing, is together transferred to a disk pelletizer, where pelletization takes place. The mix is allowed to stiffen. The end product from this process is considered to own poorer characteristics than aforementioned two processes namely hydrothermal and sintering owing to the lack of firing. The process of CB has a several advantages such as:

- This process plants have tendency to deal with lower operational and capital costs than sintering/rotary kiln firing plants;
- The CB process plants are also exposed less environmental impact than the other thanks to no emission of exhaust greenhouse gases. Also, both processes need control of particulate emission and might have waste water flow.
- The end product costs tend to be lower for CB material than for sintered material (Ramme et al., 1995).

Indeed, CB process is a kind of bonding which explains the capacity for FA to react with calcium hydroxide at ambient temperature. The main manufacturing process of LWFAs consists of pelletizing (also called agglomerating) in which FA, Portland cement and water, and curing for several days (Güneyisi et al., 2012; Döven, 1996; Gesoğlu, 2004; Koçkal, 2008; Booya, 2012).

2.3 Pelletization Process

2.3.1 Definition of the Pelletization Process

The agglomeration of fines aggregate and/or crushing of rock are the ways to reach to the ranges of target sieve size. Indeed, the moisturized particles are agglomerate inside the drum. Moreover, the binders can add to the drum before it rotated. Fresh pellet would be formed at the end of this process. On the other hand, pellet can sinter in order to gain higher strength (Baykal and Döven, 2000).

2.3.2 Theory of Pelletization

When the fine grain material is moisturized, the liquid film covers the grains surface and forming meniscus among the grains structures like bridges (Figure 2.4a). Actually, inside the balling disc, the particles forming as spherical structures which is the bonding forces between grains are improved due to the centrifugal and gravitational forces (Figure 2.4 b and c) (Jaroslav and Ruzickova, 1987).

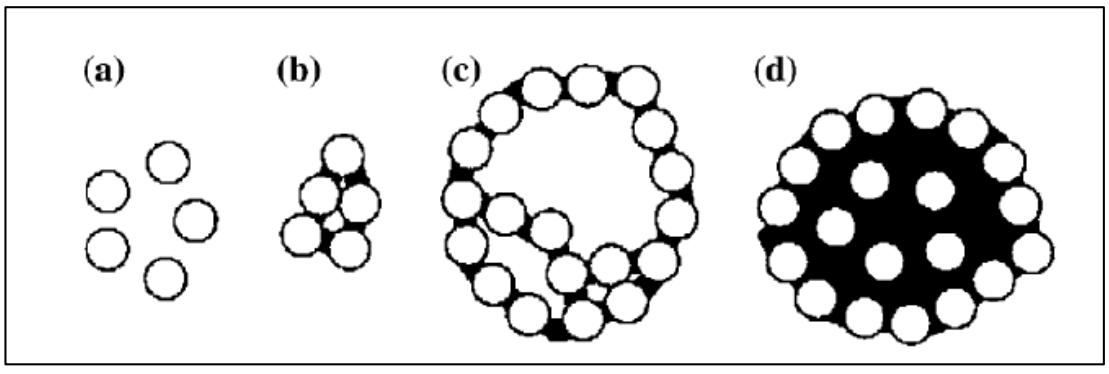

Figure 2.4 Mechanism of pellet formation (jorslav and Ruzickova, 1987)

In pelletization process, the force progressive on the pellets expels the air which is fills the free gap between the single fragments present the voids to fragments also water. As the fragments take closer, the structure comes to be denser whenever enhances the structure consistency and causes the fresh pellets to possess adequate intensity for

handling and accumulating conditions (Asaad, 2011). The maximum strength of pellets is attaining when the capillaries filled by water during manufacture period. Moreover, the lack of adequate water cause an air voids entrapped inside the structure, which is control the capillary activity.

For FA palletization, the optimum water content ranges between 20-25%. In effect, the feeding percentage of the binder and moisture content control the pelletization procedure and thereby significantly affected on the granulomere distribution of particles. The pelletizing process is strongly dependent on the water content condition. Hence, the wetness or moisture of particles cause a connections or bond bridges between them and move closer. As shown in Figure 2.5, the spherical structure mechanism indicated through the moisture content. Actually, the structure becomes softer whenever the capillary strength is reduced due to high moistening. Moreover, the structures have random sized it easily to destroy by the mechanical forces produced in the balling disc (Asaad, 2011; Gesoğlu, 2004; Jaroslav and Ruzickova, 1987).

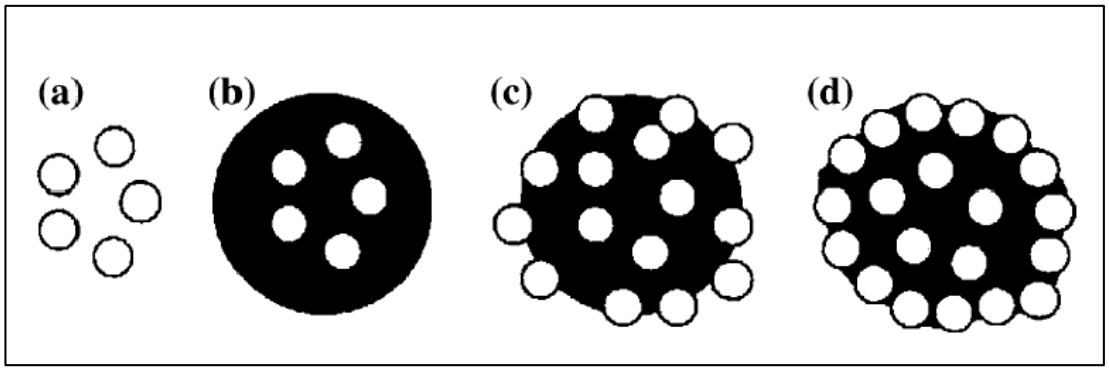

Figure 2.5 Process of ball nuclei forming (water components above ideal position) (Jaroslav and Rurickova, 1987)

2.3.3 Hardening Properties of LWA

ASTM C 618 defined two type of FA, class-C and class-F. These classes are established in the chemical constitution and resulting from various kinds of coal burning. Actually, Class-C of FA is generally manufactured via burning of lignite and sub bituminous coal. The FA aggregates are permeable material and to enhance the strength of the pellet it blend with other material such as cement, metakaolin, limestone, glass powder, bentonite and ceramic powders. (Geetha and Ramamurthy, 2011) stated that the clay binders such as metakaolin or kaolinite impart higher fines price. The percent of binder component is obtained by the mass of FA. Hardening the pellets is conducted through various processes such as cold bonding, autoclaving and sintering. The curing system is further significant to improve the strength of aggregate. Hence, cold-bonded FA aggregates are hardened in various curing procedures like normal water or autoclaving curing.

In effect, the autoclave and steam curing system is less efficient to enhance the characteristics of aggregate as compare with standard water curing system. It was reported that for high early strength aggregate, standard water curing system can be more reliable (Manikandan and Ramamurthy, 2008). Moreover, higher strength aggregate can be obtained after 8 - 10 h in autoclave curing (Topcu and Uygunoğlu, 2007).Sintering procedure can be explained by burning the cold bonded pellet in a muffle furnace at temperature between 800–1200 C°. However, replacing of NA by LWFAs results higher strength of the aggregate because the aggregate particles contact with each other to form the crystalline construction (C-S-H) (Verma et al., 1998).

2.4 Difference between Normal Weight Concrete (NWC) and Lightweight Aggregate Concrete (LWAC)

NWC is differs from LWAC through various phases such as mixing hardening and failure phase. In the mixing phase, the high absorption capability and porosity of LWA significantly influence in the workability of produced concrete (Neville et al., 1987) and efficient water/binder ratio (ACI 211 .2, 1998). In the hardening phase, the isolating ability of LWAC will increase the temperature of hydration. The water at first instant in the porous aggregate fragments may influence the moisture stage in the hardening procedure to a great extent. Volume variations happen with the variations in the stage of water in the pore technique in the early phase of hardening. In the hardened properties, the differences between LWAC and NWC are mostly expected in the elastic modulus of elasticity and strength of the aggregate as well as differences in the aggregate matrix and transition zone. These differences lead the grade of heterogeneity of concrete. Moreover, the properties of the ITZ are concluded by the surface properties of the aggregate, in addition to the pore structure and the basic water content of the aggregates (Isserman and Bentur, 1996). Some counteraction products, e.g. CH, relying on the pore structure of the aggregates, will even penetrate inside the pores of the aggregates. This is further acceptable in aggregates with higher absorption and larger pores (Isserman and Bentur, 1996).

In LWAC, ITZ is not the weakest connection; generally, LWA has lesser modulus of elasticity than NA in the mortar stage, which is generate further stress in the mortar. With equivalent modulus of elasticity for the mortar and LWA and, the stress will be further evenly dispensed in LWAC than in NWC. As a topic of reality, ITZ will slightly be cramped by oblique compressive stress. Hence, the crack introduction of LWAC

happens at a high-stress degree expected to the elastic suitability of the stages. The strength and rupture toughness of LWA are significantly lesser than those of NWA of regular origin, and perhaps in spite of the mortar stage. The strength of LWA can be the strength upper limit of LWAC (Bremner and Holm, 1986; Chi and Huang, 2003).

2.5 Interface between Lightweight Aggregate and Cement Paste

In effect, there are three phases comprised in concrete; the aggregate, cement paste and ITZ phase between coarse aggregate and cement mortar. In general, ITZ is the weakness region in NWC. The main differences between LWC and NWC are the fracture path and water absorption. In LWC, failure line directly passes through LWA particle because the matrix will be the stronger when compared to the LWA. Thus, fracture path moves around into the particle. In the case ofNA, the fracture path moves around into the particle because the particles will be more strength compared with cement paste and ITZ. The whole water content is extremely for LWA owing to the high absorption. Tensile strength is reduced in drying situations by greater moisture gradients although this effect is somewhat relieved by the effects of increased hydration (Mindness et al., 2003).

ITZ between cement paste and aggregate has a significant position in examining mechanical characteristics of concrete. Schneider and Chen (1992) investigated the morphology of the interface between the expanded clay grains and the hardened cement paste by using scanning electron microscopy. It was reported that the rough surface and porous structure of the aggregate are advantageous properties for using in cement paste. Likewise, Zhang and Gjorv (1990) found that because of the variety of LWA, ITZ between aggregate and cement paste is dissimilar from another based on the micro structural characteristic of LWA.

Husem (2003) showed that the bond strength of aggregate-cement paste bond is improved by pores of LWA. Additionally, Lo et al. (2007a) indicated that the adhesion of the aggregate between cement pastes was influenced by the pore size and surface characteristics of LWA. Wesserman and Bentur (1997) examined the resulting effects on the concrete strength by modifying the aggregate properties.It was concluded that the strength of concrete produced with different LWA did not correlated with the strength of aggregates, despite the matrix was in the same w/b ratio. In the study of Wesserman and Bentur (1996), it was noticed that the difference in concrete strength could not constantly related the aggregate strength.

These inclinations could be related with the physical and chemical processes occurred in ITZ, which is effect on the whole strength rather than strength of aggregate. However, the chemical procedure was related to pozzolanic activity of LWA; this process was effective only in the later stages, beyond 28 days. The improvement in strength because of these effects arranged between 20 and 40 percent. Such effects should be taken into consideration in the design of LWC of optimum features.

2.6 Bond Strength

The bond characteristic between reinforcing steel bar and concrete deem as the one of the most significant characteristics in reinforced concrete constructions. Indeed, the bond strength of steel and concrete control the mix of friction, adhesion and assistance of the ribs in deformed steel. The adhesion process is the initial characteristic started by the applied load. Actually, it is slightly negligible ignition interlock of paste into weaknesses on the steel bar top surface and slightly a potential chemical interaction between surfaces (Cosenza and Zandonini, 1999; Lungren, 1999). The other two processes, friction and rib support, leave into activity when adhesion fails and some

proportional move starts between concrete and steel bars. After that, this period important since slip may be noticed, as well as the structure and delay of cracks.

There are a massive knowledge deals with bond strength behavior between reinforcing steel bar and concrete as well as some pattern equation proposed by investigators (Gjorv et al., 1990; Valcuende and Parra, 2009; Ožbolt et al., 2002; Lundgren, 1999; Kayali and Yeomans, 2000; Harajli et al., 2002; Banholzer et al., 2005). Hence, Elfgren and Noghabai (2002) investigated the influence of steel bar diameter, cover thickness of concrete and the crack spaces on the strength of bond between concrete and reinforced steel. Actually, there are several researchers investigate the bond strength between reinforcing bars and concrete produced via incorporating LWA (Mor, 1992; Orangun, 1967; Kayali and Yeomans, 2000; Hassan et al., 2010).

In LWC, it was reported that the bond strength and embedded length ranging between 20 and 35 MPa, respectively. Generally, post elastic strain and bond splitting value of LWC are lower than equivalent if NWC due to the inferior strength of LWA. ACI 318 (1995) specified the embedded lengths for LWC to be magnified by a factor of 1.3 over the lengths desired for NWC (Holm and Bremner, 2000). Hence, Zhang and Gjorv (1990) investigated that the interface between the LWA and cement pastes and described the mechanical interlocking of the mix by a chemical interaction in the shape of pozzolanic effect. Also, Mehta (1986) reported that depending on the surface structure of aggregate, the characteristics and micro-structure of the ITZ will be change. In addition, Gjorv et al. (1990) investigated that the morphology and microstructure of the ITZ are influenced by compressing silica fume (SF) to the concrete, so both porosity and thickness of the ITZ are decreased.

SF is a pozzolanic material essentially effects on the characteristics of the subsequent materials used as an admixture in a concrete mixture. These effects deal with the strength, tensile, modulus of elasticity, air void contend, permeability, shrinkage, abrasion resistance, and bonding strength with reinforcing steel bars, chemical attack resistance, corrosion reduction of embedded steel reinforcement and alkali silica reactivity resistance. In addition, inclusion of SF lowers the workability of the mixture (Xu and Chung, 2000).

Mor (1992) described the effect of SF on the concrete as follows:

- Decreased the calcium hydroxide (CH) crystals in the ITZ.
- Accelerate the reaction between CH and SF because the pozzolanic response.
- Decreased agglomeration of free water to the interface during casting of samples.

Indeed, SF significantly enhanced the adhesion of concrete; so incorporate SF in LWC will improve the cohesion of concrete and thereby increase its bond strength.
Hossain (2008) studied the bond strength properties of LWC and NWC compared to other deformed reinforcing bars. The mainly significant effect was in which the bond strength of deformed bars in NWC was greater when compared by those of LWC. The bond strength of NWC samples was established to be varieties between 1.08 and 1.14 times greater than LWC.

2.7 Self-Compacting Mortars (SCMs)

SCM is a new technology developed in the recent years which can be used for repairing and strengthening the reinforced concrete structures and then make these structures secure for earthquakes. Recently, SCM became common in the repair works, which

the mortar can flow easily through cross section of element and owing high permeability (Şahmaran et al., 2006).

In order to identify the properties of SCM, several tests should be conducted before production of SCM, which is affected by it′s mortar phase. Sakai et al. (2006) reported that it can produce lightweight SCM via using 0.9 kg/m^3 superplasticizer and 1.1 kg/m^3 chemical viscosity enhancer; the compressive strength of produced mortar varied between 10-35 MPa. Similarly, Felekoglu et al. (2006) investigate the effect of powder selection on the rheology and mechanical performance of SCM.

Moreover, the influence of powder materials on the self-compacting ability, viscosity and strength had been investigated in the author′s study through a set of test methods such as mini slump, V-funnel tests, viscosity measurements and compressive strength tests. Test results showed that limestone powder reduced flow ability and increased V-funnel flow times; also, compressive strength results showed that limestone fillers was more effective than FA in the term of early strength gain. Thus, Felekoglu et al. (2007) developed SCM with steel filaments. In their study, with filament addition, compressive and tensional strength increased but workability decreased.

In the mix design theory of SCM, the higher content of cement and fines results an increase in flowability. Usually, different type of inert fillers and supplementary cementitious materials are added. The use of rich sands is effective way for alternative source of filler. Benabed et al. (2012) studied the rheology and mechanical properties of SCM made with various types of sands. Crushed rock, river sand, dune sand and a mixture of different sands were used in that study. Moreover, several tests conducted such as mini-slump flow, V-funnel flow time and viscosity measurement. The

experimental results showed that the rheology and strength properties enhanced whenever crush and river sands were used; While, it decrease for dune sands. The authors concluded that 10–15% of limestone in crush sand could be used successfully in the production of SCM with good rheological and strength properties. However, the usage of dune sand (up to 50%) result a reduction in compressive strength in mortar with binary and ternary sands.

In the same regard, Şahmaran et al. (2006) studied the effectiveness of mineral additives and chemical admixtures in SCM production. Four mineral additives are used in that study, superplasticizer and viscosity modifying admixtures. The workability of SCM determined through mini slump flow and mini V-funnel test. Moreover, the Ultrasonic pulse velocity and strength aspects were determined for 28 and 56 days. The Authors stated that the use of mineral additive, FA and limestone powder significantly increased the workability of SCM. While FA increased the setting time of the mortars.

Bager et al. (2001) also studied the rheology of SCM and investigate the influence of grading and particle shape on the rheological parameters of the mortar. The results indicate that, for same particle shape, the yield stress and the viscosity decrease whenever fineness of aggregate decreased (increasing number of grading). Moreover, change of particle shape from rounded to angular produce variable result of yield value and the viscosity. The results also indicated that it is possible to design SCM with proper rheological properties through a wise choice of constituents. Nunes et al. (2011) investigate the influence of cements produced on the rheological properties of SCM. The results indicate that cement variation should be taken into account when talking about robustness of SCC mixtures.

2.8 Lightweight Mortars (LWMs)

In general, LWM is mainly differs from normal mortars by the aggregate type. These mortars can be used for repairing purposes because it's only contained fine material. Also, it is used for special architectural works due to its capability of flow. In effect, because LWM did not have coarse aggregate, the risk of shrinkage cracks might be increased (Husem, 2003; Öz, 2014). Hence, Spiesz et al. (2006) use expanded-glass to produce LWM. The results indicate that the permeability of LWM significantly enhanced comparing with vibrated LWM. Similarly, Husem (2003) investigate the effect of bond strength between aggregate and mortar which it can be an important role for determining mechanical properties of concrete.

The results revealed that the bond strength between LWA and cement paste was about 2.5 times higher than equivalent of NA. In effect, cement paste can penetrate into the pores on the surface of LWA easier than NA. Thereby, the bond strength between aggregate and cement paste enhanced. Westerholm et al. (2008) investigate the influence of crushed fine aggregate on the rheological properties of mortars such as yield stress and plastic viscosity. Moreover, the effect of grading and particle shape of the fine aggregates has been evaluated by viscometer. The results revealed that the properties and type of aggregate have a significant effect on the water demand and workability of the mortar.

Actually, using LWC has an advantage in economy, environmental and structure element′s safety. Topçu et al. (2008) stated that the structures inertial forces during earthquakes and destructive forces become weaker for building built by lightweight materials. Likewise, Gönen et al. (2011) studied the resistance of self-compacting lightweight concrete (SCLWC) to high temperature. For this, pumice aggregate was

used to produce natural and lightweight concretes subjected to 20°, 300°, 600° and 900°C temperatures. The results indicate that concretes produced with volcanic pumice were more resistive against high temperatures than the concretes produced with natural-river aggregate. Moreover, temperature resistance increases whenever the amount of pumice aggregate increase. However, the loss of temperature resistance became similar for both types of concretes at 600 C°, in 900 C°. The pumice aggregate cause a decrease in the concrete by about 25% and then the corresponding strength also decreases by 15%. While the thermal conductivity and temperature resistance would be increased.

In Turkey, there are rich underground deposits of LWA such as pumice could be used in construction sector (Açıkel, 2013). For this regard, Gönen (2010) studied the influence of aggregate type and curing conditions on the mechanical properties of SCLWC containing expanded perlite and pumice aggregates. In that study, compressive strength and flexural tensile strength at 7, 28 and 90 days were determined for both SCC and SCLWC to evaluate each type of concrete. The results indicated that the compressive strength of SCLWC was in the range of 50-65 MPa according to curing conditions. In this regard, Günaydın (2006) manufactured SCLWC by using low cost LWA. Fresh properties such as settling diffusion, V-cone flow and L-Box tests were performed as well as mechanical properties.

It is well known that the superplasticizer and high amount of fine material enhanced the flowability and segregation resistance of concrete. Therefore, the increase in total bonding agent increased compressive strength (Gönen, 2010; Açıkel, 2013). Hence, it can be claimed that SCC is really advantageous for construction sector with less workmanship, less construction time, no need for vibration energy, allowing aesthetic

design and other advantages. In the term of cost, SCC has always a problem in this regard. However, different materials and additives could be used to decrease the cost such as LWA. Nowadays, there is a trend to use LWA for production a superior and economical SCC (Topçu, 2008; Öz, 2014).

2.9 Self-Compacting Lightweight Mortars (SCLWMs)

In general, SCLWM has a special mix design and production, which it can be used in specific works and repairs because it can be injected in narrow cross-sectional member of any structure. Indeed, SCLWM can fill all the spaces and will not cause an extra dead load to the structure; also, it can be achieving a proper compressive strength SCLWM (Felekoğlu et al., 2006; Öz, 2014).To manufacture it, very fine materials and chemical additives should be used. Indeed, the aggregate properties and it′s fineness are the main factors that affect the mortar characteristics.

Gönen (2009) studied on mechanical properties of SCLWM by using expanded perlite aggregate to produce the mortars as a partial replacements of 10, 20, 30, 40 and 50% by volume of NA. Slump, V-funnel flow time, unit weight and apparent porosity as well as mechanical properties of SCLWM had been conducted. The results indicated that the unit weight of mortars decreases whenever the LWA replacement percentage increased. Moreover, the compressive strength of SCLWM was varied between 21-72 MPa depending on the present level of LWA. Examples of this study include that incorporated 40% of expanded perlite rather than NA results a unit weight and compressive strength of 1470 kg/m^3 and 41 MPa, respectively.

2.10 Self Compacting Concrete (SCC)

2.10.1 Definitions

EFNARC (2005) defined SCC 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 (1999) 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 molds by itself without the need of compaction or vibration (Okamura, 1999).

In effect, Enhancement the working environment and maximized productivity was the main reason to develop this concrete technology. SCC has met the challenge successfully and it is used more and more in routine practices (RILEM TC Final Report 188, 2006).

2.10.2 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. Specification and guidelines for self-compacting concrete (EFNARC, 2005) and (RILEM TC Final Report 188, 2006) 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 the case of workability requirements, the following important advantages can be acquired (Okamura, 1999):

- 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).

2.11 Self Compacting Lightweight Concretes (SCLWCs)

Generally, SCLWC is an innovative type of concrete which unifies the favorable properties of LWAC and SCC. Aforementioned, SCLWC can place without vibration, fill the formwork and enclose reinforcement without any bleeding or segregation (Wu et al., 2009). The use of SCLWC can be useful to obtain the significant reduction in

the total mass of structure which can result in reduced structural members sections and facilitate construction (Kim et al., 2010). Furthermore, the segregation of LWA can be prevented in SCC because the concrete did not need vibration. In effect, there is a lack of information in the literature for using LWA in the production of SCC because most of the studies focused on the mix design method and fresh properties of SCC.

The most popular method to design SCLWC introduced by Okamura (1999) and it based on the cement paste and mortar test prior to changing the properties of the superplasticizer, cement, and fine aggregate and pozzolanic material. However, it is difficult to apply for producing the ready mixed concrete. To avoid this obstacle, some researchers used a new mix design method suggested by Nan (2001). In spite of its simplicity, this method had some problems about the fluctuating range of packing factor (PF). For this Choi et al. (2006) modified PF and applied to design the high-strength SCC of which comprising LWA. The test results were evaluated with respect to the standard of second class rating of Japan Society of Civil Engineering (JSCE). All mixes satisfied the expected capacity in the tests of slump flow and time required to reach 500 mm of slump flow (s) of SCC. However, time required to flow through V-funnel (s) satisfied only with the mixes in which used 25% and 75% lightweight coarse aggregate (LWCA) and 25% lightweight fine aggregate (LWFA), respectively.

In general, the mechanical properties of SCLWC represent 75% of SCC. However, SCC with 50% LWFA caused a decrease of 6% in comparison with reference concrete. Similarly, the elastic moduli of SCC ranged between 24-33 GPa. Wu et al. (2009) designed two type of SCLWC depending on the water absorption rate of expanded shale via the overall calculation method with constant fine and coarse aggregate. Fresh properties were tested through slump flow, V-funnel, L-box, U-box, and Surface

settlement tests as well as the column segregation test and the cross-section images for the uniformity of distribution of LWA along the specimen. The results indicate that the two types of fresh SCLWC was satisfactory in the terms of fluidity, deformability, filling ability, uniform aggregate distribution and minimum resistance to segregation.

Wang (2009) also produced two types of SCLWC made from dredged silt with particle densities of 800 kg/m^3 and 1060 kg/m^3 respectively. To improve hardened properties of SCLWC, pozzolanic materials such as FA and slag was added to the fresh mix, thus three different w/b ratio (0.28, 0.32 and 0.40) with three different volumes of mixing water (140, 150 and 160 kg/m^3) were designed. It was observed that slump and slump flow diameter of SCLWC ranged between 26-27 cm and 51-58 cm, respectively. Moreover, regardless of w/b ratio, the hardened SCLWC reached about 70% of their compressive strength at 7 days. While splitting tensile strength was reached to value changing between 1.5-2.2 MPa at 91 days. Also, SCLWC with low w/b ratio ensured higher chloride penetration resistance, a fewer of cracks and lower weight loss as well as better ultrasonic pulse velocity. Moreover, it can be concluded that SCLWC had good hardening and durability characteristics. Kim et al. (2010) evaluated the properties SCLWC incorporated two type LWA, first type aggregate had a density of 1.58 g/cm^3 produced with rhyolite fine powder, and the other with a density of 2.07 g/cm^3 produced from wastes such as screening sludge. It was revealed that when the density of SCLWC decreased, the segregation resistance deteriorated and in the same time, the flowability improved. Moreover the filling ability was not affected by the density of LWA. Also, replacing 75% of NA by LWA was caused a decrease in compressive strength by 10% compare with reference concrete. While, for the second type of aggregate, 100% replacement resulted a decrease in compressive strength of SCLWC by31%.

Türkmen and Kantarcı (2007) applied five different cure conditions to SCLWC including 5%, 10% and 15% expanded perlite aggregate. In air curing condition the compressive strength of SCLWC incorporated 5%, 10% and 15% expanded perlite aggregate was higher than those of reference concrete. It was showed that the capillarity coefficient value depended on the curing time, curing conditions, and the percent of expanded perlite aggregate. For lime saturated water curing condition capillarity coefficient decreased with time. The increment of expanded perlite aggregate cured in air for 28 days resulted in an increase of apparent porosity.

Topçu and Uygunoğlu (2010) investigated the effect of pumice, volcanic tuff and diatomite on the properties of SCLWC. The mixtures were designed by preparing different combinations of w/b ratio with the total constant powder content and superplasticizer dosage levels. The results showed that the decreasing ratio of unit weight for SCLWC were ranged between 30-35%, 22-31% and 34-38% by replacing crushed limestone with pumice, tuff and diatomite, respectively. The decrease in w/b ratio was resulted an increase in the compressive strength and splitting tensile strength of SCLWC. Moreover, the decreasing ratio of flexural strength was lower than that of compressive strength and splitting tensile strength.

Bogas et al. (2012) produced SCLWC having a compressive strength within the range of 37.4-60.8 MPa. For this, two different expanded shale aggregate having particle densities 1068 kg/m^3 and 1290 kg/m^3, respectively were replaced with NA. The slump flow diameter and slump flow time altered between 66-75 cm and 10-15 s for SCLWC. Additionally, the effect of the volume for coarse aggregate, the volumetric ratio of fine aggregate to mortar and fine material to fine aggregate, water content to fine materials were discussed. The results showed that deformation capacity of SCLWC was hardly

altered by the fine materials and fine aggregate ratio but the aggregates influenced the rheology of cement paste and mortar. In effect, the volume of coarse aggregate affected the filling and passing ability of SCLWC due to having higher sphericity of LWA. It was recommended that the ratio of water content to fine materials and fine material to fine aggregate varied between 0.8-1 and 0.41-0.49, respectively to obtain self compactability. The elastic modulus of SCLWC was found to be slightly higher than SCC including NWA. This might be attributed to the stiffness of LWA.

2.12 Initial and Final Setting Times

2.12.1 Characterization of Setting Time

Setting times typically occurs after a few hours of hydration during the acceleratory period when C-S-H and CH are rapidly forming. Other hydration reactions like formation of calcium aluminate hydrate or secondary gypsum may involve abnormal setting. While, normal setting is attributed to calcium silicate hydration (Odler, 1998). Odler (1998) discussed the relationships between setting and hydration and concluded that normal setting occur due to formation of C-S-H. From a microstructural point of view, cement particles initially form a suspension in water through flocculated or dispersed paste. In effect, particles connected each other by hydration products and if it already connected in a flocculated structure, the connections will be strengthen. Thus, without hydration products, the network is weak in connection and easily broken making the mixture plastic. While with hydration, the particles interrelate together and eventually produce the rigidity (or penetration resistance) that we recognize as setting.

For a dispersed paste, hydration is needed to establish connections between particles. In detail, it undoubtedly matters what hydration products are responsible for setting, but in a broad sense it probably does not. It is likely that only a limited amount of

hydration is required for setting, at least at water-to-cement ratios (w/c) typically encountered in structural concrete. So setting is produced by the development of a three dimensional network of solid particles with sufficient strength to resist deformation at modest shear stress.

It should be noted that the hydration also causes a progressive increase in solids content, which in turn cause setting (Bentz, 2008). Similarly, due to hydration, setting develop three-dimensional percolated network of cement particles. Percolation is a convenient criterion for set because it can be assessed in microstructural-based models. In effect, it can be reflect the changes in microstructure by setting. Therefore, experiments were performed on pastes with a range of microstructures-various w/c levels and with and without superplasticizer. These tests were done in laboratory over many years and by different investigators, often with different materials and sometimes following different procedures.

2.12.2 Penetration Resistance

The ASTM standard tests for setting time utilize penetration resistance (Figure 2.6). However, the tests are different for cement, mortar and concrete. These differences probably reflect the challenges posed by each material and different historical evolution of the standards. Concrete is tested using (ASTM C403, 2008).

Figure 2.6 Penetration resistance apparatus (Ahmadi, 2000)

2.12.3 The Proctor Test

The proctor test based on the penetration resistance and it is measured using a series of needles. The needle diameter and the applied load are adjusted as needed to maintain penetration at the required level and these parameters are used to compute the penetration resistance. As depicted in Figure 2.7, the initial set occurs when the penetration resistance is 3.5 MPa and final set occurs when the penetration resistance is 27.6 MPa. Although collection of mortar is tedious, it is undoubtedly sensible to test mortar rather than concrete, as penetration resistance of concrete would be highly variable according to whether or not the needle makes contact with coarse aggregate. Cement paste is tested according to ASTM specifications test methods for time of setting of hydraulic cement by vicat needle (ASTM C191, 2008). Hence, initial set occurs when the needle penetrates only 25 mm, while final set occurs when the needle no longer penetrates. It is sensible to use such a stiff initial consistency for this test because the needle penetrates too easily in typically fluid paste.

Figure 2.7 Showing the cube during and after the penetration test of setting time (Güneyisi and Gesoğlu, 2008)

2.12.4 Comparison between the Proctor and Vicat Methods

In effect, the comparison showed that the proctor provides a better measure of setting than the Vicat measurement. The proctor results agreed with rheology and it can be performed on pastes of w/c levels more typical in structural concrete. In order to use the proctor test for paste, it is necessary to determine the penetration resistance in paste that corresponds to initial and final set in concrete (Chung et al., 2010).

Actually, Chung et al. (2010) explained that initial set of paste occurred when the penetration resistance was 2 MPa and final set occurred when the penetration resistance was 14 MPa. With these criteria, penetration resistance was measured for pastes with different w/c levels. As shown in Figure 2.8, the penetration resistance versus time was fitted with exponential functions to measure initial and final setting times. Moreover, w/c was increased from 0.35 to 0.60, both initial set and final set increased progressively.

It was recorded that initial set increased from 150 min to 360 min and final set increased from 220 min to 470 min, changes of about 80%. Hence, using the same approach, penetration resistance was measured for plain and superplasticized pastes. As shown in Figure 2.9, similar relationship fitted with exponential functions to measure initial and final setting times. Indeed, the addition of 0.25% superplasticizer both initial set and final set increased. Also, initial set increased from 243 min to 344 min and final set increased from 322 min to 445 min (Christensen, 2006).

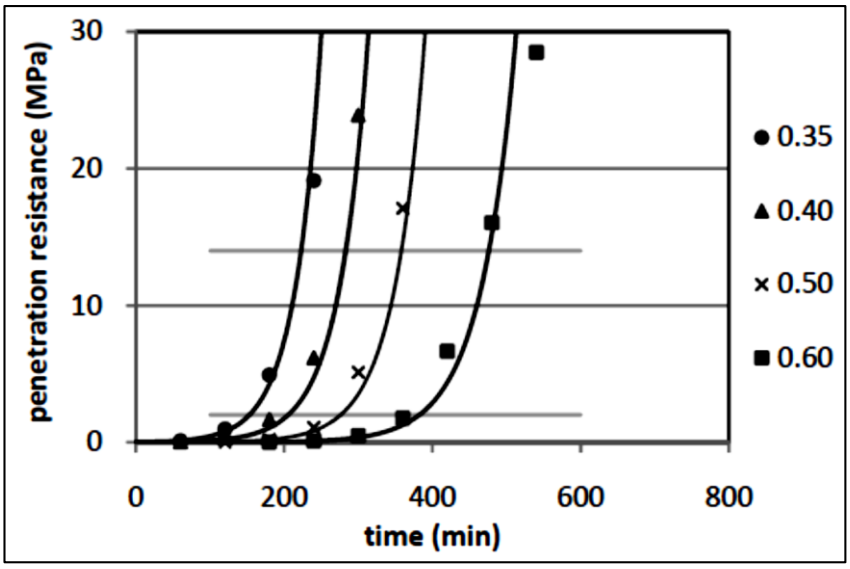

Figure 2.8 Penetration resistance of cement pastes with various w/c levels (Christensen, 2006)

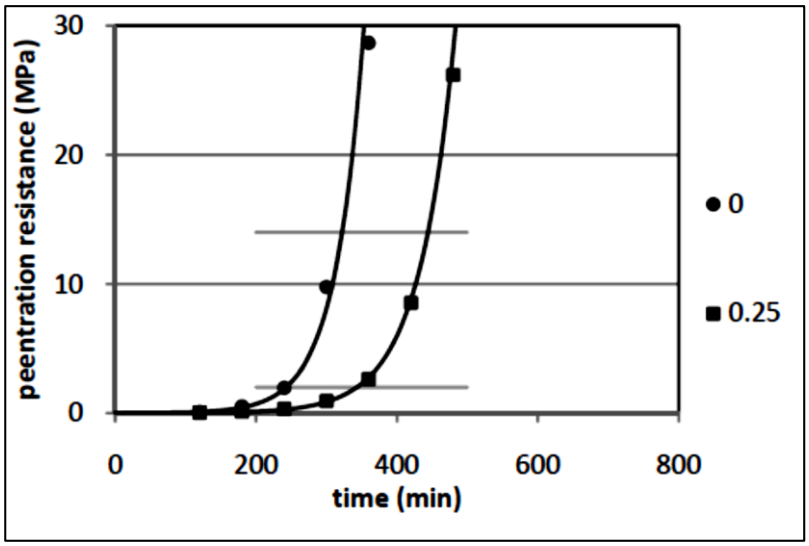

Figure 2.9 Penetration resistances of plain and superplasticized cement pastes (Christensen, 2006)

CHAPTER 3

EXPERIMENTAL PROGRAM

3.1 Introduction

In this thesis, two-part experimental program was conducted to investigate the properties of the self-compacting mortars made with FA fine lightweight aggregates. In the first stage, artificial lightweight FA aggregates were produced through the pelletization of FA and cement at ambient temperature. After the fresh pellets were cured for 28 days, the hardened FA aggregates were sieved into fractions of 0.25-4 mm sizes to utilize in the production of SCLMs. The mini slump flow diameter and mini V-funnel time tests were carried out to identify the required properties and the characteristics of fresh SCLM mixes. Type F, FA supplied from Çatalağzı Thermal Power Plant, Zonguldak, Turkey, was utilized both as a secondary binder material at a 25% replacement level by weight of cement in the production of mortar and as for producing LWA. A polycarboxylic-ether type superplasticizer (SP) with a specific gravity of 1.07 kg/lt was employed to obtain the required workability in all mortar mixtures. Chemical compositions and physical properties of PC and FA are given in Table 3.1.

Table 3.1 Physical and chemical properties of cement and FA

Chemical analysis (%)	**Cement**	**FA**
CaO	62.6	2.2
SiO_2	20.2	57.2
Al_2O_3	5.3	24.4
Fe_2O_3	4.0	7.1
MgO	2.8	2.4
SO3	2.7	0.3
K_2O	0.9	3.4
Na_2O	0.2	0.4
Loss of ignition	3.0	1.5
Specific gravity(g/cm^3)	3.15	2.25
Blaine Fineness(m^2/kg)	326	287

3.2 Materials

3.2.1 Cement

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

3.2.2 Superplasticizer

Sulphonated naphthalene formaldehyde-based superplasticizer used to obtain target workability and reducing the balling effect of fiber (Tsai et al., 2009; Kumar et.al., 2005). It had a specific gravity of 1.07 g/cm^3. The properties of superplasticizer are given in Table 3.2.

Table 3.2 The properties of superplasticizer

Property	Superplasticizer
Name	Daracem 200
Color	Dark Brown
State	Liquid
Specific Gravity [kg/cm3]	1.07
Chemical	Sulfonated Naphthalene Formaldehyde
Freezing Point	-4

3.2.2 Fly Ash (FA)

FA class F identical to ASTM C618 (2008) was supplied mainly from Ceyhan Sugozu thermal power plant. It had a specific gravity of 2.25 g/cm^3 and 287 m^2/ kg of Blaine fineness. The physical and chemical properties of FA are provided in Table 3.1.

3.2.3 Lightweight FA Aggregates (LWFAs)

Cold-bonding process was used in the production of artificial LWFAs. For this, fine particle mixture of both FA and cement in particularized proportions (90% FA and 10% PC) was pelletized by moistening in an inclined rotating pan with a diameter of 80 cm and a depth of 35 cm (Figures 3.1 and 3.2).

The pelletization was completed after about 20 min. Dry powder mixture of about 10-13 kg was fed into the pan, then the creation of ball shaped fresh pellets were started with spraying of water to the mixture. Water amount adjusted as 21-22% by weight of the dry powder and, used to form spherical pellets with the motion of rolling disc. Subsequently, LWFAs were well-kept in sealed plastic bags and stored for hardening in a curing room at a temperature of 20C^o and a relative humidity of 70% for 28 days

(Gesoğlu et al., 2012a; Gesoğlu et al., 2012b). Thereafter, the hardened FA aggregate was sieved into fractions of 0.25-4 mm sizes to be used in SCM production.

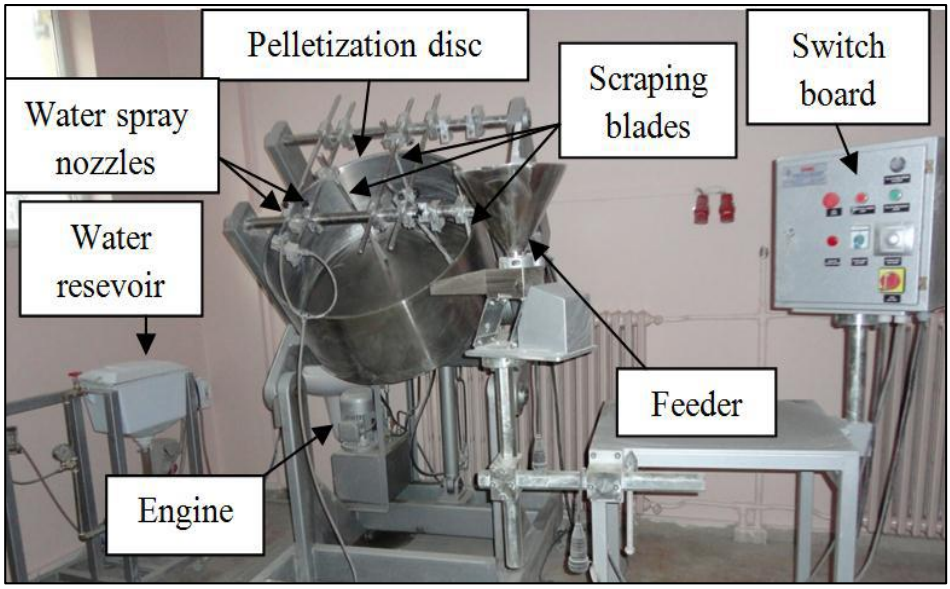

Figure 3.1 The general view of the pelletization disc

(a) **(b)**

Figure 3.2 (a) Photographic view of 45º angle (b) Formation of fresh artificial lightweight aggregates

Figure 3.3 Photographic view of sieved cold bonded lightweight fine aggregate (LWFAs)

After production specific gravity and water absorption tests were performed according to ASTM C 127 (2007) to determine properties of LWFAs. Tests showed that water absorption after 24 h was 21.15% while specific gravity of LWFAs in the terms of bulk, apparent, and saturated surface dry conditions were 1.46, 2.10, and 1.76, respectively. Figure 3.4 exhibits the absorption rate profiles measured up to 15 days. Moreover, sieve analysis and physical properties of artificial lightweight aggregates are listed in Table 3.3.

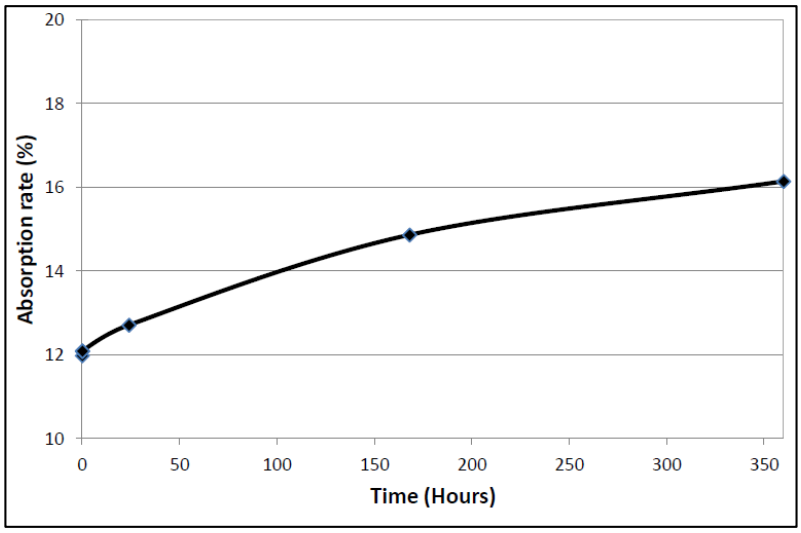

Figure 3.4 Absorption rate profile of the LWA

Table 3.3 Sieve analysis and physical properties of natural and artificial lightweight aggregates

Sieve size (mm)	NA (%)	AFAs (%)
16	100	100
8	100	100
4	86.6	100
2	56.7	75.5
1	37.7	28.9
0.5	25.7	12
0.25	6.7	4
Fineness modulus	2.9	2.8
Water absorption (%)	21.1	0.5
Specific gravity (g/cm3)	2.4	1.8

The crushing strength of LWA was determined according to BS 812, part 110 (1990). The crushing force was measured by a dial gage and it was transformed to the load. Figure 3.5 showed the sketch of crushing strength test apparatus. The statistical force applied at for failure for a number agglomerates statistically representative is defined

the crushing strength or more often called as crushing value. The crushing strength test results calculated by Equation 3.1 are presented in Figure 3.6.

$$\sigma = \frac{2.8P_{max}}{\pi X^2} \tag{3.1}$$

Where Pmax, is the fracture load and X is the distance between loadings of points (Yashima et al., 1987; Li et al., 2000; Mangialardi, 2001; Cheeseman et al., 2005). ASTM C 127 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.

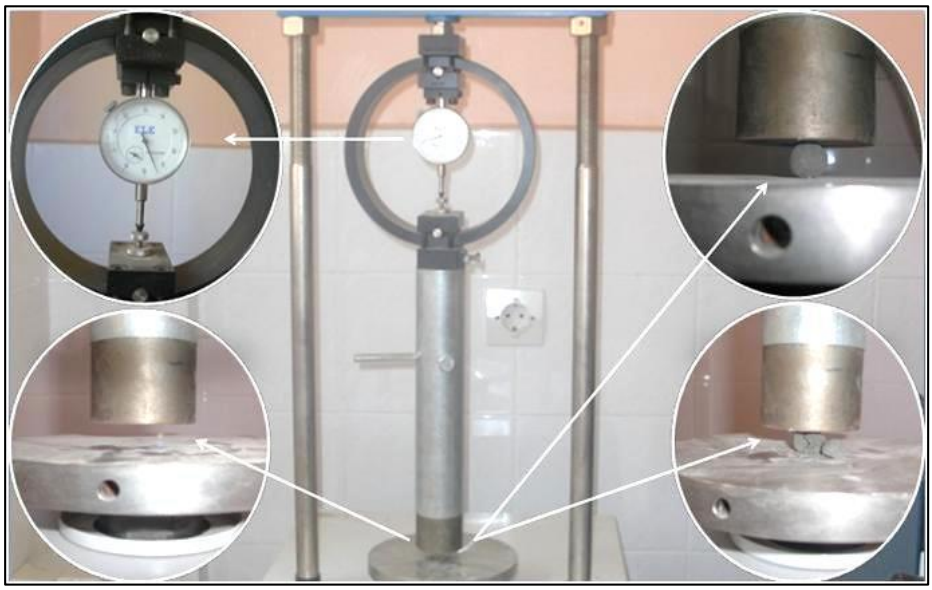

Figure 3.5 Crushing strength test apparatus

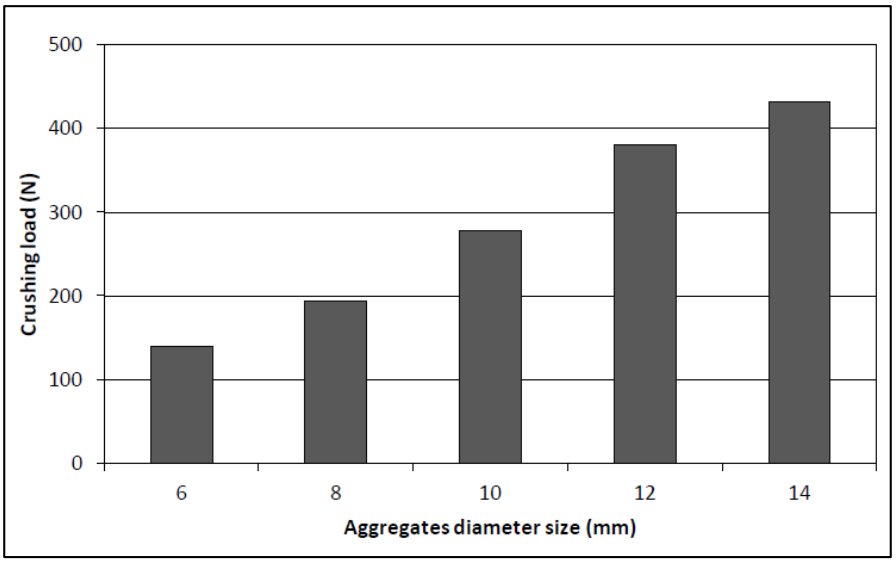

Figure 3.6 Results of crushing strength of LWA

3.2.4 Natural Aggregates (NA)

The fine aggregate used with a maximum size of 4 mm. The water absorption in natural river sand was 0.66 percent and specific gravity of 2.39 was used in SCM production. The particle size gradation obtained through the sieve analysis, physical properties, and specific gravity of the fine aggregates are presented in Table 3.3.

3.3 Mixture proportions

Totally, sixteen mortar mixtures at four variable w/b ratio were designed to investigate the effect of LWA on the fresh properties in the term of setting time of SCM as well as strength aspects. For this, the mixture was scheduled into four series based on the w/b ratio for each series; thus, w/b of 0.33, 0.37, 0.4 and 0.44 employed for series I, II, III and IV respectively. Accordingly with w/b ratio, binder content used in this study was 540, 520, 500 and 480 kg/m^3 respectively. While, the volume fractions of LWA was 0, 20, 40 and 60% for each series. As illustrated in Table 3.4, the mortar mixture with 100% NA was regarded as “control mix”; thereby, each series had a control mix to reveal the effect of variable percentage of LWA on the properties of SCM.

In all mixes, FA, as cementitious materials, was used by 25% of the total binder content. Thus, mix codes were determined according to the mixture composition. For example, 0.33NA100AFA0 indicated that SCM was designed with w/b of 0.33, the NA content of 100% and AAs of 0%, and so on. In the present study, trial batches were produced for each mixture until the desired slump flow was obtained. Besides setting time, tests conducted on fresh mortar were: mini slump flow diameter and mini V-funnel flow time as well as compressive strength of SCM. Thereby, 100 mm cubes for initial and final setting time tests were prepared and 50 mm cubes were also employed for compressive strength test in conformity (ASTM C109, 2007).

Table 3.4 Mortar mix proportions in kg/m^3

Series No.	Code	w/b	Binder content	Cement	FA	Water	NAs	LWA	HRWRA
Series I	0.33NA100AFA0	0.33	540	405	135	178.2	1483.9	0.0	12.4
	0.33NA80AFA20	0.33	540	405	135	178.2	1187.2	242.2	12.4
	0.33NA60AFA40	0.33	540	405	135	178.2	890.4	484.3	12.4
	0.33NA40AFA60	0.33	540	405	135	178.2	593.6	726.5	12.4
Series II	0.37NA100AFA0	0.37	520	390	130	192.4	1469.0	0.0	11.4
	0.37NA80AFA20	0.37	520	390	130	192.4	1175.2	239.7	11.4
	0.37NA60AFA40	0.37	520	390	130	192.4	881.4	479.4	11.4
	0.37NA40AFA60	0.37	520	390	130	192.4	587.6	719.1	11.4
Series III	0.4NA100AFA0	0.4	500	375	125	200.0	1476.9	0.0	7.5
	0.4NA80AFA20	0.4	500	375	125	200.0	1181.5	241.0	7.5
	0.4NA60AFA40	0.4	500	375	125	200.0	886.1	482.0	7.5
	0.4NA40AFA60	0.4	500	375	125	200.0	590.8	723.0	7.5
Series IV	0.44NA100AFA0	0.44	480	360	120	211.2	1469.8	0.0	6.2
	0.44NA80AFA20	0.44	480	360	120	211.2	1175.9	239.8	6.2
	0.44NA60AFA40	0.44	480	360	120	211.2	881.9	479.7	6.2
	0.44NA40AFA60	0.44	480	360	120	211.2	587.9	719.5	6.2

3.4 Preparation and Casting For the Test Specimens

In effect, to control the extreme water absorption of artificial aggregates (AAs), they were immersed in water for 30 minutes to ensure saturated surface dry condition (SSD) before mixing process (Gesoğlu, 2004; Joseph et al., 2009; Güneyisi et al., 2015) . Then, the aggregate was taken out of water and put on mesh for the outflow of immoderate surface water for about 30 s. As shown in Figure 3.7, the extra water on the surface of the pellets was rubbed out manually by a dry towel. This is an effective way to obtain SSD condition for the aggregates (Gesoğlu, 2004; Güneyisi et al., 2007; Manikandan et al., 2007). Firstly, AFAs in SSD condition was mixed with NA for about two minutes. Mixing water containing HRWRA was added gradually into the mixture and mixing continued for about eight minutes. After that, SCM was filled into steel molds for initial and final setting time tests without any vibration or compaction. Then, the compressive strength specimens were demolded and cured by water at 21±2C^{o} until testing age.

For this, trial batches were produced for each mixture till the desired slump flow was obtained. After the mixing process was completed, tests were carried out on fresh mortar to assess mini slump flow diameter, mini V-funnel flow time. The 50 mm cubes were also employed for compressive strength and one cube (100 x 100) mm for initial and final setting time tests by the apparatus penetration were cast full without any vibration or compaction. After one day of casting, they were put down and stored in water at 21±2C^{o} until the time of testing.

Figure 3.7 Preparation of LWFAs to SSD condition before mixing process

3.5 Test Methods

3.5.1 Fresh Properties

Tests carried out on fresh mortar involved mini-slump flow, mini-V-funnel flow time and Initial and final setting time by penetration test. Slump flow diameter (Figure 3.8) and V-funnel flow time (Figure 3.9) were measured according to the procedure recommended (EFNARC, 2005).

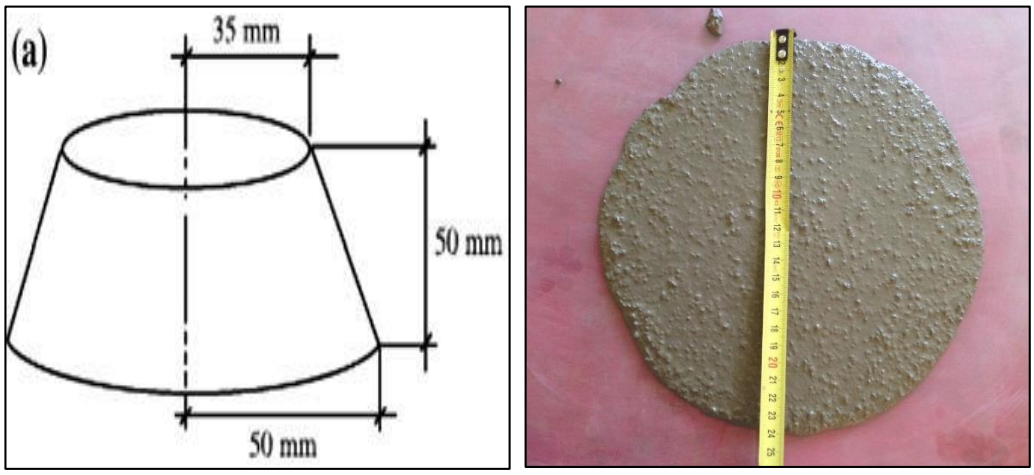

Figure 3.8 Mini-slump test for fresh mortar

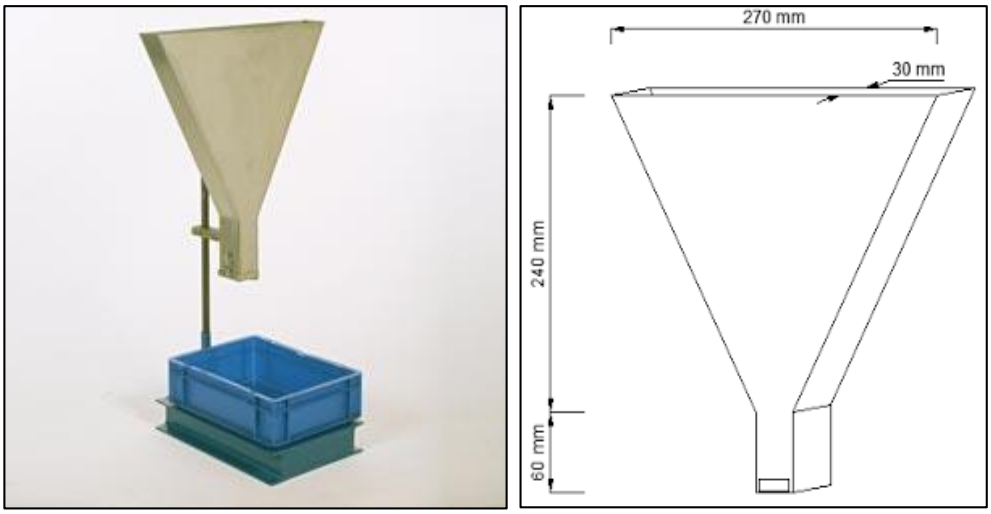

Figure 3.9 Mini-V-funnel test for fresh mortar

3.5.2 Initial and Final Setting Times

The initial and final setting time of SCM was determined through the penetration test in conformity with ASTM C403 (2008). Although this test method covered the determination of the setting time for concrete, but it can be used to measure the penetration resistance of mortars derived from the concrete mix (Ahmadi, 2000). In effect, initial and final setting time can be defined as the elapsed time, after initial contact between cement and water, required for the mortar to reach a penetration resistance of 3.5 and 27.6 MPa, respectively (ASTM C403, 2008). To conduct the setting time test, the mortars were placed inside a 100 mm cube container and stored in a controlled environment of 20±2 C^{o} and 65±5% relative humidity during the test duration. Then, the force requiring penetrating standard of 5 mm diameter needles by 25 mm inside the SCM specimens was measured at regular time intervals during the test period. As depicted in (Figure 3.10), a spring reaction-type, ELE penetration resistance apparatus conforming to (ASTM C403, 2008) was used to measure the setting time for SCM. Thus, the initial and final setting times were recorded whenever the penetration resistance reached above mentioned values. Thereby, the times of

initial and final setting were determined by penetration resistance versus elapsed time chart for each mixture.

Figure 3.10 Measurement of setting times of the mixtures

3.6 Tests for Hardened Properties

3.6.1 Compressive Strength

Compressive strength test was performed on 50x50x50 mm cube specimens at 3, 7, 28, 56 and 90 days coinciding with ASTM C39 (2012) for all LWFA. Three cubes for each mixture investigated with a machine having 2000 KN capacity and loading rate of 0.8 KN/sec Figure 3.11.

Figure 3.11 Compressive strength test machine with 2000 kN capacity

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Slump Flow Diameter and V-funnel Flow Time of SCM

The slump flow diameter shifting between 23.8 cm and 28.7 cm was achieved ash shown in Figure 4.1. It was observed that slump flow diameter constantly decreased by increasing the artificial lightweight aggregate replacement level at all w/b ratios. The lowest slump flow diameter values were obtained at 60% artificial lightweight aggregate replacement level.

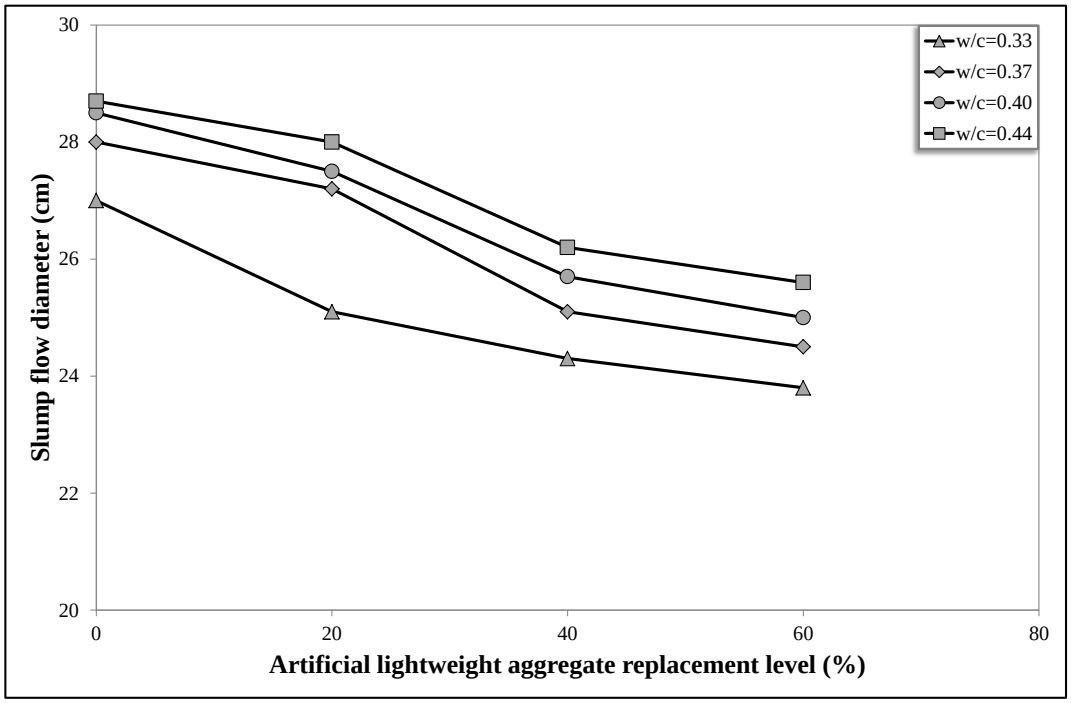

Figure 4.1 Slump flow diameter of the self-compacting mortars versus replacement level of artificial lightweight aggregate

Thus, compared with control mixtures, the percentage of decrease in the slump flow

diameter was about 11.9%, 12.5%, 12.3%, and 10.8% at the AAs replacement level of 60% for the w/b ratios of 0.33, 0.37, 0.40, and 0.44, respectively. The percent passing of the AAs from the 0.5-mm sieve was about 12.0 while that of NA was approximately 25.7. Namely, the fine proportion of NA is more than that of the AAs. This caused the lower flowability of the mortar since the flowing of mortar was achieved because of the rolling of small particles. This is the reason of decrease in slump flow diameter by increasing the AAs content. Obviously, slump flow results revealed that increasing the w/b ratio decreased the cohesiveness of the mortar which resulted in a bigger slump flow diameter. Moreover, the mortars manufactured at higher w/b ratio had a more flowable cement paste. For this reason, the tendency of the mortar to flow increased. For instant, the slump flow diameter of control mixture at w/b ratio of 0.33 was about 27.0 cm, while the slump flow diameter of the other control mixtures manufactured at w/b ratios of 0.37, 0.40, and 0.44 were about 28.0, 28.5, and 28.7 cm (Table 4.1).

In addition to slump flow diameter results, V-funnel flow time also indicated that the SCM produced at higher w/b ratio had higher flowability characteristic. The results of V-funnel flow time with respect to AAs content was presented in Figure 4.2. It can be easily seen from the figure that utilization of the AAs reduces the flowability of the mortars. It can be caused due to the low specific gravity of the AAs and also its lower finer content. Flowing of mortar from the V-funnel is due to its own weight and when the AAs utilized instead of NA resulted in lighter mortar.

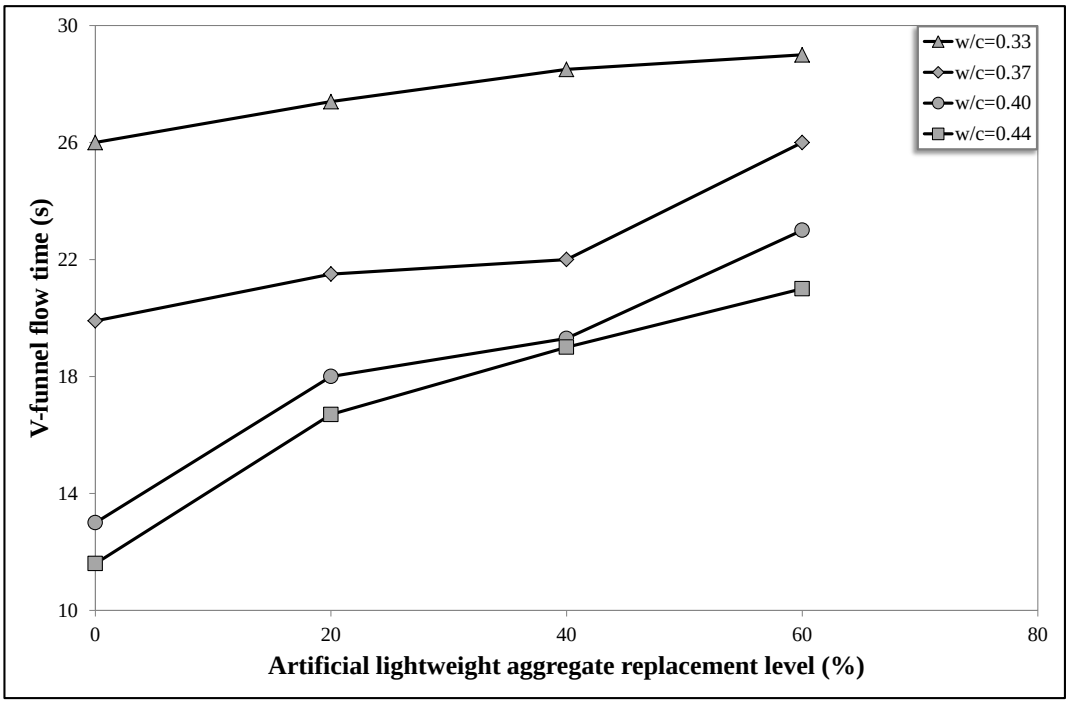

Figure 4.2 V-funnel flow time of self-compacting mortars versus replacement level of artificial lightweight aggregate

For this reason, the flowing time was increased. Increasing the AAs content form 0% to 60% increased V-funnel flow time from 26.0 to 29.0 s, 19.9 to 26.0 s, 13.0 to 23.0 s, and 11.6 to 21.0 for the SCM manufactured at w/b ratios of 0.33, 0.37, 0.40, and 0.44, respectively. Although the replacing the NA with AAs at certain levels increased the V-funnel flow time, the results are acceptable for application of such mortars. Furthermore, since AAs consist of 10% cement and 90% FA, these aggregates tend more to involve in the hydration reaction compared with inert performance of NA (Lo et al., 2004). Thus, a further part of mixing water will be involved in the hydration and consumed causing a decrease in the fluidity of mortar. Likewise, this reaction produces a denser microscopic structure owing to high rate of calcium silicate hydrate (C-S-H) (Güneyisi et al., 2012).

Table 4.1 Fresh properties and strength results of SCM

Series No.	Code	Slump Diameter (cm)	V-funnel (sec)	Compressive Strength (MPa)				
				3	7	28	56	90
Series I	0.33NA100AFA0	27.0	26.0	54.7	62.6	86.8	98.2	107.0
	0.33NA80AFA20	25.1	27.4	40.9	50.8	73.5	81.0	90.2
	0.33NA60AFA40	24.3	28.5	35.1	39.0	55.8	60.1	69.6
	0.33NA40AFA60	23.8	29.0	23.1	27.5	38.4	45.6	50.9
Series II	0.37NA100AFA0	28.0	19.9	51.7	60.5	74.5	87.3	96.4
	0.37NA80AFA20	27.2	21.5	38.6	43.4	63.6	71.5	78.6
	0.37NA60AFA40	25.1	22.0	26.4	34.0	47.1	57.5	65.6
	0.37NA40AFA60	24.5	26.0	22.9	26.8	33.7	41.6	49.2
Series III	0.4NA100AFA0	28.5	13.0	44.5	52.8	63.5	72.8	83.5
	0.4NA80AFA20	27.5	18.0	36.5	40.5	56.1	65.3	73.4
	0.4NA60AFA40	25.7	19.3	25.4	31.4	44.0	53.4	60.0
	0.4NA40AFA60	25.0	23.0	19.8	24.9	30.5	37.9	44.5
Series IV	0.44NA100AFA0	28.7	11.6	35.8	45.9	59.3	67.7	79.7
	0.44NA80AFA20	28.0	16.7	26.2	36.5	52.1	60.2	68.8
	0.44NA60AFA40	26.2	19.0	22.9	28.7	40.3	51.0	57.1
	0.44NA40AFA60	25.6	21.0	17.2	25.2	28.2	35.3	44.0

4.2 Initial (IS) and Final (FS) Setting Times

The results of initial and final setting times for the SCM produced in this study are graphically depicted in Figure 4.3 and Figure 4.4, respectively. It is deemed as an essential standard consistency, beside the strength and soundness of cement and mortar. It is essential that cement or mortar set neither too rapidly nor too slowly. In the first case there may be insufficient time to transport and place the concrete before it becomes too rigid. While, too long setting period tends to slow up the work unduly, also it may postpone the construction time of the structure because of inadequate strength at the desired age.

Hence, the setting time property has a great importance, particularly for in-situ works. The results of IS that can be defined as the duration to limit the handling and placing of mortar and/or concrete was illustrated that increasing the w/b ratio decreased the IS of mortar. However, this situation occurred due to the decreasing of the superplasticizer content by increasing the w/b ratio. In the mixture, by this way the demand for superplasticizer that was used to achieve the desired flowability properties was decreased. When the superplasticizer content in the mixtures decreased, the hardening of the cement paste accelerated since the polycarboxylic ether based superplasticizer delay the hardening of the cement paste. The IS for the SCM produced with the w/b ratio of 0.33, 0.37, 0.40, and 0.44 without the AAs were about 599 min, 446 min, 385 min, and 340 min, respectively, whereas the final setting time for them were about 894 min, 775 min, 676 min, and 550 min, respectively. Because, increasing the w/b ratio directly reasoned to increasing of the water content.

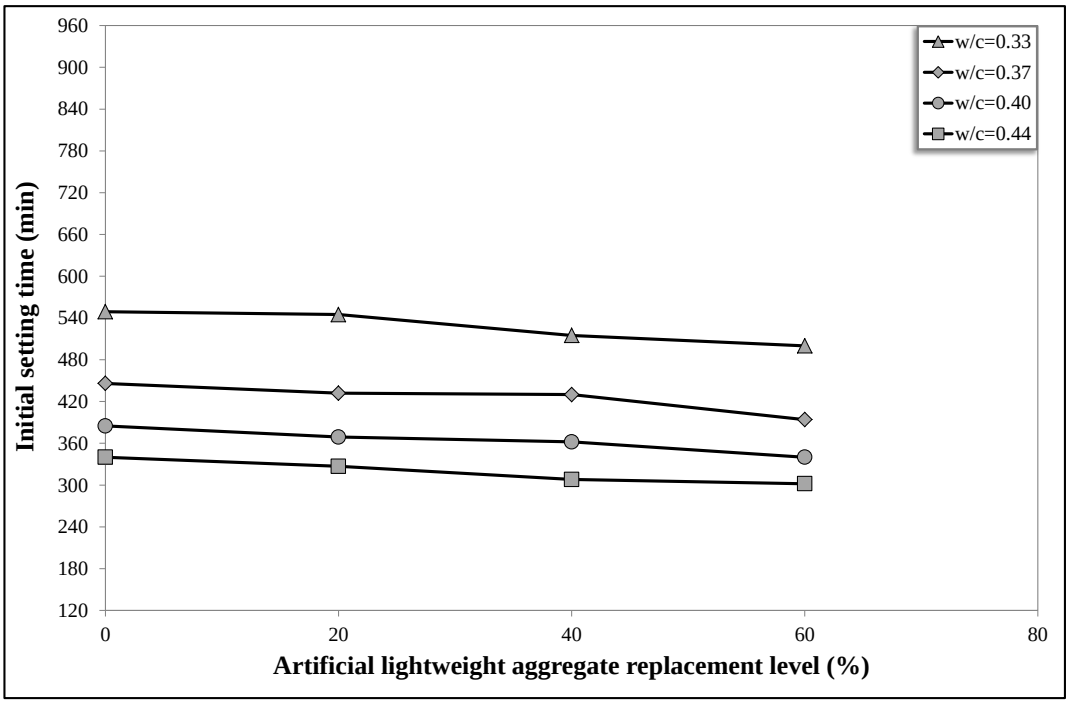

Figure 4.3 Variation in initial setting times of the SCM with respect to AAs content

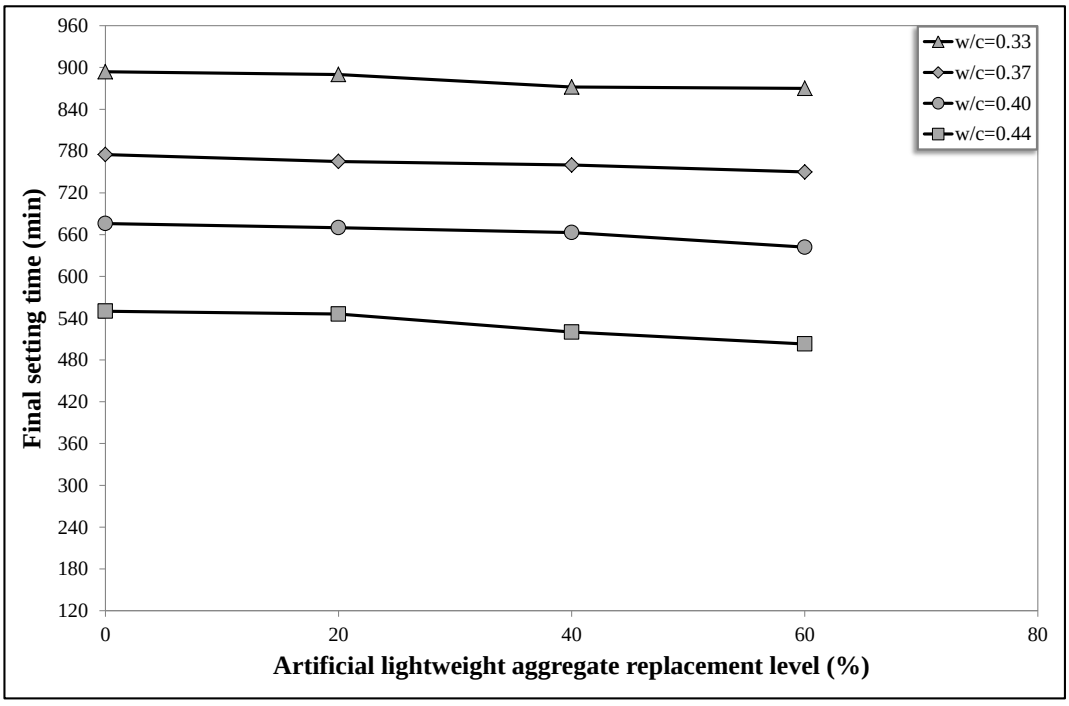

Figure 4.4 Variation in final setting times of the SCM with respect to AAs content

The results showed that decreasing the w/b ratio namely increasing the superplasticizer content caused increasing the final setting time. Decreasing the superplasticizer content from 12.4 kg/m^3 to 6.2 kg/m^3 resulted in approximately 43.2% and 38.5% decreasing of the initial and final setting times, respectively. However, significant effect of the AAs utilization was not observed because measuring the initial and final setting time by using ASTM C403 (2008) standard depend on the hardening of the cement paste.

For this reason, changing the aggregate type was not directly influenced the initial and final setting times. Actually, dense shell forms around the artificial AAs particles due to the effect of cement paste infiltration through the AAs pores and well-hydrated cement grains. Thereby, a much denser binder phase can be produced causing acceleration in setting time (Lam, 2005; Güneyisi, 2008). Around the AAs, the amount of hydrated cement paste increased since the cement particles easily found water to hydrate that was also known as internal curing effect (Akçay, 2007). For this reason, the small amount of decreasing in the setting times by increasing the AAs content was investigated.

4.3 Compressive Strength of SCM

The compressive strength development of the SCM with respect to replacement level of AAs is indicated in Table 4.1 and Figures 4.5, 4.6, 4.7 and 4.8.

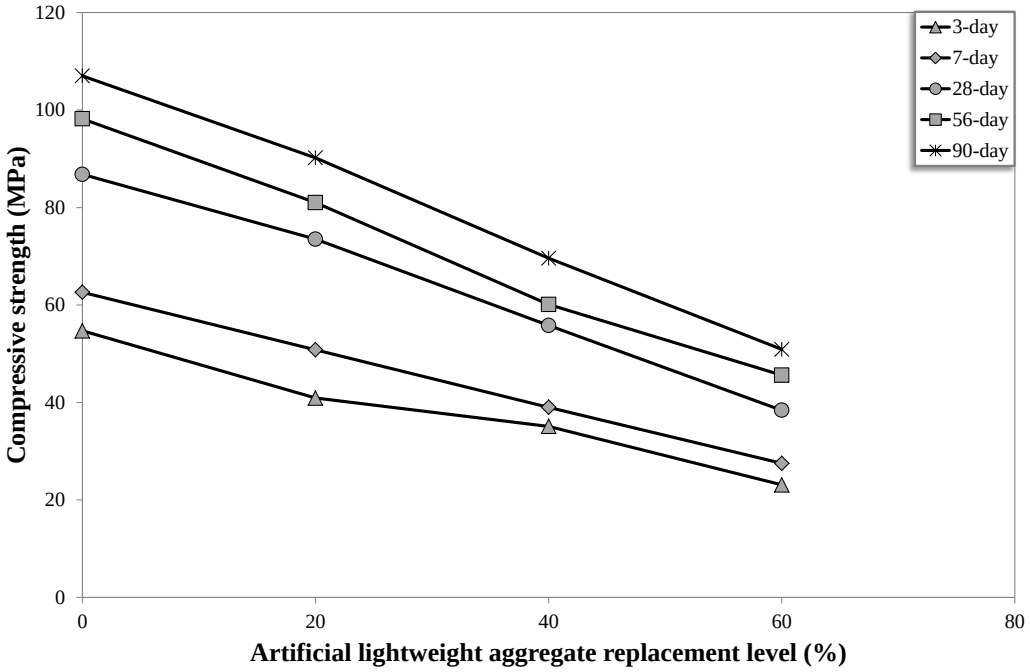

Figure 4.5 The compressive strength regarding to replacement level of AAs at w/b of 0.33

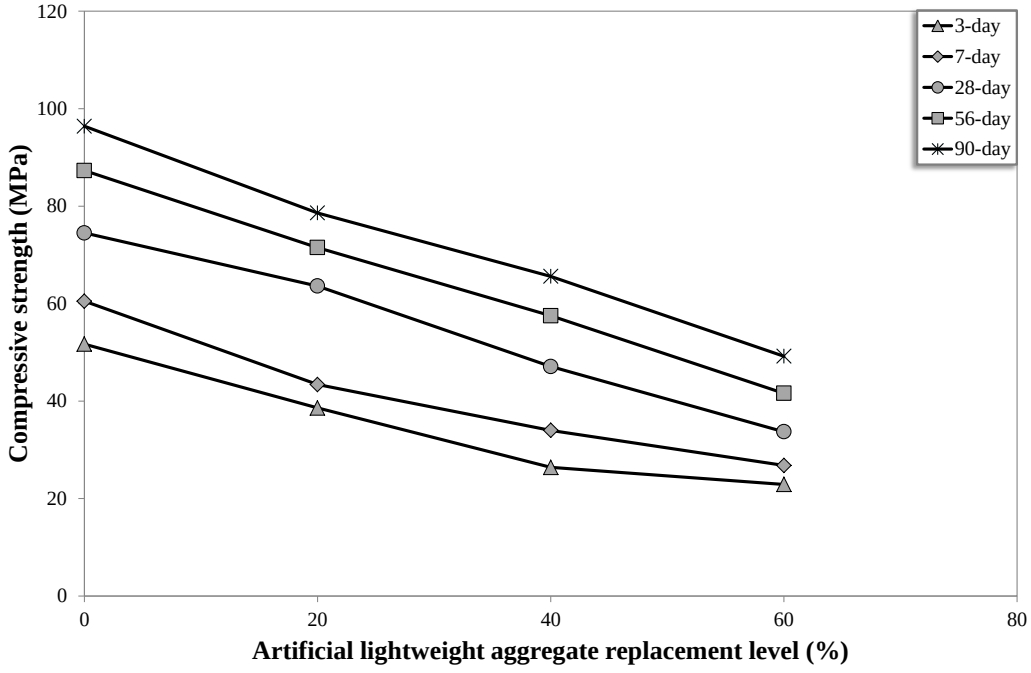

Figure 4.6 The compressive strength regarding to replacement level of AAs at w/b of 0.37

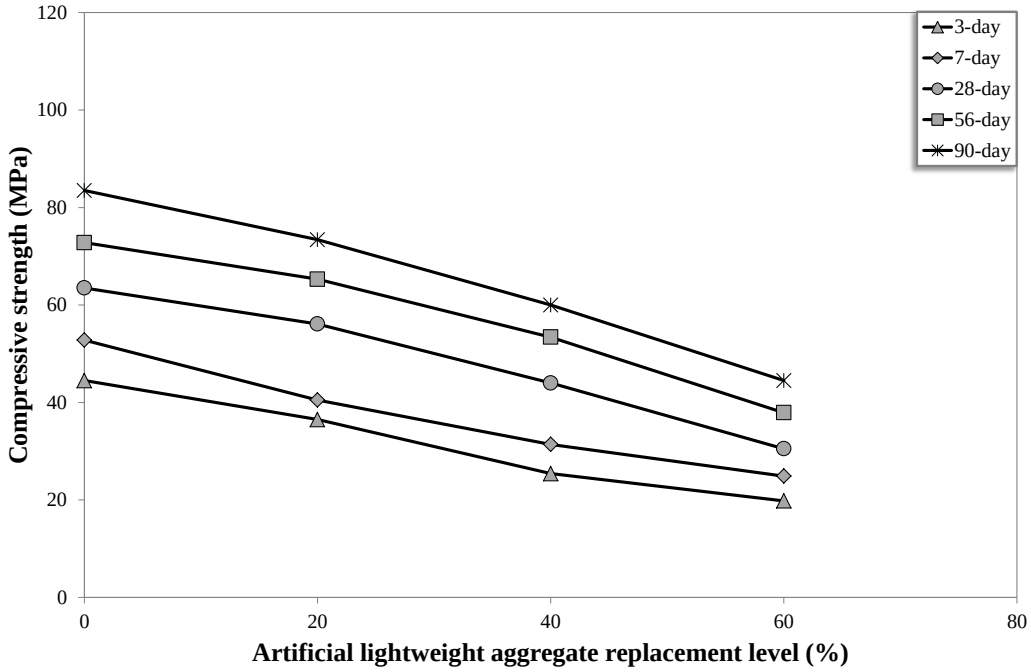

Figure 4.7 The compressive strength regarding to replacement level of AAs at w/b of 0.4

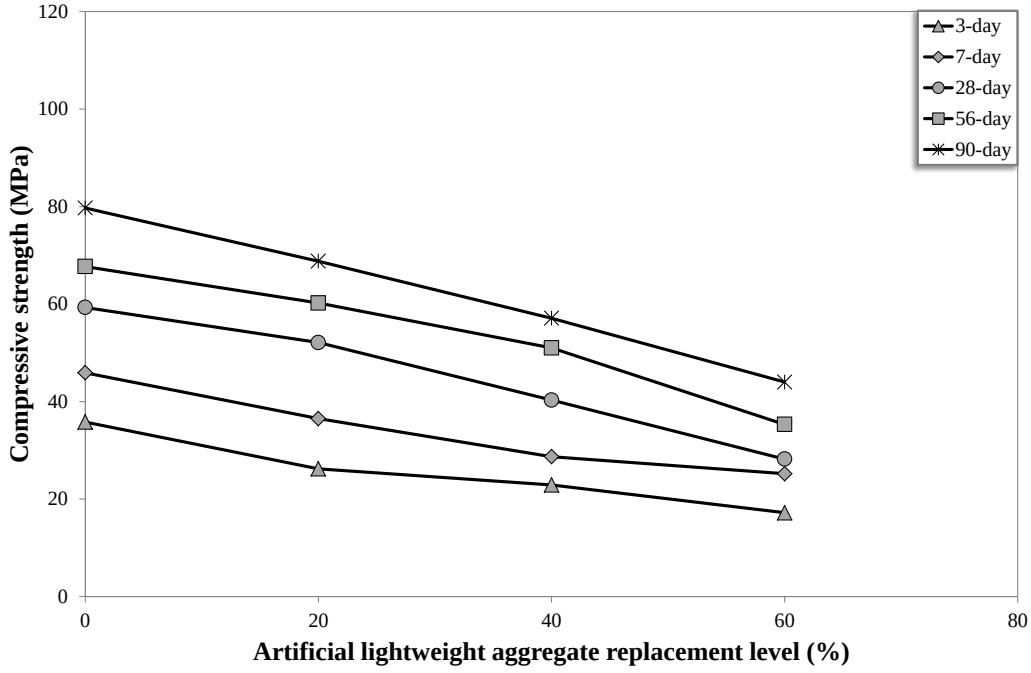

Figure 4.8 The compressive strength regarding to replacement level of AAs at w/b of 0.44

It can be obviously seen that the compressive strength of the SCM was reduced by utilization of the AAs. The AAs has lower particle strength compared with NA. For this reason, increasing the AAs content resulted in systematical decreasing in the compressive strength of the mortars. Moreover, the AAs particles obtained by agglomeration of FA and cement powder with water.

During the agglomeration process, spherical FA particles stick each other and some amount of voids remained in the particles. This situation is the reason of the lower specific gravity of the AAs produced in this study. The lower specific gravity and higher water absorption produce more porous, cellular and then weak aggregates. Hence, the strength, particle size distribution and water absorption capacity of the AAs can be considered as a decisive factor indicating the final strength of mortar (Kayali, 2008). However, the lost in the compressive strength due to the use of AAs can be balanced by decreasing the w/b ratio.

The effect of w/b ratio on the compressive strength of the SCM was also experimentally investigated. The results indicated that decreasing the w/b ratio resulted in significant increasing in the compressive strength. The compressive strength of the SCM was measured at 3-day, 7-day, 28-day, 56-day, and 90-day specimens. The highest compressive strength values were observed at the age of 90 days. FA incorporation had an important effect on the compressive strength at the later age since the secondary hydration reaction was started due to the pozzolanic properties of FA. The 3-day compressive strength values changing between 17.2 and 54.7 MPa was achieved in this study while the 7-day, 28-day, 56-day and 90-day compressive strength values were between 25.2 and 62.6 MPa, 28.2 and 86.8 MPa, 35.3 and 98.2 MPa, and 44.0 and 107.0 MPa, respectively. The compressive strength test results

revealed sort of high early strength, particularly at the first 7 days. Table 4.1. Decresing the w/b ratio from 0.44 to 0.33 at 0% AAs content increased the compressive strength values as much as 52.8%, 36.4%, 46.4%, 45.1%, and 34.3 MPa at the age of 3, 7, 28, 56, and 90 days, respectively, while the increasing rate due to the decreasing of w/b ratio was about 34.3%, 9.1%, 36.2%, 29.2%, and 15.7% at 60% AAs content at the aforementioned testing ages, respectively.

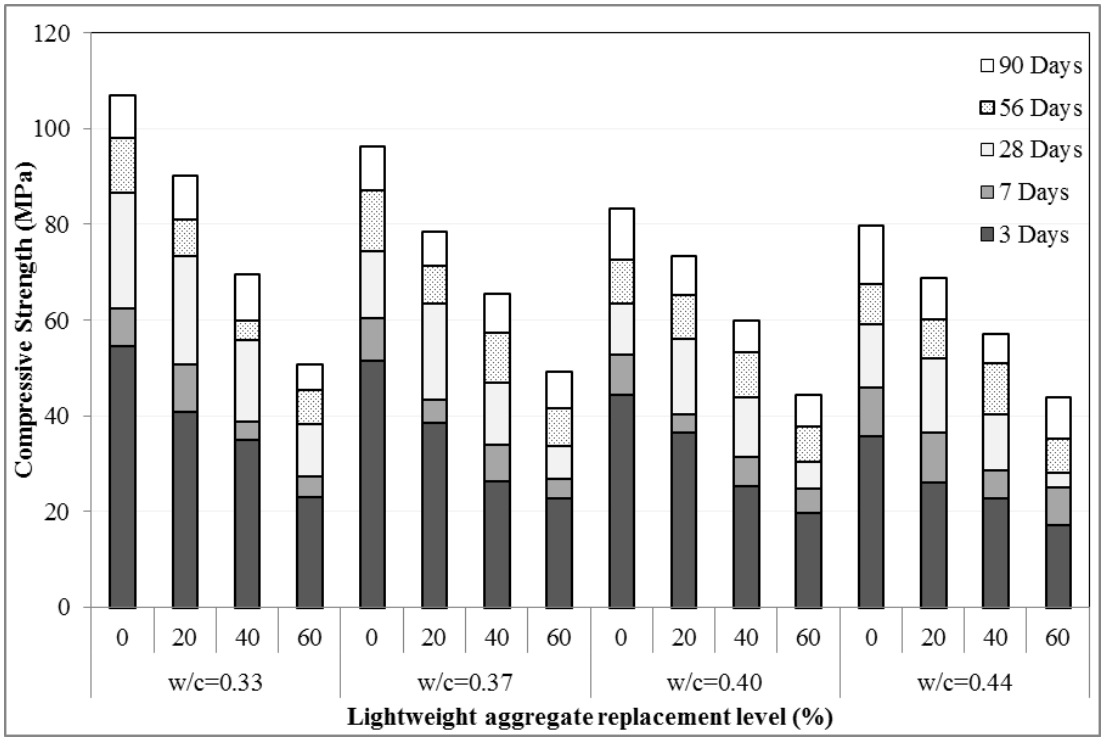

Figure 4.9 Effect of replacement level of AAs on the various age of compressive strength

In conventional mortar and concrete, the interfacial transition zone (ITZ) is the weakest component inside its matrix because of the higher porosity and presence of higher amount of $Ca(OH)_2$ as well as the biggish width of this area (about 50-100 μm). While for LWA, the ITZ is strengthened through decreasing the width of this region to become approximately 5-10 μm (Lo, 2004; Lo and Cui, 2004).

Hence, the failure phase transfers from ITZ into aggregate phase, which is inevitably weak. (Figure 4.10) emphasizes the aforementioned opinion and shows the difference between the failure shape of control mixture and 60% AAs mortars. Clearly, it could be claimed that the failure line passed through the ITZ phase in the case of control mortar, because the high percentage of intact NA was available. Conversely, for AAs mortars, most of aggregates suffered from shear failure indicating that the failure line had passed through aggregate phase (Figure 4.6-b).

(a) (b)

Figure 4.10 Failure shape of SCM (a) made with 100%NA and (b) made with 60% AAs

In this study, all SCM examined herein revealed sort of high initial strength in early ages, particularly at the first 7 days. In series I, for example, the compressive strength represented about 65% of total mortar strength (at 56 days). This is attributing to the absence of the “wall effect” or “surface effect”, which occurs at the surface of the normal weight aggregate. Also, the lack of a distinct boundary at the ITZ improves the integrity of lightweight mortar (Lo, 2004; Lo and Cui, 2004). Moreover, the high quantity of water available in the ITZ increases the amount of hydrated cement on the

surface of LWA compared with inner regions, owing to abundance of hydration product on the aggregate surface. However, LWA provide an interesting feature for mortar or concrete; it is a better bond between the aggregate and the surrounding hydrated cement paste than NA (Takada, 1999).

The reason for this lies in the fact that the surface texture of these aggregates has more roughness than equivalent NA, which is conducive to a good mechanical interlocking. Also, the roughness of LWA stimulates the ettringite crystals to form on the outer skin of the aggregate. Actually, the ITZ between the LWA and cement paste is tight and is characterized by a mechanical interlocking in combining chemical interaction in the form of pozzolanic reaction. Hence, the voids disperse inside and on the surface of aggregate allowing the C-S-H structure to form and grow with minimal hindrance (Lam, 2005). Some of the cement paste often infiltrates into the open surface pores of LWA particles (Neville, 1995). Indeed, the particle size distribution of cement and other cementitious materials, the viscosity of the paste and microstructure of the surface layer of the aggregate control the amount of cement paste penetration (Zhang and Gjorv, 1992). So, regardless of the weakness of AAs, the strength of a specific type of semi-LWA mortars (such as artificial slag aggregate mortars) is expected to be higher than NA mortars and/or concrete (Gesoğlu et al., 2012).

CHAPTER 5

CONCLUSIONS

According to the experimental results achieved from the study presented above, the following conclusions can be drawn:

- Slump flow diameter decreased whenever the AAs was incorporated. Also, increasing the w/b ratio resulted in higher slump flow diameter of the SCM.

- Producing the SCM with higher w/b ratio enhanced the flowability and decreased the demand for superplasticizer. However, the AAs utilization negatively affected the flowability of the mortars when V-funnel flow times were considered.

- Test results showed that both initial and final setting times of the SCM was significantly affected by the water-to-binder ratio. However, decreasing in the superplasticizer content due to reduction in the demand for it by increasing the w/b ratio significantly affected the initial and final setting times. The results indicated that decreasing the superplasticizer content reduced the initial and final setting times. Moreover, the utilization of the AAs caused slight decreasing.

- The compressive strength of the self-compacting mortars remarkably influenced by the AAs content. Decreasing in the compressive strength was observed by increasing the AAs. However, decreasing the w/b ratio importantly increased the compressive strength values of the mortars at the mortar ages of 3-day, 7-day, 28-day, 56-day, and 90-day.

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