Effect of Cold Bonded and Sintered Fly Ash Lightweight Aggregates on Permeability and Corrosion Behavior of Concrete

University of Gaziantep

Civil Engineering

M.Sc. Thesis

Supervisor

Assoc. Prof. Dr. Erhan GÜNEYİSİ

by

Özgür PÜRSÜNLÜ

January 2013

REPUBLIC OF TURKEY
UNIVERSITY OF GAZIANTEP
GRADUATE SCHOOL OF NATURAL & APPLIED SCIENCES
CIVIL ENGINEERING DEPARTMENT

Name of the thesis: Effect of Cold Bonded and Sintered Fly Ash Lightweight Aggregates on Permeability and Corrosion Behavior of Concrete

Name of the student: Özgür PÜRSÜNLÜ

Exam Date: 16 January 2013

Approval of the Graduate School of Natural and Applied Sciences

Assoc. Prof. Dr. Metin BEDİR
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master Science

Prof. Dr. Mustafa GÜNAL
Head of Department

This is to certify that we have read this thesis and that in our consensus/majority opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master Science

Assoc. Prof. Dr. Erhan GÜNEYİSİ
Supervisor

Examining Committee Members	Signature
Assoc. Prof. Dr. Erhan GÜNEYİSİ	………………
Assoc. Prof. Dr. Mehmet GESOĞLU	………………
Assist. Prof. Dr. Nihat ATMACA	………………

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Özgür PÜRSÜNLÜ

ABSTRACT

EFFECT OF COLD BONDED AND SINTERED FLY ASH LIGHTWEIGHT AGGREGATES ON PERMEABILITY AND CORROSION BEHAVIOR OF CONCRETE

PÜRSÜNLÜ, Özgür
M.Sc. in Civil Engineering
Supervisor: Assoc. Prof. Dr. Erhan GÜNEYİSİ
January 2013
66 Pages

This thesis reports the finding of an experimental study carried out on the strength and durability related properties of the lightweight concretes (LWC) including either cold bonded (CB) or sintered (S) fly ash aggregates. CB aggregate was produced with cold bonding pelletization of class F fly ash (FA) and Portland cement (PC) while S aggregate was produced by sintering the fresh aggregate pellets manufactured from FA and bentonite (BN). Two concrete series with water-to-binder (w/b) ratios of 0.35 and 0.55 were designed. Moreover, silica fume (SF) with 10% replacement level was also utilized for the purpose of comparing the performances of LWCs with and without ultrafine SF. The properties of LWCs were evaluated in terms of compressive strength, water sorptivity, rapid chloride ion permeability, gas permeability, and accelerated corrosion testing after 28 days of water curing period. The results revealed that S aggregate containing LWCs had relatively better performance than LWCs with CB aggregates. Moreover, the incorporation of SF provided further enhancement in permeability and corrosion resistance of the concretes.

Key Words: Cold bonding, Corrosion, Permeability properties, Concrete, Sintering

ÖZ

SOĞUK BAĞLAMA VE SİNTERLEME YÖNTEMİYLE ÜRETİLMİŞ UÇUCU KÜL HAFİF AGREGALARIN BETONUN GEÇİRİMLİLİK VE KOROZYON DAVRANIŞI ÜZERİNE ETKİSİ

PÜRSÜNLÜ, Özgür
Yüksek Lisans Tezi, İnşaat Mühendisliği
Danışman: Doç. Dr. Erhan GÜNEYİSİ
Ocak 2013
66 Sayfa

Bu tez çalışmasında, soğuk bağlanmış ve sinterlenmiş uçucu kül agregası içeren hafif betonların dayanım ve durabilite ile ilgili özellikleri deneysel olarak araştırılmıştır. Uçucu kül ve bentonit'den üretilen taze agrega tanelerinin fırında sinterlenmesi ile sinterlenmiş agrega üretilirken, F tipi uçucu kül ile çimentonun soğuk bağlama yöntemi ile soğuk bağlanmış agregalar üretilmiştir. Su/Bağlayıcı oranı 0.35 ve 0.55 olan iki seri beton tasarımı yapılmıştır. Buna ek olarak hafif betonların silis dumanlı ve silis dumansız performanslarını kıyaslamak için %10 oranında silis dumanı çimento ile yer değiştirilerek kullanılmıştır. 28 günlük kür süresi sonunda hafif betonların özellikleri, basınç dayanımı, su geçirimliliği, hızlı klorür geçirimliliği, gaz geçirimliliği ve hızlandırılmış korozyon testleri bakımından değerlendirilmiştir. Sonuçlar, sinterlenmiş agrega içeren hafif betonların soğuk bağlanmış agrega içeren hafif betonlara göre daha iyi performans gösterdiğini ortaya çıkarmıştır. Ayrıca, üretimde silis dumanı kullanımı özellikle geçirgenlik ve korozyon dayanımının artırılmasını sağlamıştır.

Anahtar Kelimeler: Soğuk bağlama, Korozyon, Geçirimlilik özellikleri, Beton, Sinterleme.

This thesis dedicated to my wife and my son

For their endless patience and support

ACKNOWLEDGEMENTS

The author would like to thank to; Assoc Prof. Dr. Erhan GÜNEYİSİ for his guidance, supervision and patience throughout the study.

My special thanks to Assoc. Prof. Dr. Mehmet GESOĞLU for sharing his valuable experience and time throughout the study.

Research assistant Kasım MERMERDAŞ, for helping in every step of the study and being always around, with his continuous and endless support.

Research assistants H. Öznur ÖZ and Süleyman İPEK. I thank them all for their support and friendship throughout the preparation of this thesis.

Finally I would like to thank to my wife A. Tuba PÜRSÜNLÜ for being the invisible support and her encouragement.

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LIST OF SYMBOLS / ABREVIATIONS

ASR	Alkali Silika Reaction
BN	Bentonite
C	Coulumbs
CB	Cold Bonded
E	Modulus of Elasticity
FA	Fly Ash
RHA	Rice Husk Ash
K_g	Apparent gas permeability coefficient
LECA	Light Weight Expanded Clay Aggregate
LWA	Lightweight Aggregate
LWAC	Lightweight Aggregate Concrete
LWC	Lightweight Concrete
MK	Metakaolin
NWC	Normal Weight Concrete
PC	Portland Cement
RCPT	Rapid Chloride Permeability Test
S	Sintered
SF	Silica Fume
WA	Water Absorption
W/B	Water/Binder
W/C	Water/Cement

CHAPTER 1
INTRODUCTION

1.1. General

Management of industrial waste materials is one of the most significant environmental issues. Concrete technology can propose some solutions for recycling some industrial wastes such as silica fume (SF), rice husk ash (RHA), fly ash (FA), blast furnace slag, etc. For couple of decades usage of such minerals as a cement replacement substance has been practiced by many investigators. However, utilization of industrial waste powder materials such as FA and blast furnace slag in production of artificial aggregate has attracted the attentions of investigators and practitioners as an alternative way for larger consumption (Gesoğlu et al., 2012a; Koçkal, 2008).

Since aggregate is the main occupants of concrete (about 65% to 75% of total concrete volume), it may be considered as an effective solution to use such waste materials as artificial aggregate in concrete. Artificial aggregates can be manufactured through processing of different materials and production methods like cold bonding pelletization and sintering (Gesoğlu et al., 2012a; Arslan and Baykal, 2000; Gesoğlu, 2004; Dongxu et al., 2002, Cheeseman and Vindi, 2005; Joseph and Ramamurthy, 2009; Gesoğlu et al., 2012b). Cold bonding is a kind of bonding technique that activates the ability of pozzolanic powder material to react with portlandite at ordinary temperatures to form a bonding material. Pelletized aggregates are left to cure for several days to produce an aggregate with proper strength to be used in concrete production (Koçkal, 2008). On the other hand, sintering method which is mainly based on atomic diffusion is a common application for mass production of lightweight aggregates. Because, aggregate particles, immediately after pelletization process are treated with high temperatures up to 1200 ^{o}C, and become ready for use without keeping for long term curing periods.

Although huge amount of fly ash exist as a result of industrial process up to 15 million tons per year from a wide variety of industries, only a small portion is benefited in the construction industry in Turkey (Turkish Standard Institute, 2010). Therefore, using FA in production of artificial aggregate can be considered as an effective way for recycling. Although general trend for production of artificial aggregates is governed by sintering method, the energy saving concern has led the researchers to benefit from cold-bonding pelletization process for production of artificial aggregates.

In manufacture of cold bonded (CB) and sintered FA aggregate quantity and type of binder has important effect on the characteristics of final product (Cheeseman and Vindi, 2005; Gesoğlu et al., 2012b; Koçkal, 2008; Koçkal et al., 2011; Geetha and Ramamurthy, 2011; Ramamurthy and Harikrishnan, 2006) In the study of Koçkal (Koçkal, 2008), it was reported that using of 10% bentonite with 1200 ^{o}C in production of sintered fly ash aggregate, provided high strength and low specific gravity. Geetha and Ramamurthy (Geetha and Ramamurthy, 2006) used different types of clay binders for sintering process. They proposed that for 10% bentonite containing aggregates sintering temperature and duration of about 1000 ^{o}C and 95 min. provided optimum properties for the artificial aggregates produced from pulverized bottom ash.

In this thesis, two different lightweight aggregates, namely cold bonded (CB) and sintered (S) fly ash aggregates were used as coarse aggregate in concrete production. For the manufacture of aggregates, 10% Portland cement (PC) and 10% bentonite were used as binders for CB and S aggregates, respectively. Based on the findings presented in the literature, parameters for sintering process were selected as 1100 ^{o}C as sintering temperature and 60 min. as sintering duration. CB aggregates were kept in sealed plastic bags for 28 days in order to obtain proper strength and water absorption. After completing the aggregate production, concrete mixtures were prepared and tested at 28 days of curing in order to evaluate the mechanical, permeability, and corrosion properties. For this, 60% of the total aggregate volume was replaced with coarse CB or S aggregate. Furthermore, being one of the most commonly used mineral admixtures, silica fume (SF) was also utilized as a cement replacement material at 10% level of substitution to enhance the performance of the lightweight concretes. Compressive strength was measured as mechanical property while water sorptivity, rapid chloride permeability, and gas permeability of concretes were tested as permeability properties. Moreover, being one of the most important durability properties, the corrosion behavior of concretes were also monitored through an accelerated corrosion testing.

1.2. Outline of the Thesis

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

Chapter 2 – Literature Review: A literature survey was conducted on the transport properties. The previous studies on the use of fly ash for producing lightweight aggregate are investigating.

Chapter 3 – Experimental Study: Materials, mixtures, production, curing conditions, sintering and cold bonding process, and test methods are described.

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

Chapter 5 – Conclusion: Conclusion of the thesis and recommendation for the future studies are given.

CHAPTER 2
LITERATURE REVIEW

2.1. FLY ASH

Fly ash is a general name used for the residual products of combustion that rise with flue gases. Fly ashes diameter change between 1 μm–150 μm. Fineness of Fly ash more than Portland Cement. Types of coal and quantities of incombustible particles determine the chemical ingredients of fly ash. The major chemical constituents in fly ash are silica, alumina and oxides of calcium and iron. Iron, alumina, silica, oxides of calcium are some fly ash chemical constituents. The reason of why we can use to fly ash in concrete and cement, is Puzzolonic activities, fineness. Amount of Fly ash is 75–85% of the total coal ash. Remaining parts of it are boiler slag and bottom ash. This remaining parts coarser than fly ash. Also their natures are not puzzolonic whereas Fly ash has puzzolonic nature. Each Power Plants mineralogical compositions and puzzolonic features can change where it's produced. In some cases they cannot used in cement and concrete (Siddique, 2008).

2.1.1. Mineralogical Composition

The mineralogical composition of FA is dependent on the features and composition of the coal burned in the power plant. The characteristics of coal directly influence the mineralogical, chemical properties of FA. Rate of cooling, burning temperature can be considered as the other crucial factors affecting the properties of fly ash. The minerals exist in fly ash are listed in Table 2.1 (Wesche, 1991).

Table 2.1 Minerals in fly ash (Wesche, 1991)

Material	Percantage %
Hematite	1.1-2.7
Magnetite	0.8-6.5
Quartz	2.2-8.5
Mullite	6,5-9.0
Free CaO	max 3.5

2.1.2. Chemical Composition

Major components of fly ashes are SiO_2, Al_2O_3, Fe_2O_3 and occasionally CaO. The mineralogy of fly ashes is very diverse. If SiO_2 >%35, fly ash have good pozzolanic activity. Fly ashes divided into three groups by ASTM C618: Class N, Class C, and Class F fly ash. Class F fly ashes may contain a greater amount of carbon than those belonging to Class C. Class F fly ashes are produced by older anthracite , burning of harder, and coal which properties are puzzolonic and not exceed 20% lime (CaO). Class F fly ash is generally used for mass concrete and sulfate resistant concrete. Class C fly ash is generally used for high early strength concretes. Main difference between Class C fly ash and Class F fly ash is lime content. Class C (CaO) content generally more than %20 (Wikipedia, Fly Ash).

Chemical compositions of fly ash according to types are listed in Table 2.2 (ASTM C618). Chemical composition of fly ash which produces in Turkey, is shown Table 2.3.

Table 2.2 Chemical compositions of some fly ashes (ASTM C618)

	Class N	Class F	Class C
Min $S_iO_2+Al_2O_3+Fe_2O_3$	70	70	50
Max SO_3	4	5	5
Max. Moisture Content	3	3	3
Max. Loss of İgnition	10	6	6

Table 2.3 Chemical compositions of some fly ashes in Turkey (Aruntaş, 2006)

(%)	Afşin-Elbistan	Çatalağzı	Tunçbilek	Çayırhan	TS 639	ASTM C 618	
						F	C
SiO_2	27.4	56.8	58.59	49.13	-	-	-
Al_2O_3	12.8	24.1	21.89	15.04	-	-	-
Fe_2O_3	5.5	6.8	9.31	8.25	-	-	-
S+A+F	45.7	87.7	89.79	72.42	>70	>70	>50
CaO	47.0	1.4	4.43	13.2	-	-	-
MgO	2.5	2.4	1.41	4.76	<5	<5	<5
Na_2O	(N+K) 0.3	(N+K) 3.0	0.24	2.2	-	<1.5	<1.5
K_2O	-	-	1.81	1.76	-	-	-
SO_3	6.2	2.9	0.41	3.84	<5	<5	<5
K.K	2.4	0.6	1.39	0.72	<10	<12	<6

2.1.3. Physical Properties

Variety of physical properties of fly ash depends on the properties of coal which is burned in thermal power plants. Fly ashes are generally grey colored. The color of fly ash becomes darker by the increasing quantity of unburned carbon. Fly ash includes 60%-90% very fine glassy particles. The fineness of fly ash is important because it affects the rate of pozzolanic activity and the workability of the concrete. The shape of fly ash is spherical and diameter of it ranges between 1-200 µm. Approximately 75% diameter of fly ash particles is smaller than 45 µm. Density of Fly ash ranges between 2.2-2.7 g/cm^3. Specific surface area of fly ash which is similar to ordinary Portland cement can be used without grinding (Aruntaş, 2006).

2.1.4. Usage of fly ash as a construction material

Fly ash are used in concrete around the globe for over 50 years. In the United States of America more than 6.000.000 t, and in Europe more than 9.000.000 t are used annually in cement and concrete. Because of so many advantages it is used for every part of concrete industry like in precast, off-shore structures, etc. (Cao et al., 2008).

Table 2.4 Usage of fly ash as a construction material (Aruntaş, 2006)

Material	Usage of fly ash
Cement	Raw Material, Admixture, replacement material
Aggregate production	Production of fine, coarse and lightweight aggregate
Concrete	Admixtures, replacement material
Brick, Refractory brick	Admixtures
Adobe	Binder
Construction material	Wall, block,brick, tile etc.
Several usage	Dams, Highways, nuclear power plant, Soil Stabilization

Advantages of fly ash usages are; reducing Portland cement demand, reducing volume of land filled fly ash, conserving water by reducing water demand in concrete mixes. The physical and mechanical benefits of fly ash usages are; increasing strength, increasing durability and sulfate resistance by decreasing permeability. It reduces alkali-silica reaction (ASR) and corrosion of reinforcing steel.

2.2. Lightweight Aggregate (LWA)

Aggregate can amount to 60-80% of the total volume of concrete; therefore, the choice of aggregate directly impacts the performance of concrete Lightweight aggregate (LWA) is described as aggregate having a particle density of less than 2.0 ton/m^3 or a dry loose bulk density of less than 1.2 ton/m^3 per BS EN 13055. Those properties are mainly derived from entrapped pores within the structure of the particulates and vesicles occurring at surface. For structural concrete proper aggregates are required as well as low cement paste content together with low water absorption capacity. Particle density means that the mass per unit volume of individual aggregate particles. Dry loose bulk density is the mass of dry particles included within a given volume. Figure 2.1 shows that difference between particle density and dry loose bulk density (Newman and Choa, 2003).

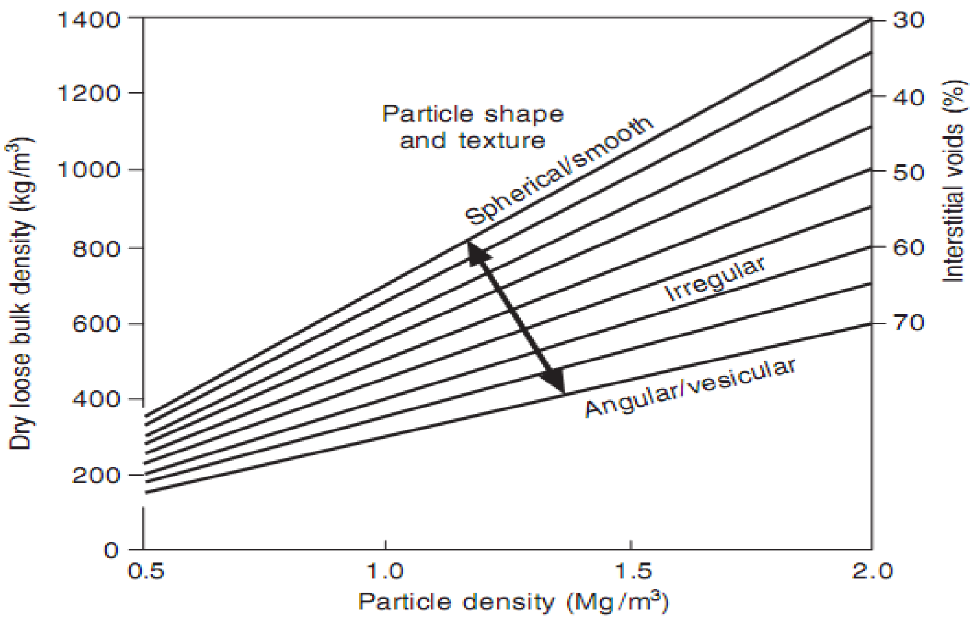


Figure 2.1 Relationship between particle density and dry loose bulk density of LWA (Newman and Choa, 2003)

2.2.1. Manufactured LWA

The requirement of aggregates all types has been increasing by economic growth, Artificial and manufactured aggregates are more expensive solution than normal natural aggregates but the overall costs of aggregate is more sensitive to to transport charges than to the cost of manufacture. Therefore it can be optimum solute on for some cases. Some LWA densities and usage of them are shown on Figure 2.2 (Popovics, 1992).

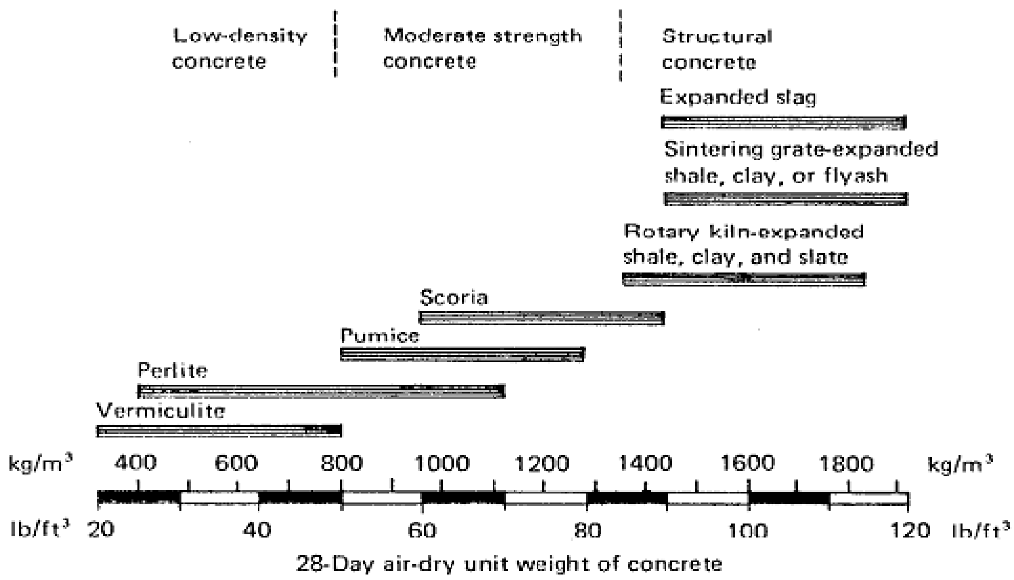


Figure 2.2 Approximate unit weight and usage of LWAC (Popovics, 1992)

2.2.1.1. Foamed Slag Aggregate

In the operation of blast –furnace, the iron oxide ore is reduced to metallic iron by means of coke, while the silica and alumina constituent combine with lime, to form a molten slag. The composition of slag are, CaO 30-50%, SiO_2 28-38%, Al_2O_3 8-24%, MgO 1-18%, Fe_2O_3 0.5-1%, SO_3 2-8%. This slag issues from the furnace as a molten stream at 1400-1600 ^oC. When it is cooled slowly it appears crystalline and grey materiel is called as “air cooled slag”. Cooling of the slag with a large excess of water produce “granulated slag”. Chilling with a controlled amount of water, applied in such a way as to trap the stream in the mass, gives a porous product of pumice-like character , termed “ foamed slag”, or “expanded slag” which on cooling is used as a lightweight aggregate (Short et al., 1978).

Alternative methods of expansion include spraying water onto the molten material when it is being tapped from the blast furnace so that the material is cooled rapidly, with steam becoming entrapped within the structure of the particle. At the completion of foaming the slag is removed and stockpiled, from where it is subsequently crushed and graded to size. The aggregate shape is very angular with an open vesicular surface texture shown on Figure 2.3 (Newman and Choa, 2003).

Foamed slag can be used as aggregates in concrete blocks, roof screeds and in insulating concretes (Popovics, 1992).

Figure 2.3 Typical foamed slag particles (Newman and Choa, 2003).

2.2.1.2. Furnace Clinker

Clinker has been used as an aggregate for about 90 years. Dry density of it 720-1040 kg/m^3.Advantage of clinker are low cost and availability. Furnace clinker contains sulfates and chlorides this is the reason of why it cannot be used as a structural concrete material. Especially it is used for concrete blocks. Production of On the plant fuel is ignited on the surface of the fire-bed, and if the temperature is high enough to fuse the ash, this will drip through the bed and freeze into glassy globules in the cooler zone below. Softened ash remains plastic for a long time, it may coalesce into large clinkers (Short and Kinnuburgh, 1978).

2.2.1.3. Expanded Perlite

This is one of the lightest aggregate. The fundamental mechanism of solid rock expansion is that the rock reaches fusion to such a limited extent that the pores in the rock become plugged by melted material, but at the same time the material remains viscous enough to keep the developed streams and/or gases inside under pressure.

This then expands the particle, developing a porous internal structure that is retained on cooling. If the rock reaches the fusion point at a temperature as low as 700-800 ^{o}C, then by heating it further, the whole rock particle becomes plastic; therefore, the expansion takes place more or less equally in all three dimensions. This is what happens in the case of perlite. For best results, the heating should take place rapidly but so that the intensive steam formation coincides with the fusion of the perlite. In this way, the minimum amount of steam can escape from the particle; thus the maximum amount of perlite expansion develops. It is used in large quantities both all developed countries with Portland cement, magnesium oxychloride cement, water glass, and so on. It can be used for fire protection of steel (Popovics, 1992).

2.2.1.4. Light Weight Expanded Clay Aggregate (LECA)

LWA can be obtained from the process of expanded clay. There is two different processes to get LECA. These are wet processes and dry processes. Moisture content and bulk densities vary according to selected process. The wet and dry process are described below (Chandra and Berntsson, 2002).

Wet Process: In a rotary kiln adding and mixing bloating clay and water we produce LECA. It is used especially in Norway and Sweden. At the end of the kiln it became aggregates which have different shapes and sieve sizes.

Dry Process: It is produced from shale, a soft rock, which is crushed, dried, and milled into powder. Soft rock and shale are crushed and milled before pelletization process. Limestone adds to pellets it covers the surface. Strength of Pellets is high. These pellets are added to rotary kiln. Expansion of pellets is under controlled.

2.2.1.5. Vermiculate

The expansion of vermiculite is similar to that of perlite except that vermiculite expands mostly in one direction as a result of its laminar structure. The technical properties of such aggregates are similar to those of expanded perlite. Vermiculite is used generally for insulating concretes It is used for structural fire protection.

Vermiculate expands with temperature and it protects the structural steel parts against the fire (Popovics, 1992).

2.2.2. Production of Lightweight Fly Ash Aggregate

Amount of Fly ash production which is coal based waste material of thermal power plants, is continuously increasing with energy consumption. However, Utilization of fly ash as LWA became important. Recycling of ash residues, reservation of fossil fuels, reduction of fossil fuel emissions, less storage areas for waste materials are some potential benefits of usage of FA as LWA Sintering method, hydrothermal hardening and cold bonding methods are three different methods to produce LWA with fly ash. LWA manufacturing with fly ash is shown below in Figure 2.4 (Wesche, 1991).

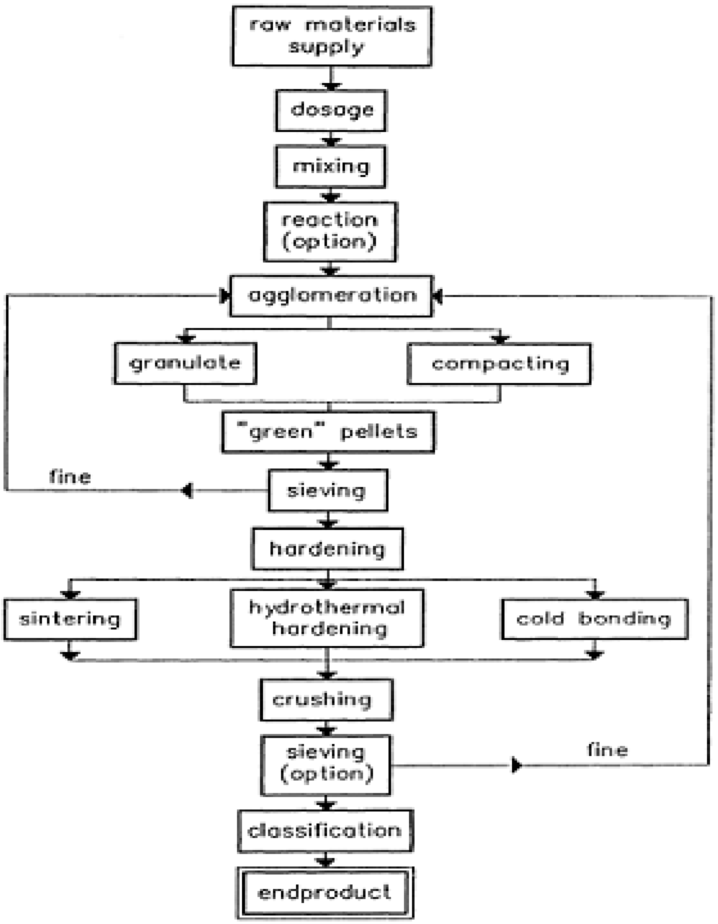


Figure 2.4 Process steps in fly ash aggregate manufacture (Wesche, 1991)

2.2.2.1. Sintering Method

Fly ash is pelletized and then sintered in a rotary kiln, shaft kiln, at temperatures in the range 1000 to 1200°C. Variations in the fineness and carbon content of fly ash are a major problem in controlling the quality of sintered fly ash aggregate.

The process uses above 90% fly ash as major raw material mixing with small volume additive. The additive can be clay, bentonite etc. After pelletizing, and agglomeration the pellets will be added to a sintering machine. The physical characteristic of natural aggregates is not better than LWA (Ramme et al., 1995).

2.2.2.2. Hydrothermal Hardening

Bonding is achieved by addition of cement and/or lime to FA to accomplish a chemical reaction which provides bonding the materials together in the hydrothermal process. Following the reaction of FA and lime, the mix is pelletized in an inclined rotating drum. After this process, the pellets are transferred to an autoclave in order to provide convenient hardening under saturated steam with a certain level of pressure (Ramme et al., 1995).

2.2.2.3. Cold Bonding

Cold bonding (CB) method is more simple method than others. A mix of lime, ash, and water following the mixing, is together transferred to a disk pelletizer, where pelletization takes place. The mix is permitted 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.

Advantages of CB are;

- CB process plants have tendency to deal with lower operational and capital costs than sintering/rotary kiln firing plants;
- CB process plants are also exposed less environmental impact than the other thanks to no emission of exhaust greenhouse gases. Both processes need control of particulate emission and might have waste water flow; and,

- Moreover, end product costs tend to be lower for CB material than for sintered material (Ramme et al., 1995).

2.2.3. Pelletization Process

2.2.3.1. Definition of the Pelletization Process

Aggregates target sieve size ranges may be supplied either by the agglomeration of fines by crushing of rock. Moisturized particles agglomerate in drum. Binders can add to drum before the rotation. At the end of this process we get the pellet which is called as fresh pellet. Pellets shouldn’t crush when it will transport. On the other hand, pellet can sintered because of to get high strength (Baykal and Döven, 2000).

2.2.3.2. Theory of Pelletization

Fine-grained material when it is moisturized, liquid film covers the surface of the grains, which forms meniscus between the grains, structures like bridges (Figure 2.5a). In a situation the particles are rotated in a balling disc, they form spherical structures with enhanced bonding forces between grains due centrifugal and gravitational forces (Figure 2.5 b and c) (Jaroslav and Ruzickova, 1987).

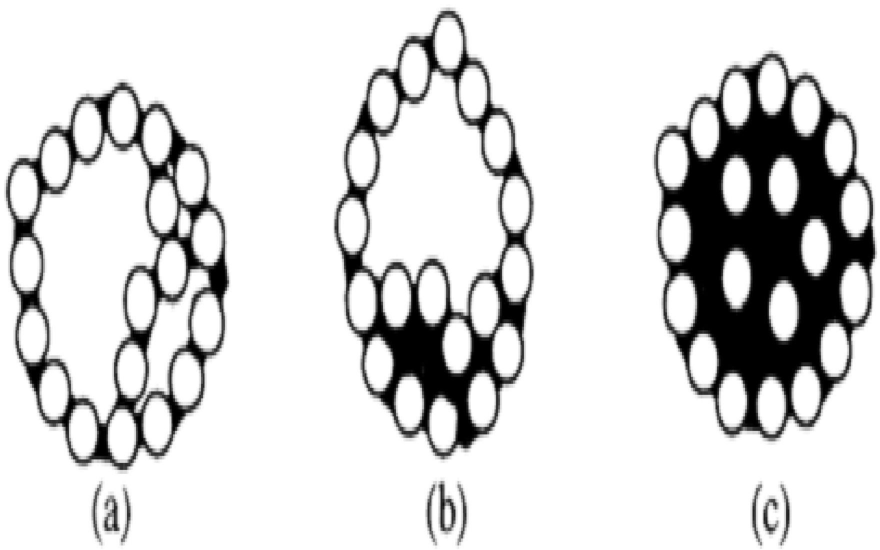


Figure 2.5 Mechanism of pellet formation (Jaroslav and Ruzickova, 1987)

In pelletization process, the force advanced on the pellets expels the air that fills the free gap between the individual fragments, existing the voids to fragments also water. As the fragments take closer, the structure comes to be denser, whatever 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 may just be attained if all the capillaries are filled by water for the time of manufacture. The lack of adequate water reasons aired voids to be entrapped inside the structure, which controls the capillary activity. Optimum water content ranges between 20-25% for fly ash pelletization. It is also more significance in the pelletization process the granulometric distribution. This may be controlled through the pelletization procedure by monitoring the feeding percentage of the binder and moisture content. The process of ball formation for the water content is fewer than the best condition as shown in Figure 2.6. In this condition, the wetness particles become connected with water bond bridges and move closer. While the mechanism of sphere structure is indicated by wetness content above perfect, as was shown in Figure 2.7. In this condition, the capillary strength is reduced because of father moistening and the structure is softer. Now the structures are random sized and because it is fresh and may be easily destroyed by the mechanical forces produced in the balling disc (Asaad, 2011; Gesoglu, 2004; Jaroslav and Ruzickova, 1987).

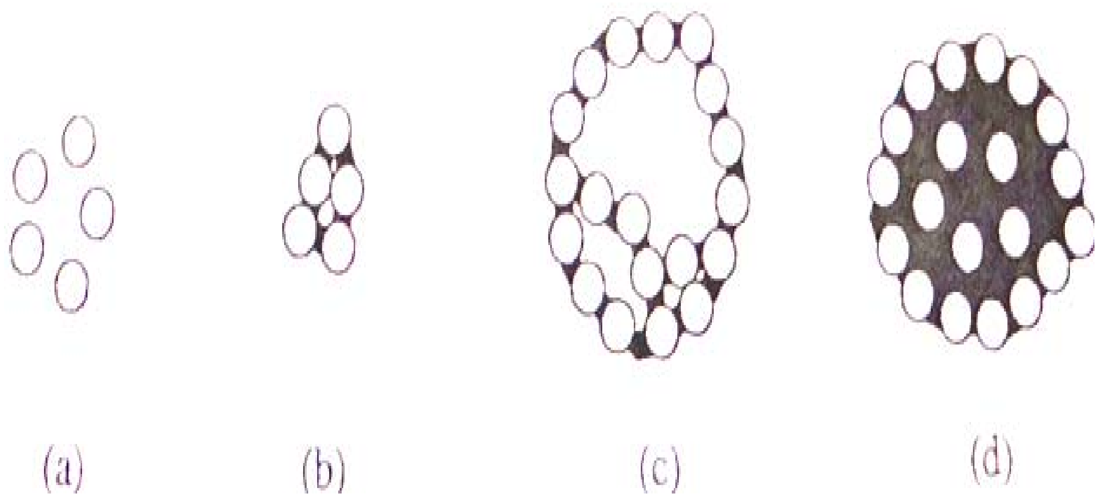


Figure 2.6 Mechanism of ball nuclei formation (when water content under best state) (Jaroslav et al., 1987)

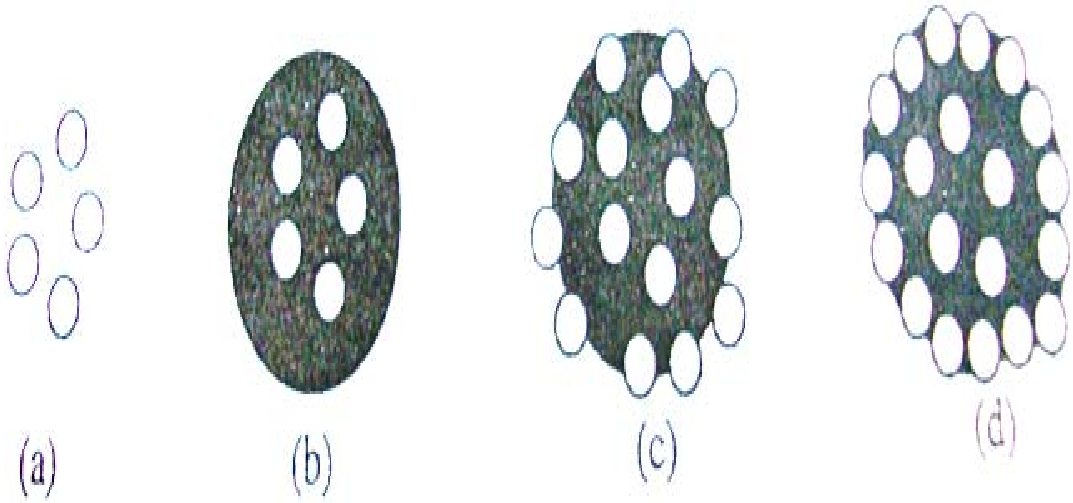


Figure 2.7 Mechanism of ball nuclei formation (when water content above best state) (Jaroslav et al., 1987)

2.3. Lightweight Aggregate Concrete (LWAC)

2.3.1. Definitions

Concrete has been the most popular material used for several types of structure for many years. The production of concrete is dramatically increasing. Main advantages of concrete can be listed as workability, durability, strength and economy. But also it has same disadvantages such as dead weight, insulation properties. Concretes can divide two categories according to density as normal weight concrete (NWC), light weight concrete (LWC).

LWC has been utilized as structural material since ancient times; However, LWC has become much more familiar in recent times. There are three ways to get LWC. First; by omitting the finer sizes from the aggregate grading called as ‘no-fines’ concrete. Second; by creating gas bubbles in cement slurry: after setting, a strong coral-like cellular structure is formed known as ‘aerated concrete’. Third; by replacing the gravel or crashed rock by hallow, cellular, or porous aggregate which includes air in the mix. Third one is called as Lightweight aggregate concrete (LWAC) First It consists of entirely lightweight aggregate (LWA) called as “All LWA” , or a mixture of lightweight and normal-density aggregates called as “Sand LWA”. During the current century so many improvement occur on LWC technology (Chandra et al., 2002).

There are no distinct densities requirements for LWCs. Density and strength requirement of LWC are varied for each norm. The concrete has a minimum 28-day compressive strength of 17 MPa., density range specify between 1120 and 1920 kg/m^3 (ACI213, 2003).

According to European Norms, Lightweight-concrete (LWC) is defined as having an oven-dry density of not less than 800 kg/m^3 and not more than 2000 kg/m^3 (EN 206-1, 2000).

According to ASTM C330, maximum permissible density of LWC is 1840 kg/m^3.

2.3.2. Advantages of LWAC

It reduce the material requirement when the higher percentage of dead loads to total loads, such as bridge decks. Sizes of footing are automatically decreasing. We can build up extra floors to your buildings safely, in the range or soil bearing capacity. There is decreasing of molding costs by reducing of total weight of each slab. Figure 2.8 indicates the LWACs are more resistant to fire than NWC. Earthquake loads can reduce by decreasing of total weight. LWAC supplies faster building rates. Transportation and handling costs lower than NWC. Water and chloride ion permeability of LWAC were lower than NWC (Koçkal and Özturan, 2011).

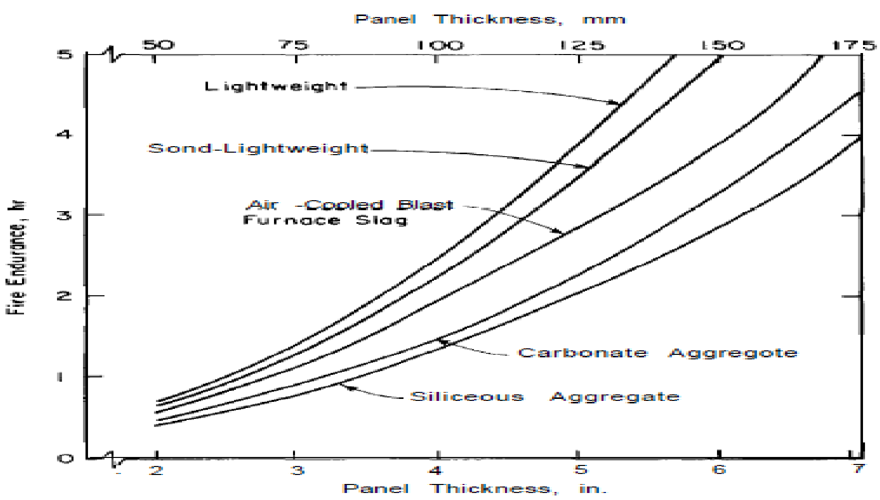


Figure 2.8 Effect of slab thickness and aggregate type on fire endurance of concrete slabs. (ACI 216, 1994)

2.3.3. Properties of Lightweight Aggregate Concrete

2.3.3.1. Density and Compressive Strength

Dry density of LWAC varies from about 800-2100 kg/m^3 for cube strength strengths ranging from about 7-80 MPa. The relationship between density and cube strength of LWAC varies considerably. Variation is shown on below Figure 2.9 for 4 types of aggregates (Short and Kinnuburgh, 1978).

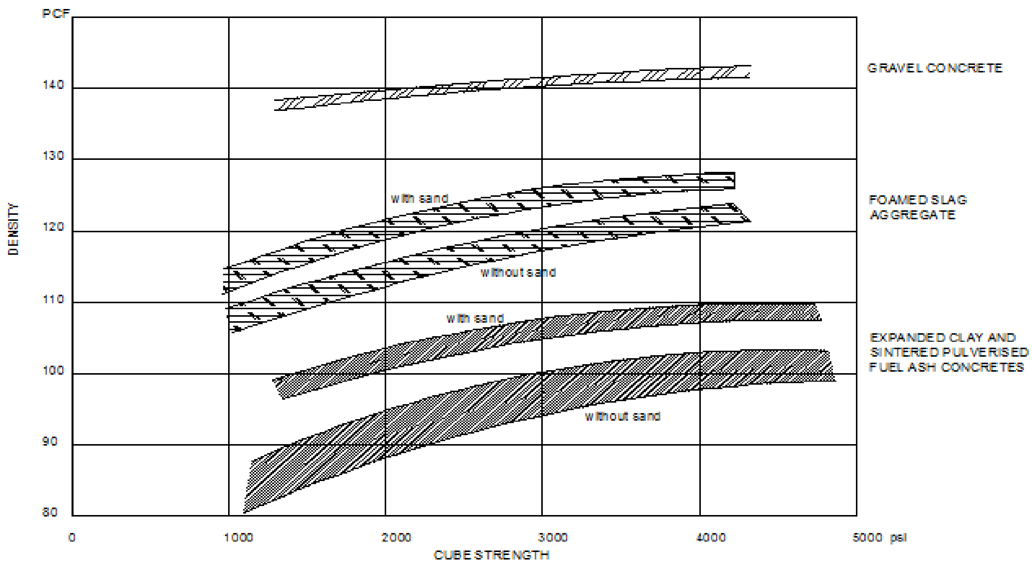


Fig. 2.9 Relationship between the cube crushing strength and dry density of various type of concrete at 28 days (Short and Kinnuburgh, 1978)

Cement content, age of concrete, water/cement (W/C) ratio, aggregate types are the major parameters affect the compressive strength of LWAC. Increasing density of aggregate increases the compressive strength. The good aggregate-cement bond and the similarity between the stiffness of the aggregate and matrix in LWAC result in an efficient mix with a strength approaching maximum theoretical strength. The good bonding aggregate with cement increase the strength. We can not compare W/C ratio in NWC with LWAC because of water absorption. However, the effect of free water in the mix is similar to that in NWC. Increasing of free water reduces the compressive strength (Short and Kinnuburgh, 1978).

2.3.3.2. Modulus of Elasticity

Cement colume, water/binder (W/B) ratio, aggregate types are the major reasons affect the modulus of elasticity (E) of concrete. E modulus of the mixture changes between 12000 to 26000 MPa. The influence of the aggregate on the E-modulus of the matrix is shown in Figure 2.10. Increasing density of sand increases the matrix stiffness. For the relationship of E-modulus and compressive strength, it has to be distinguished between matrices with natural sand and LWA (see Figure 2.11) (Chandra and Berntsson, 2002).

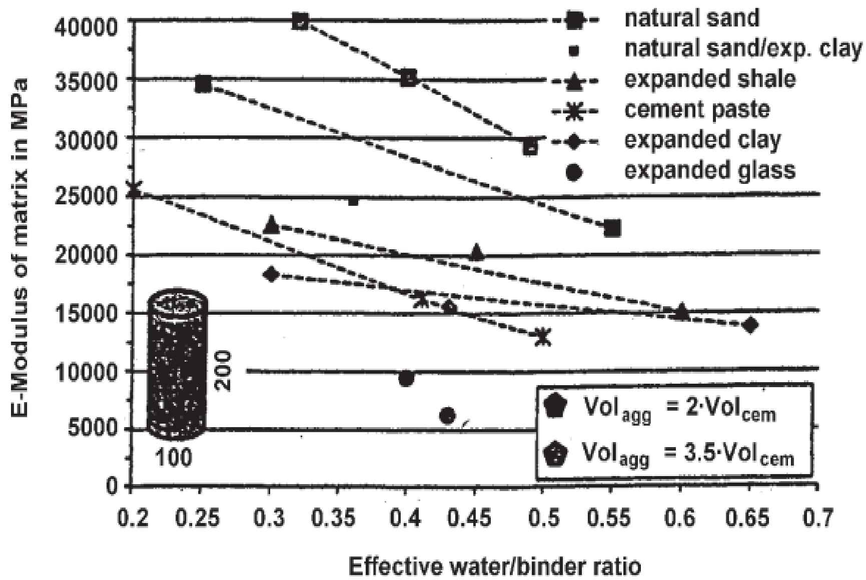


Figure 2.10 Dependence of E-modulus of different matrices on the water/binder ratio and the share of aggregate (Chandra and Berntsson, 2002)

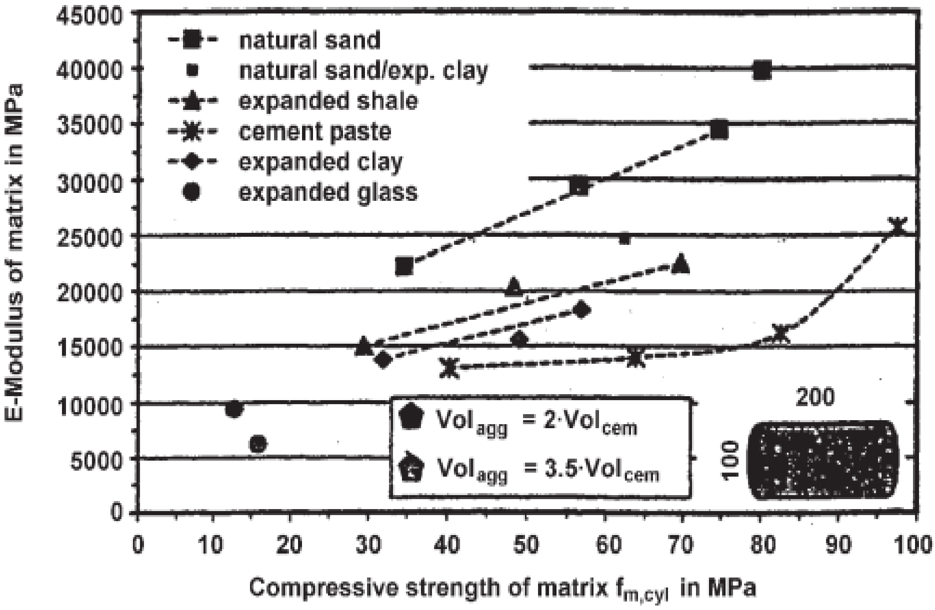


Figure 2.11 Relationship between E-modulus and compressive strength of different matrices (Chandra and Berntsson, 2002)

2.3.3.3. Tensile Strength

Tensile strength is important when considering cracking in concrete elements. The factors influencing compressive strength also influence tensile strength. The principal differences between lightweight aggregate concrete and normal weight concrete are due to;

- Fracture path

This normally travels through, rather than around, lightweight aggregate particles. The behavior is similar to normal weight concrete made with crushed aggregates in that the flexural/compressive strength ratio is higher (Figure 2.12) (Newman and Choa, 2003).

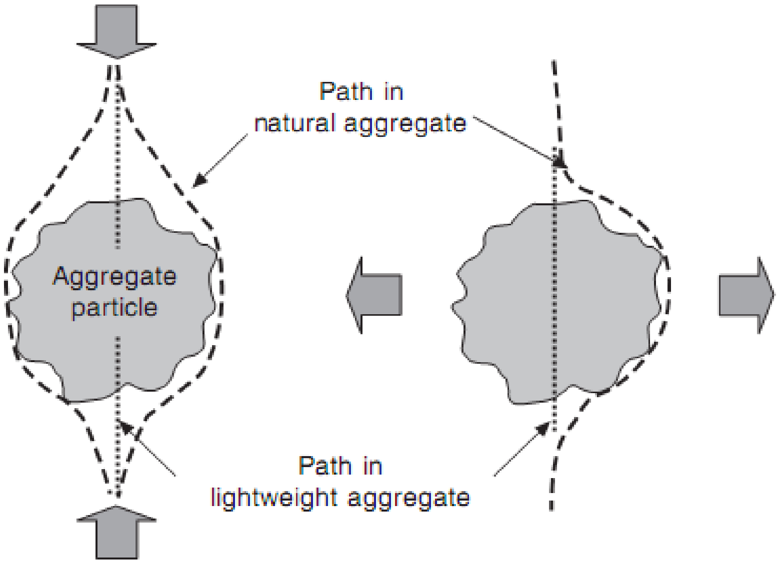


Figure 2.12 Fracture paths in lightweight and normal weight concretes. (Newman and Choa, 2003)

- Total water content

This is higher for lightweight aggregate concrete due to the absorption of the lightweight aggregate. Thus, in drying situations greater moisture gradients can cause a significant reduction in tensile strength although this effect is somewhat alleviated by the effects of increased hydration (Figure 2.13) (Newman and Choa, 2003).

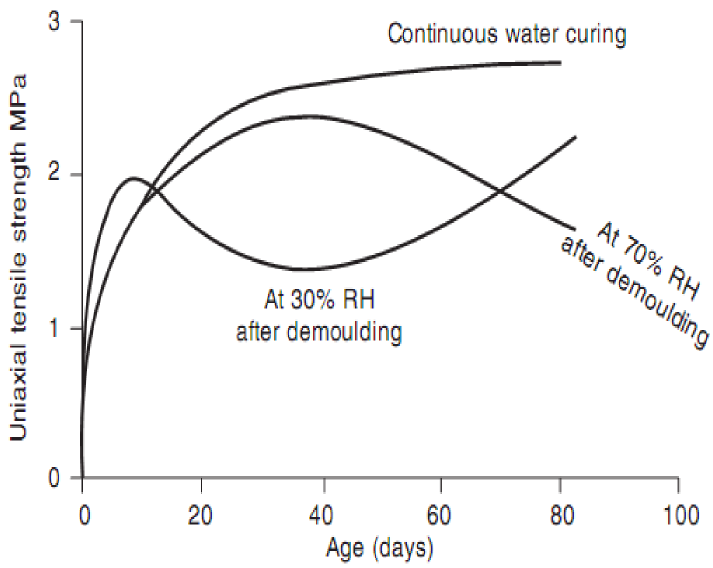


Figure 2.13 Effect of drying on tensile strength (Newman and Choa, 2003).

2.3.3.4. Water Absorption

Water absorption (WA) of most LWA has a tendency to be considerably higher than that of normal weight aggregates. For this reason, LWA incorporating concretes have relatively higher absorption capacity than normal weight concretes. However, the difference is not as large as expected due to the aggregate particles in LWA concrete are surrounded by cement paste matrix. It has been reported that water absorption of lightweight concrete is directly not related to durability and this might be due to the inconvenience, when comparing concretes, of considering absorption values based on mass rather than volume (Short et al., 1978).

2.3.3.5. Permeability and Durability

The durability is major properties of LWC. It is primary objective that concrete should be resist the weather conditions for which it has been designed throughout the life of structure (Neville and Brooks, 2003).

We can built more durable structures with LWC Ingredient selection and proportioning improve the durability of LWC. Freezing and thawing resistance of air-entrained LWC better than NWC because of minor cracking in aggregates (Ozyıldırım, 2009).

The chloride ion penetration and low carbonation depth are main advantages of LWC It is used especially for in off-shore structures (Kayali, 2008).

Due to the porous feature of lightweight aggregate (LWA), its compressive strength is relatively low and adsorption capacity is high. Capacity of adsorption is higher than NWC, Compressive strength is lower than NWC. To get enough compressive strength we should add more cement (Hwang and Hung, 2005).

2.3.3.6. Corrosion

Corrosion of steel embedded reinforcement in concrete is the best known problem affecting the durability of reinforced concrete structures. Chloride-induced corrosion is major mechanisms of deterioration affecting the long-term performance of reinforced concrete structures. The main problem of corrosion is when rebar started to corrosion it enlarges. Tensile strength of concrete is much smaller than compressive strength. Cracks occur on concrete when the corrosion starts (Broomfield, 2007).

Electrons are given up when the corrosion starts for rebar. The anodic reaction: $Fe \rightarrow Fe^{2+} + 2e^{-}$.The two electrons (2e-) created in the anodic reaction must be consumed elsewhere on the steel surface to preserve electrical neutrality. In other words we cannot have large amounts of electrical charge building up at one place on the steel. There must be another chemical reaction to consume the electrons. This is a reaction that consumes water and oxygen. The cathodic reaction: $2e^{-} + H_2O + ½O_2 \rightarrow 2OH^{-}$ Both reactions illustrates on Figure2.14 (Broomfield, 2007).

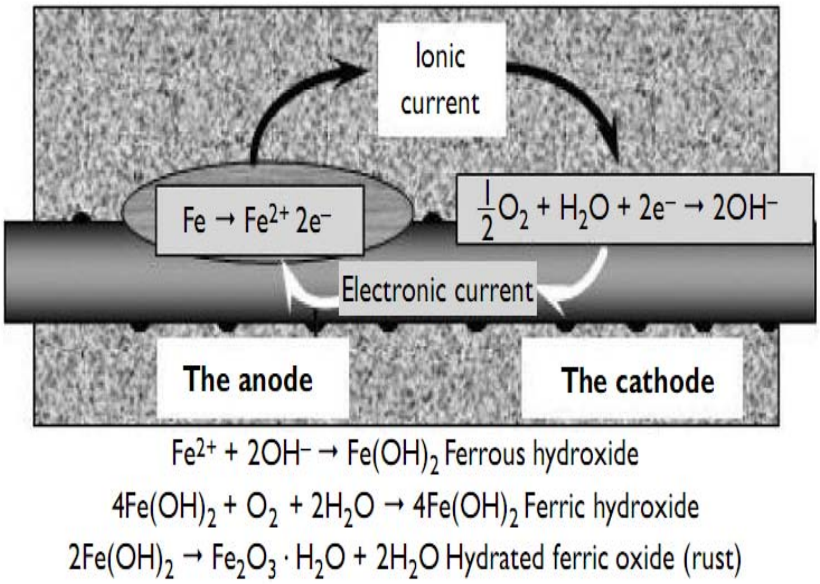


Figure 2.14 The anodic, cathodic and oxidation and hydration reactions for corroding steel (Broomfield, 2007)

The chloride resistance of concretes is therefore highly correlated with the amount distribution, and interconnectivity of the porosity. The porosity of concrete is determined by:

- The characteristics of ingredients of concrete such as type of cement, mineral admixture, aggregate shape and type, etc. For example, the type of cement influences both the porosity of the concrete and its reaction with chlorides,
- The proportions of the concrete constituents, and
- Placing, consolidation and curing of concrete.

The porosity of concrete is highly dependent on the W/C and aggregate/cement ratios whereas the type and amount of cement affect the pore size distribution and chemical binding capacity of the concrete. (Cement Concrete & Aggregates Report, 2009).

Water, oxygen, and chloride ions are most important factors in the corrosion of embedded steel and cracking of concrete, it is clear that permeability of concrete is the primary control the various processes involved in the phenomena. Concrete-mixture parameters should low permeability, e.g., low W/C ratio, adequate cement content, control of aggregate size distribution, and use of adequate mineral admixtures (Mehta, 2006; Tonini,1977).

CHAPTER 3
EXPERIMENTAL STUDY

3.1 Materials

CEM I 42.5 R type Portland cement having specific gravity of 3.14 and Blaine fineness of 326 m^2/kg was utilized for both manufacturing fly ash aggregates and preparing the concrete test specimens used in determination of concrete properties. The chemical composition of the cement is shown in Table 3.1. For the manufacture of S aggregate bentonite from the local sources was used as binder. The chemical properties of the bentonite were also illustrated in Table 3.1.

Table 3.1 Properties of Portland cement, silica fume and fly ash

Chemical analysis (%)	Portland cement	Silica fume	Bentonite	Fly ash
SiO_2	20.25	90.36	72.9	56.2
CaO	62.58	0.45	1.9	4.24
Fe_2O_3	4.04	1.31	1.0	6.69
Al_2O_3	5.31	0.71	15.2	20.17
MgO	2.82	-	1.7	1.92
SO_3	2.73	0.41	-	0.49
Na_2O	0.22	0.45	0.4	0.58
K_2O	0.92	1.52	1.1	1.89
Loss on ignition	1.02	3.11	6.2	1.78
Specific gravity	3.15	2.2	2.45	2.25

In this thesis, Class F FA conforming to ASTM C 618 was utilized for manufacturing cold-bonded and sintered artificial fly ash aggregates. It was provided from thermal power plant, named Ceyhan Sugözü, located in Turkey. FA used in this study has a specific gravity of 2.25 and specific surface of 287 m^2/kg. Table 3.1 presents the chemical and some physical characteristics of the fly ash used.

SF obtained from Norway was used as a mineral admixture in concrete production. SF has a specific surface are of 21080 m^2/kg and specific gravity of 2.2 g/cm^3. Chemical analysis and some physical properties of SF is also given in Table 3.1.

Fine aggregates were obtained from local sources. Fine aggregate was a mix of river sand and crushed limestone sand. Properties of the fine aggregates are presented in Table 3.2. Coarse aggregates used for production of LWC are either cold bonded or sintered fly ash aggregates Table 3.3. The details of the manufacturing process of these aggregates were presented in the next section.

Table 3.2 Sieve analysis and physical properties of normal weight aggregate

Sieve size(mm)	Fine aggregate (%)	
	River sand	Crushed sand
16	100	100
8	99.7	100
4	94.5	99.2
2	58.7	62.9
1	38.2	43.7
0.5	24.9	33.9
0.25	5.4	22.6
Fineness modulus	2.79	2.38
Specific gravity	2.66	2.45

Table 3.3 Properties of lightweight aggregates (LWA)

Aggregate	Ingredients	Manufacturing method	SSD* specific gravity	24 h water absorption
Cold bonded fly ash aggregate (CB)	90% FA+10% PC	Cold bonded	1.90	16.3%
Sintered fly ash aggregate (S)	90% FA+10%BN	Sintered	2.01	11.7%

* Saturated surface dry

Sulphonated naphthalene formaldehyde based high range water-reducing admixture with specific gravity of 1.19 was employed to achieve slump value of 14±2 cm for the ease of handling, placing, and consolidation in all concrete mixtures. The superplasticizer was adjusted at the time of mixing to achieve the specified slump. Its properties are given in Table 3.4

Table 3.4 Properties of superplasticizer

Property	Superplasticizer
Name	Daracem 200
Color	Dark Brown
State	Liquid
Specific Gravity [kg/lt]	1,19
Chemical	Sulfonated Naphthalene Formaldehyde
Freezing Point	-4

3.2 Production of Lightweight Aggregates (LWA)

In the first stage of the experimental program artificial fly ash aggregates were produced through the cold bonding agglomeration process of fly ash and Portland cement in a tilted pan at an ambient temperature. For this, 10% binder and 90% FA were mixed in powder form in the pelletizer shown in Figure 3.1.

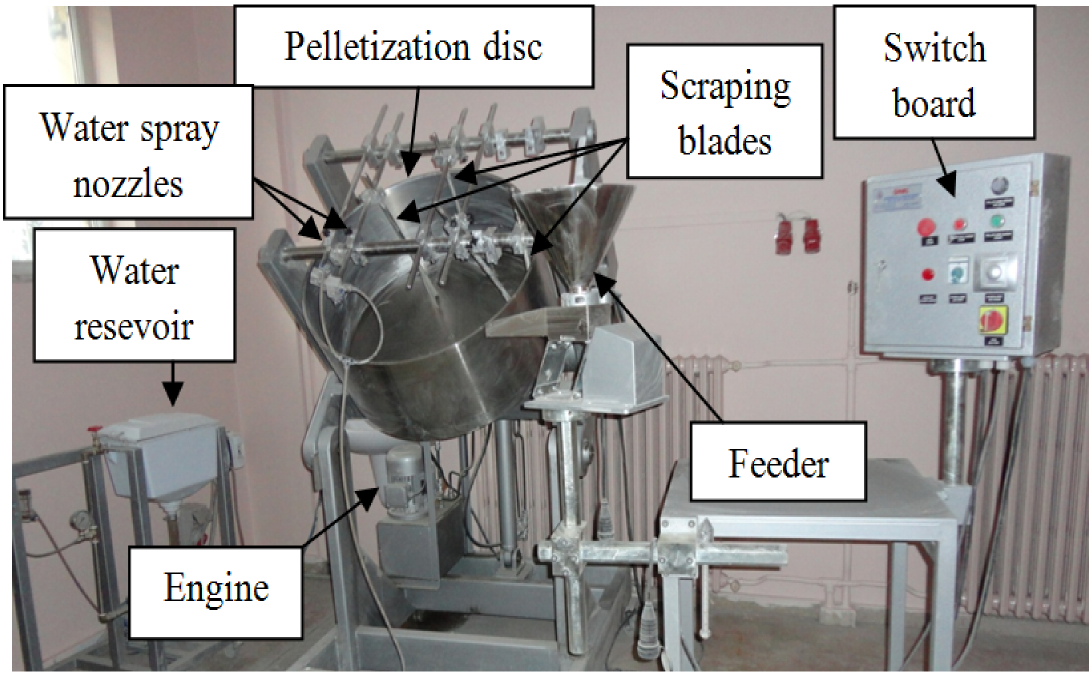


Figure 3.1 The general view of the pelletization disc

The binders used are Portland cement (PC) and bentonite (BN) for CB and S aggregates, respectively. After the dry powder mixture of about 10-13 kg was fed into the pan, the disc was rotated at a constant speed to assure the homogeneity of the mixture. The amount of sprayed water used during pelletization process has been determined as the coagulant to form spherical pellets with the motion of rolling disc (Baykal and Döven, 2000; Arslan and Baykal, 2000; Gesoğlu, 2004; Gesoğlu et al., 2007; Gesoğlu et al., 2012).

The optimum water content required for each type of powder was determined according to ASTM D2216–10 Then, the water was sprayed on the mixture with a quantity of 22 % by weight. The formation of pellets occurred between 10-12 minutes in trial productions. The total pelletization time was determined as 20 minutes for the compaction of fresh pellets. As soon as pelletization process is ended, CB aggregates were kept in sealed plastic bags for 28 days in a curing room in which the temperature and relative humidity were 21^{o}C and 70%, respectively. On the other hand, S aggregates were transferred to muffle furnace (Figure 3.2) for sintering process.

Figure 3.2 Sintered aggregates in muffle furnace

Heat cycle adopted for the sintering process was diagrammatically demonstrated in Figure 3.3

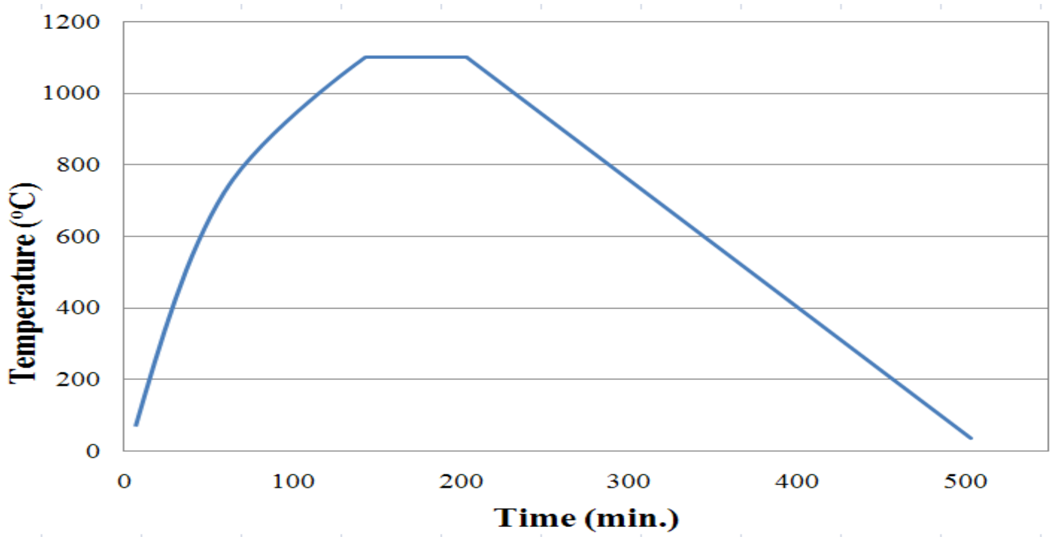


Figure 3.3 Heating and cooling cycle of the muffle furnace for sintering process

The curing methods adopted in this study are practical and simple method to fit the laboratory conditions. At the end of the curing period, hardened aggregates were sieved into fractions from 4 to 16 mm sizes to be used as coarse aggregate in concrete production.

Change in color and shape characteristics of the produced aggregates are illustrated in Figure 3.4. Grey pellets are CB aggregates. Brown pellets are sintered fly ash aggregate with bentonite binder.

a)

b)

Figure 3.4 Photographic view of a) cold bonded fly ash aggregate with PC binder (CB) and b) sintered fly ash aggregate with bentonite binder (S)

Specific gravity and water absorption tests were carried out as per ASTM C127 to determine physical properties of the artificial aggregates. The variation of water absorption (WA) profiles of CB and S aggregates are shown in Figure 3.5.

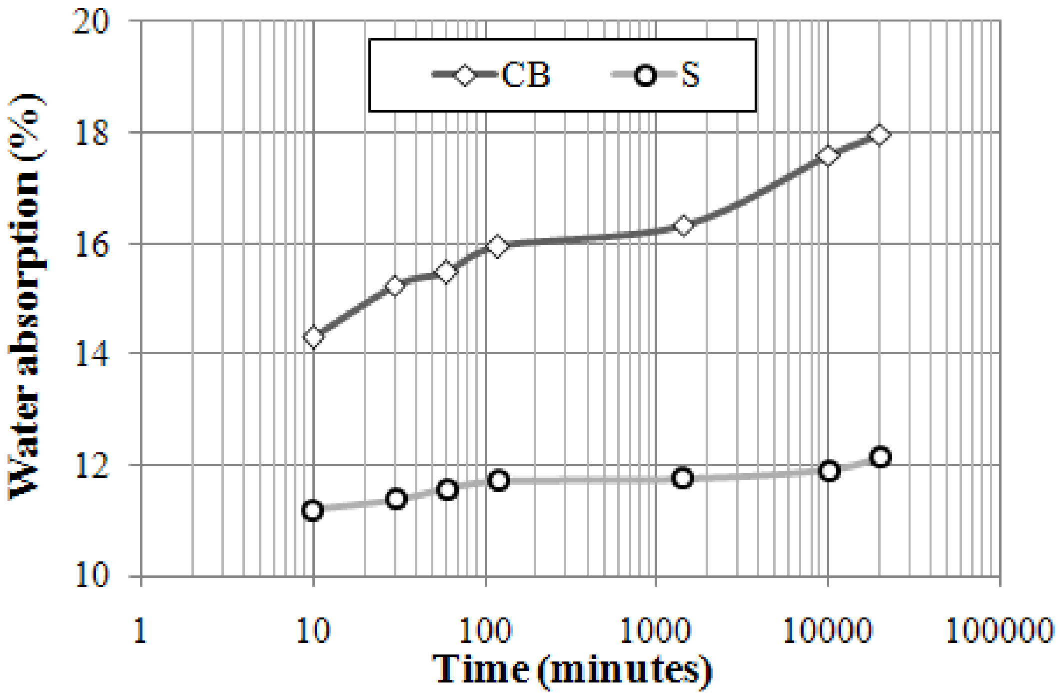


Figure 3.5 Water absorption rates of cold bonded and sintered aggregates

As seen from the figure, S aggregates had relatively lower WA values than that of CB aggregates. 24 h WA values were measured as 16.3% and 11.75% for CB and S aggregates, respectively. Moreover, crushing strength test was performed as per BS 812, part110. Practically, individual pellets were placed between two parallel plates and loaded diametrically until failure occurred. Crushing test was conducted on particles of various sizes from 4 to 8 mm by using a 28 kN capacity load-ring. A number of representative agglomerates were statistically tested and the average of the results was defined as crushing strength or generally named as crushing value. Figure 3.6 and 3.7 show the crushing strength test configuration and strength values of the CB and S fly ash aggregates produced in this study, respectively.

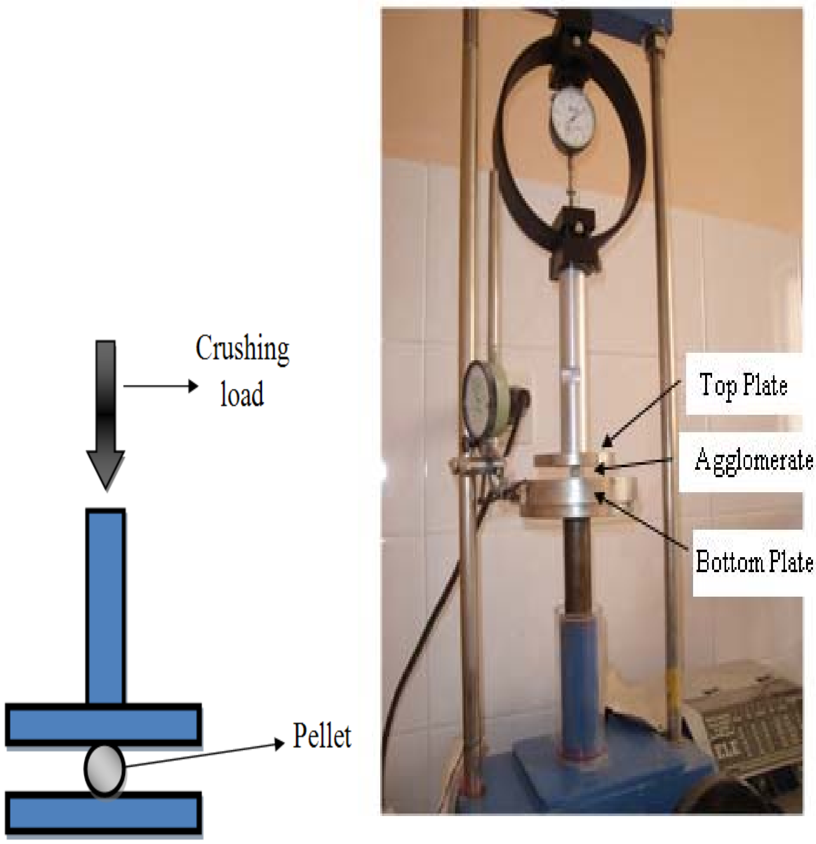


Figure 3.6 Aggregate crushing strength test configuration

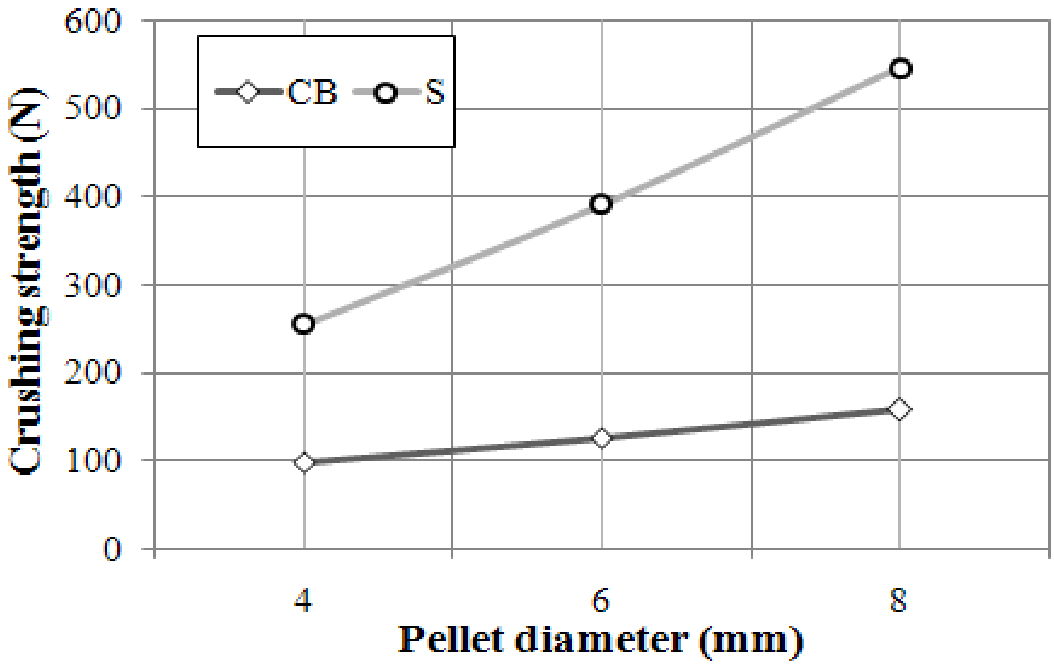


Figure 3.7 Aggregate crushing strength values of cold bonded (CB) and sintered (S) fly ash aggregates

Crushing strength values determined for S aggregates are much more higher than that of CB aggregates. Highest crushing strength values were determined as 546 N and 127 N for S and CB aggregates, respectively. In the study of Koçkal and Özturan, they reported that sintered fly ash aggregates containing 10% bentonite had almost four times higher crushing strength values than cold bonded aggregates (Koçkal and Özturan, 2011).

3.3 Concrete Mix Proportions

Two series of concrete mixtures with water-to-binder ratios (w/b) of 0.35 and 0.55 were designed to produce plain and silica fume (SF) incorporated LWCs. Total binder contents were selected as 550 kg/m^3 and 400 kg/m^3 for the concrete series with w/b ratios of 0.35 and 0.55, respectively. SF modified concretes were produced by 10% replacement of the cement with SF by the weight. All of the concretes had 60% either CB or S coarse fly ash aggregates. Thus, totally 8 different concrete mixtures were produced. The details of mixture proportions are given in Table 3.5.

Table 3.5 Details of mix proportions in kg/m^3

Mix designation	w/b	Type of LWA	SF content	Cement	SF	Water	LWA	Crushed sand	Natural sand	SP*
M1	0.35	CB	0%	550	0	192.5	690	223	401	8.25
M2			10%	495	55	192.5	679	219	395	11
M3		S	0%	550	0	192.5	727	223	401	8.25
M4			10%	495	55	192.5	715	219	395	11
M5	0.55	CB	0%	400	0	220.0	721	232	419	0
M6			10%	360	40	220.0	714	230	415	1
M7		S	0%	400	0	220.0	759	232	419	0
M8			10%	360	40	220.0	752	230	415	1

*Superplasticizer

The aggregates used for concrete production were in saturated surface dry state before mixing. The lightweight concretes produced with cold bonded (CB) or sintered (S) fly ash aggregates were designated as LWC-CB and LWC-S, respectively.

3.4 Test Methods

3.4.1 Compressive Test

Compressive strength of concretes was tested on 150x150x150 mm cubes according to ASTM C 39 by means of a 3000 kN capacity testing machine. Strength of the mixtures were determined at the end of 28 days of water curing. Compressive strength was computed from average of three specimens (Figure 3.8).

Figure 3.8 Photographic view of compressive test machine

3.4.2 Sorptivity Test

Three test specimens having the dimension of Ø100×50 mm produced cutting from the specimens of Ø100×200 were utilized in sorptivity tests for each mixture. The specimens were dried in an oven at 100 ± 5 °C until they reached the constant mass, and then allowed to cool to the ambient temperature in a sealed container. Afterwards, the side of specimen was coated by the paraffin wax. The measurement was carried out by placing the specimens on glass rods in a tray such that their bottom surface up to a height of 5 mm is in contact with water, as shown in Figure 3.9. Photographic view of sorptivity test set up is shown in Figure 3.10.

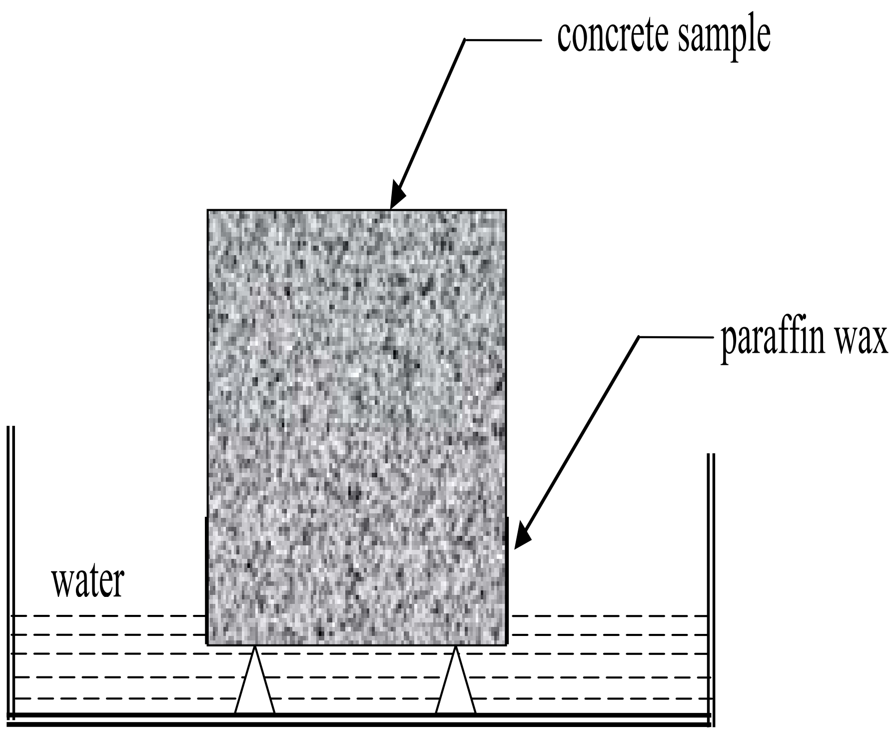


Figure 3.9 Detail of water sorptivity measurement

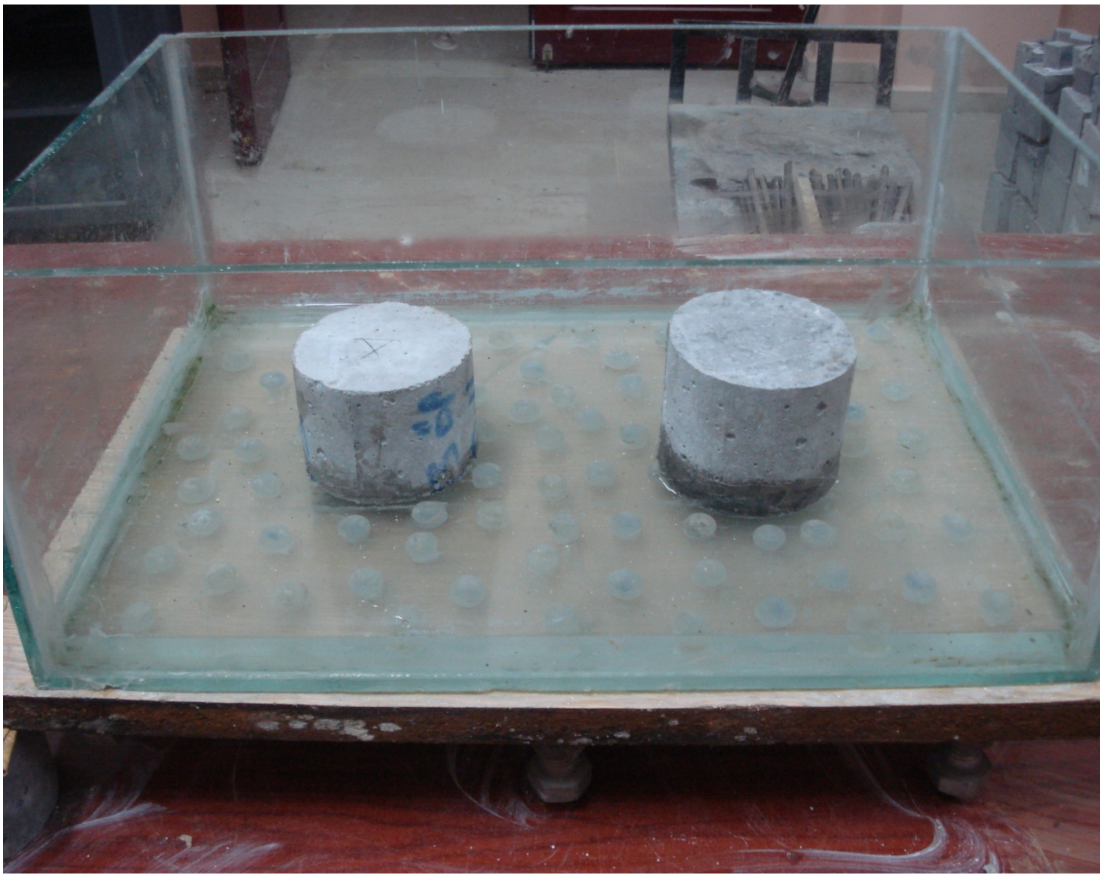
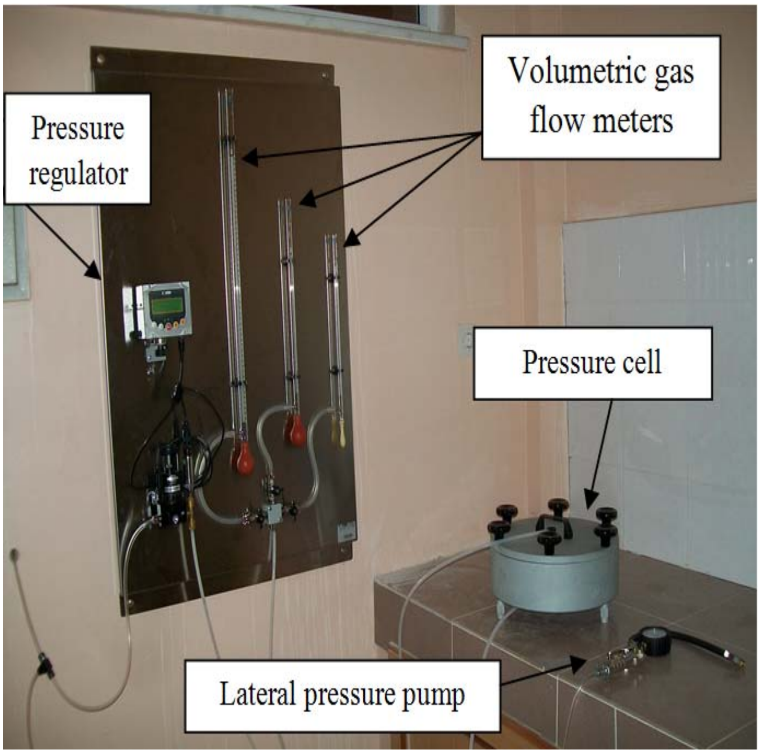


Figure 3.10 Photographic view of sorptivity measurement

This procedure was thought to permit free transportation of water through the bottom surface. The disk concrete specimens were taken from the tray and their weight at different intervals of time up to 64 minutes to assess increase in the mass. The absorbed volume of water is then computed dividing the increase in mass by the nominal surface area of the test specimen and by the density of water. These values versus square root of time were plotted on a graph and the rate of water absorption is calculated using the slope of the best fit line for each concrete mix. This test was performed at the end of 28 days of water curing.

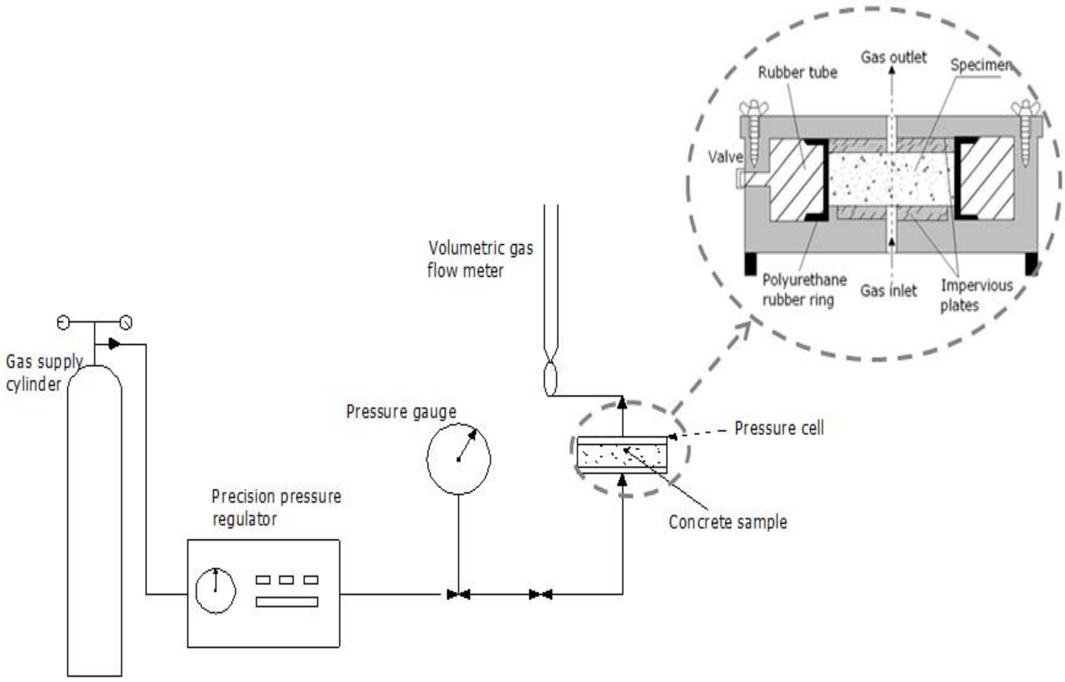
3.4.3 Gas Permeability Test

The CEMBUREAU method recommended by RILEM was followed for examinig the gas permeability of the concrete mixtures in accordance with the specification given per RILEM TC 116-PCD, 1999. The photographic view and the schematic layout of the gas permeability test set up together with details of the components of pressure cell are depicted in Figure 3.11.



Volumetric gas flow meters
Pressure regulator
Pressure cell
Lateral pressure pump

a)



Gas outlet
Specimen
Rubber tube
Valve
Polyurethane rubber ring
Gas inlet
Impervious plates
Volumetric gas flow meter
Gas supply cylinder
Pressure gauge
Pressure cell
Precision pressure regulator
Concrete sample

b)

c)

Figure 3.11. Gas permeability test: a) photographic view of the gas permeability set up, b) schematic presentation of set-up, and c) photographic view of pressure cell inside

The gas permeability of the concrete samples was measured on 50 mm height and 150 mm diameter concrete disk specimens cut from the mid portion of Φ150x300-mm cylinder. Oxygen gas was used as the permeating medium. Inlet gas pressures of 150, 200, and 300 kPa applied and gas permeability coefficients were determined for each level. Apparent gas permeability coefficient was average of these coefficients as proposed by RILEM (RILEM TC 116-PCD, 1999) Prior to the gas permeability test, oven drying process was processed. For gas permeability test, the specimens would be dried at 100±5 ^{o}C in oven to make sure each specimen weight change was less than 1%. Then, they were kept in a sealed box till test began. Three specimens for each concrete mixture were tested at the age of 28 days and the average of them was reported as a test result.

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

$$K_g = \frac{2P_2 QL\mu}{A(P_1^2 - P_2^2)} \tag{1}$$

Where K_g is the gas permeability coefficient (m^2), P_1 is the inlet gas pressure (N/m^2), P_2 is the outlet gas pressure (N/m^2), A is the cross-sectional area of the sample (m^2), L is the height of sample (m), μ is the viscosity of oxygen ($2.02x10^{-5}$ Ns/m^2), and Q is the volume flow rate (m^3/s).

3.4.4 Rapid Chloride Permeability Test (RCPT)

The resistance of the concrete to the penetration of the chloride ions was measured in terms of charge passed through the concrete in accordance with ASTM C1202 To avoid variations induced by bleeding and repetitive vibration, three 50-mm disk specimens were cut from the mid-portion of each Ø100x200-mm cylinder specimen, soon after the curing periods. The samples were conditioned as mentioned in ASTM C1202. Then, the disk specimens were relocated to the test cell in which one surface of the specimen was in touch with 0.3 N sodium hydroxide (NaOH) solution and the other surface with 3% NaCl solution. A direct current (DC) of 60 ± 0.1 volts was applied across the specimen faces, and the current across the specimen was recorded, covering a total period of 6 h. By knowing the current and time history, the total charge (coulombs) passed through the specimen was computed by Simpson's integration. The results presented are the averages from three concrete specimens. The test was performed at the age of 28 days. Photographic view of rapid chloride is shown in Figure 3.12.

Figure 3.12 Rapid Chloride permeability test (RCPT)

According to ASTM C1202 Chloride permeability in concrete classifies to five categories form “High” to negligible on the basis of the coulomb, as listed in Table 3.6

Table 3.6 Chloride Permeability Based on Charge Passed (ASTM C1202)

Charge Passed (Coulombs)	Chloride Permeability	Typical
>4,000	High	High W/C ratio (>0.60) conventional portland cement concrete
2,000–4,000	Moderate	Moderate W/C ratio (0.40–0.50) conventional portland cement concrete
1,000–2,000	Low	W/C ratio (<0.40) conventional portland cement concrete
100–1,000	Very Low	Latex-modified concrete or internally-sealed concrete
<100	Negligible	Polymer-impregnated concrete, Polymer Concrete

3.4.5 Accelerated Corrosion Test

A rapid corrosion testing technique was used to compare the corrosion performance of LWCs. In this study, the reinforced concrete specimens were immersed in a 5% sodium chloride solution leveling the midheight of the concrete cylinder. The steel bar (working electrode) was connected to the positive terminal of a DC power source while the negative terminal was connected to stainless steel plates (counter electrode) placed near the specimen in the solution. In this circuit, the steel bar is the anode, the steel plates are the cathode, and the sodium chloride solution is the electrolyte. The corrosion process was initiated by impressing an anodic potential of 12V. The impressed voltage is used to accelerate the corrosion process and to shorten the test period to fit practical laboratory testing conditions. Figure 3.13 is a schematic representation of the experimental set up for the accelerated corrosion test. Figure 3.14 is the photographic view of the accelerated corrosion test set up.

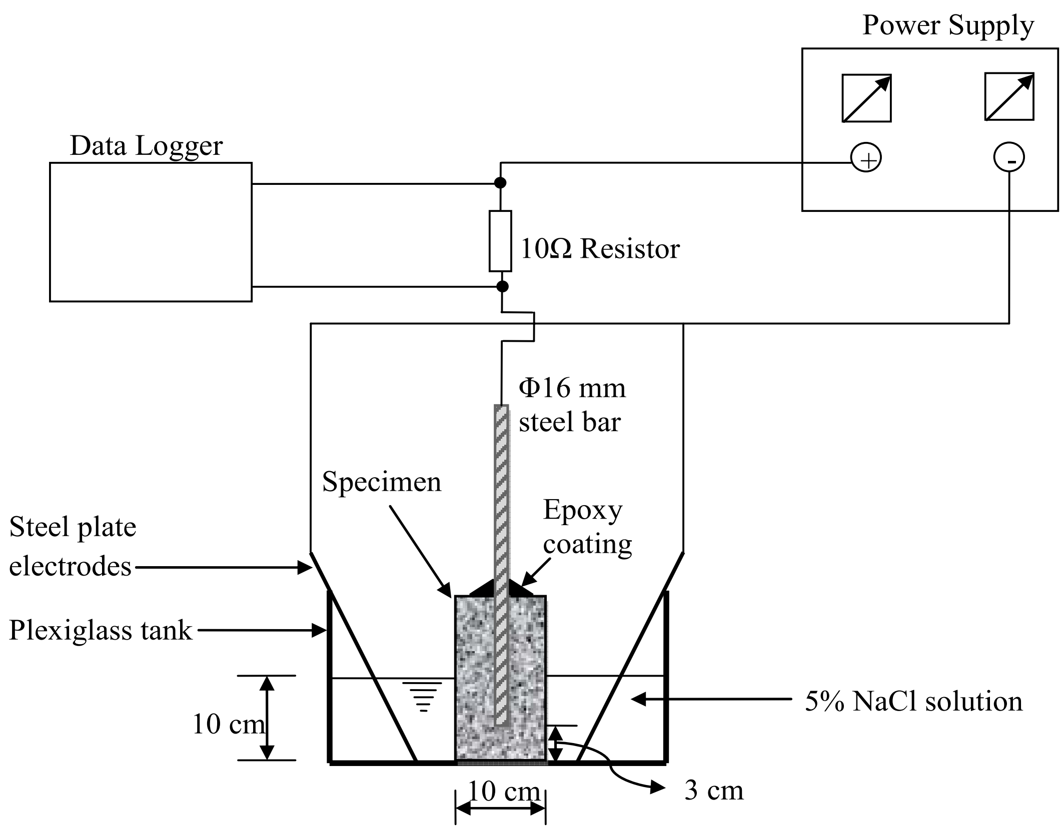


Figure 3.13 Schematic presentation of the accelerated corrosion test set up

Figure 3.14 Photographic view of the accelerated corrosion test set up

In Figure 3.15, the specimen while it was being performed, test is shown. In Figure 3.16, the specimens after termination of the test are shown.

Figure 3.15 Specimens under testing

Figure 3.16 Typical cracked samples after accelerated corrosion test

CHAPTER 4
TEST RESULTS AND DISCUSSIONS

4.1. Compressive Strength

The compressive strength test results of the concretes are given in Figure 4.1. Compressive strength of concretes varied between 30-48 MPa and 34-54 MPa for LWC-CB and LWC-S, respectively.

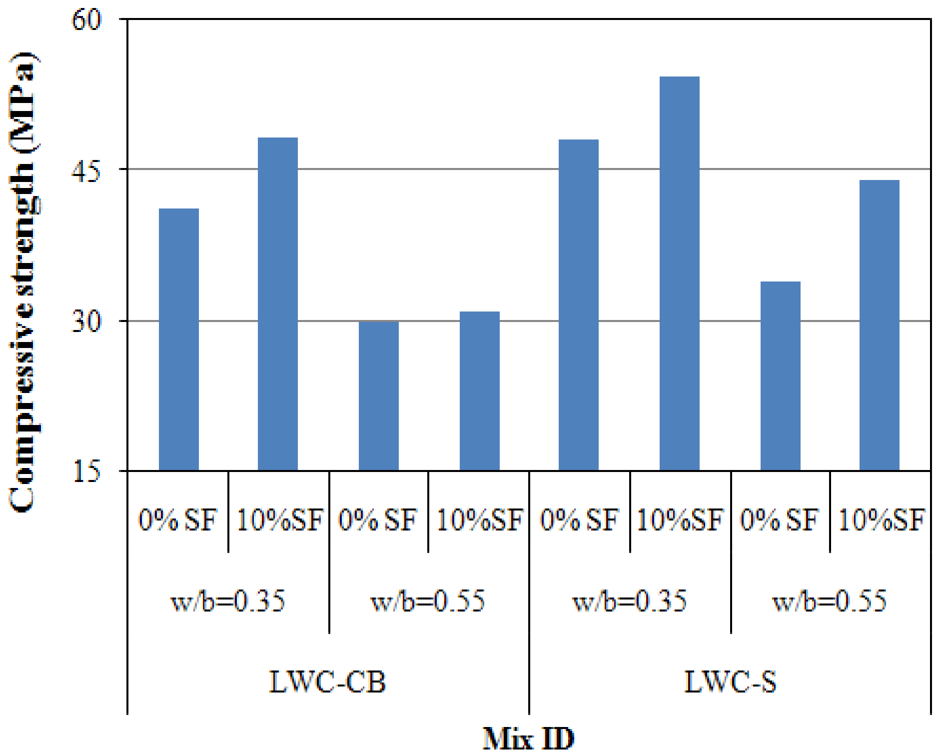


Figure 4.1 Compressive strength test results of lightweight concretes

Due to its filling and pozzolanic effect, SF incorporated concretes revealed higher strength development than plain ones (El-Khaja, 1994; Bhanja and Sengupta, 2005; Poon et al., 2006; Güneyisi et al., 2012). However, for the LWC-CB group produced with w/b ratio of 0.55, the difference between plain and SF incorporated concrete

were relatively lower than the others. For example, for LWC-S with w/b ratio of 0.55, the increase in compressive strength due to incorporation of SF was observed to be 29.4%, while for LWC-CB group the enhancement was about 3.5%.
Figure 4.1 clearly indicates the difference in compressive strength of LWCs due to utilization of different types of aggregates without depending on incorporation of SF. For both w/b ratios S aggregate containing concretes had higher compressive strength values than that of CB aggregate including ones.

The decrease in the CB aggregate incorporated concretes is due to higher porosity and lower strength of these aggregates. It is known that normal weight concretes have higher strength than LWC (Gesoğlu, 2004; Koçkal and Özturan, 2011; Gesoğlu et al., 2012). However, S aggregate incorporated LWCs can reveal proper performance in terms of mechanical properties when compared to normal weight concrete. In the study of Koçkal and Özturan (Koçkal and Özturan, 2011), it was reported that sintered lightweight aggregate manufactured with bentonite binder was used for light weight concrete production. LWCs with that aggregate had 85% and 90% of compressive strength of the normal weight concretes at 28 and 56 days, respectively.

4.2. Sorptivity Index

Water sorptivity is one of the most commonly used permeability testing due to its simplicity and ease of interpretation of the results. This test is mainly based on the water flow into the concrete by means of continuous pores. The water sorptivity coefficients of the LWCs are shown in Figure 4.2

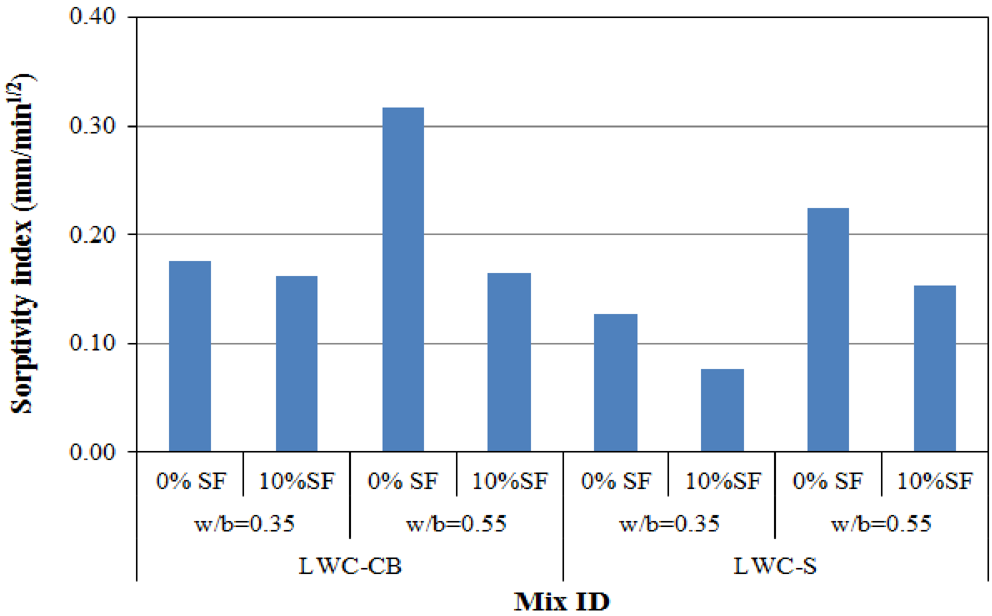


Figure 4.2 Variation of sorptivity indices of lightweight concretes

As expected, sorptivity coefficients of the concretes were decreased due to combined effects of SF incorporation and decrease in w/b ratio (Güneyisi et al., 2012). The minimum sorptivity was observed at LWC-S modified with SF at w/b ratio of 0.35 as 0.08 $mm/min^{1/2}$, while the maximum was measured at plain LWC-CB with w/b ratio of 0.55. Concretes containing SF revealed significant decrease in sorptivity values especially at LWC-CB with w/b ratio of 0.55. For LWC produced with w/b ratios of 0.35 and 0.55, the corresponding levels of decrease due to SF incorporation were 11% and 46% for LWC-CB, and 38% and 34% for LWC-S, respectively. Critical observation of Figure 4.2 indicated that when considering the fixed w/b ratio and SF content, changing type of coarse aggregate remarkably affected the sorptivity behavior of concrete. This can be considered as evidence which indicates that water absorption by capillarity of concrete depends not only on the quality of matrix, but also porosity of the aggregates. Diminishing the mean pore size and total porosity leads to reduced capillarity of concrete (Güneyisi et al., 2008; Batis et al., 2005; Chan and Xi, 1998).

This prevents the ingress of the water with its hazardous agents resulting in deterioration of concrete and corrosion of reinforcement. Therefore, minimizing sorptivity is important in order to reduce the entry of chloride-containing or sulphatecontaining water into concrete, which can cause serious devastation (Güneyisi and Mermerdaş, 2007; Chindaprasit et al., 2007).

4.3. Rapid Chloride Permeability

The ingress of water with chloride and/or other aggressive ions into concrete is the most noteworthy phenomenon in the physical-chemical mechanism of deterioration. The microstructure of concrete which chiefly controls this process is associated with water transport and the ingress of ions in concrete (Oh et al., 2002).

The resistance of concrete against chloride ion penetration as a function of electro-migration is indicated in terms of the total charge passed (Coulumbs). The variation of the total charges with respect to the type of concrete is demonstrated in Figure 4.3.

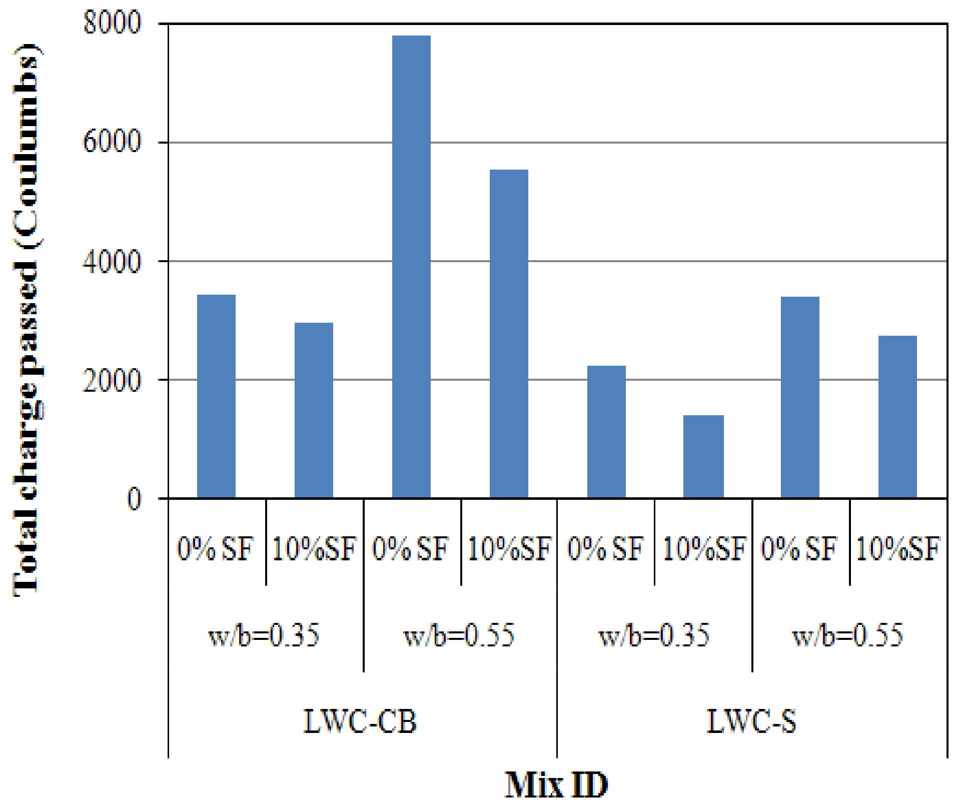


Figure 4.3 Rapid chloride permeability test results of lightweight concretes

The total charge values ranged between 2755-7784 C and 1384-3378 C for LWC-CB and LWC-S groups, respectively. ASTM C1202 classifies the chloride penetrability of concretes as “high” for total charge values above 4000 Coulumbs (C) and “moderate” for the values between 2000 C and 4000 C and “low” for the values between 1000 C and 2000 C. It was observed from Figure 14 that the concrete group LWC-CB produced with w/b ratio of 0.55 revealed high chloride permeability behaviors, irrespective of SF content. However, for LWC-S concretes even at high w/b ratio, good enhancement in chloride permeability behavior was observed. Moreover, inclusion of SF decreased the value of the total charge from 2236 C to 1384 C for LWC-S with w/b ratio of 0.35. This indicated that LWC with improved chloride permeability could be produced by using sintered aggregate and adjusting mix design parameters such as w/b ratio, binder content and use of mineral admixtures, etc.

4.4. Gas Permeability

RILEM (RILEM TC 116-PCD, 1999) recommends using 150, 200, and 300 kPa inlet pressures for computing the average gas permeability coefficient. Therefore, the apparent gas permeability coefficients of the LWCs at 28 days were determined accordingly and illustrated in Figure 4.4.

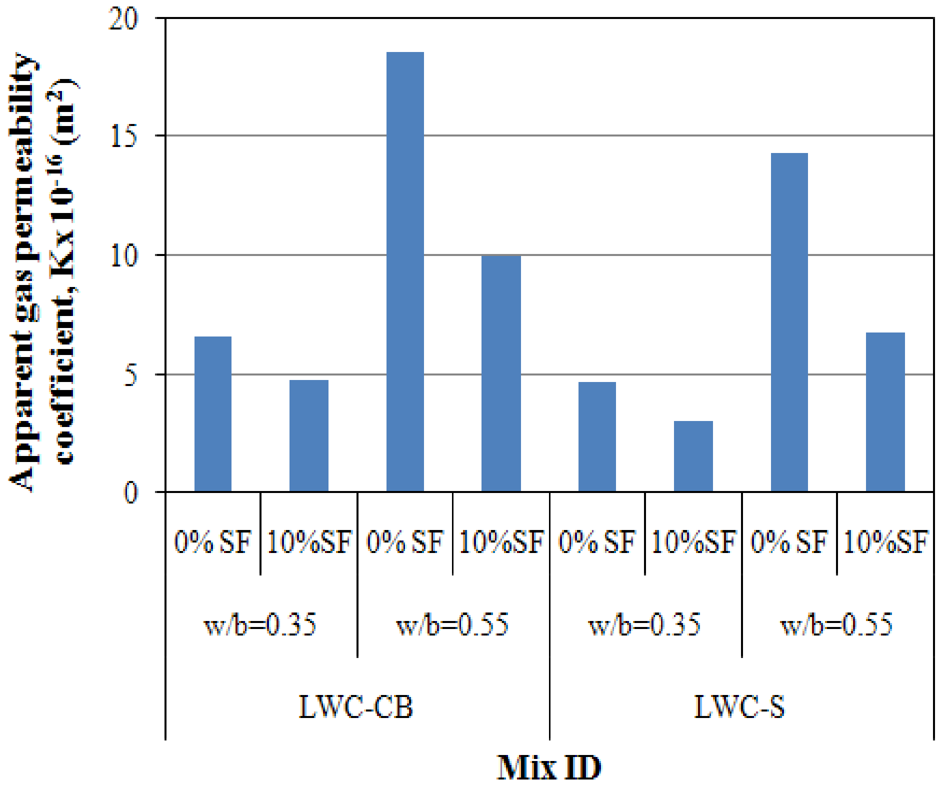


Figure 4.4 Apparent gas permeability coefficients of lightweight concretes

The maximum and minimum gas permeability coefficients were observed as $18.54x10^{-16}$ m^2 and $3.04x10^{-16}$ m^2 for LWC-CB and LWC-S concretes, respectively. In the study of Güneyisi et al. (Güneyisi et al., 2012), normal weight high performance concretes with W/B ratios of 0.25 and 0.35 were produced. They used silica fume (SF) and metakaolin (MK) as mineral admixture to enhance the permeability of concretes. They reported that 28 day gas permeability coefficients ranged as 0.97-2.04 ($x10^{-16}$) m^2 and 1.32-3.45 ($x10^{-16}$) m^2 for the concrete groups with w/b ratios of 0.25 and 0.35, respectively. In the current study, achieving the gas permeability coefficient down to $3.04x10^{-16}$ m^2 is an indication that the LWC with high performance in terms of permeability can be produced using sintered fly ash aggregate. However, concretes containing CB aggregate, especially for high w/b ratio resulted in considerably high gas permeability coefficient.

4.5. Accelerated Corrosion

Penetration of chloride ions into concrete which eliminates the original passivity can be thought as one of the main causes of reinforcement corrosion. In order to provide rapid evaluation of the corrosion behavior of LWCs accelerated corrosion test was applied. The accelerated corrosion behaviors of steel bars embedded in LWCs were studied by impressing a constant anodic potential. The time of reinforcement corrosion was determined by observing a sudden rise in the current followed by occurrence of crack of concrete specimens. Fast longitudinal crack formations were observed for the concretes at the time of sharp rise in the current. The initiation times of the cracks due to the corrosion of steel bars are shown in Figure 4.5.

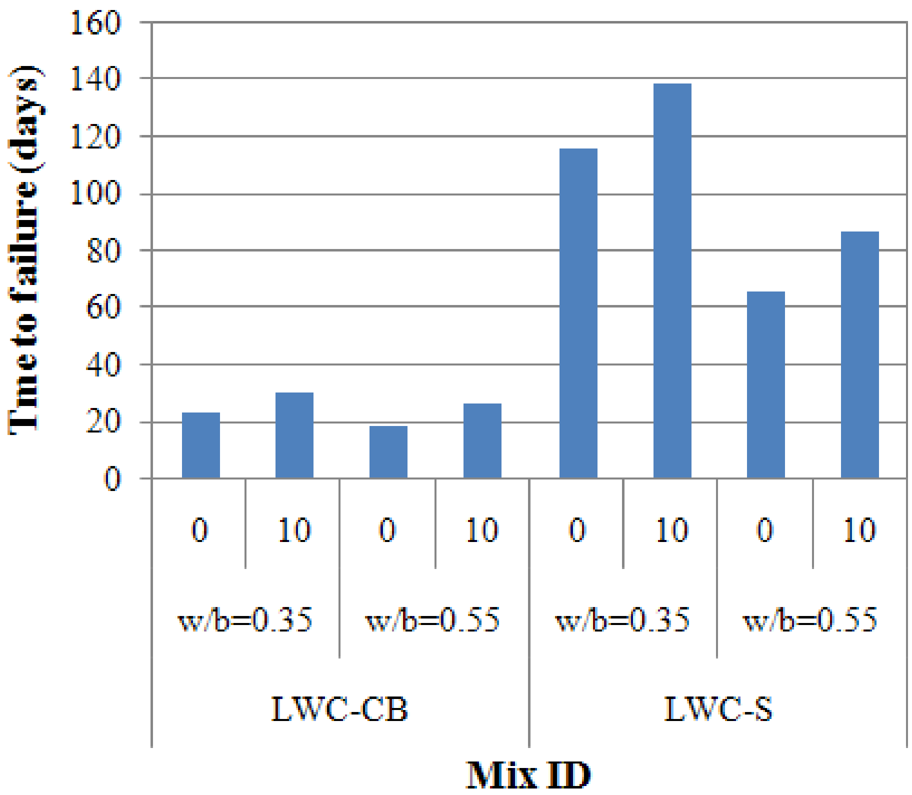


Figure 4.5 Failure times of the reinforced concrete specimens in accelerated corrosion test

Time to cracking in LWC-CB group ranged between 18-30 days while LWC-S concretes had crack initiation times between 65-138 days, depending on SF incorporation and w/b ratios. In this test, type of aggregate seemed to be the most effective parameter. For example, for LWC-CB with w/b ratio of 0.35, the addition of SF provided 30% extension in the cracking time, however, in case of utilizing S aggregate the duration for crack formation was almost 5 times longer.

4.6. Correlation of the data

Correlating the experimental data is one of the most common practices among the researchers for assessment of the findings reported. Theoretically, the main elements controlling the mechanical properties of concrete are the relative volume fractions of paste matrix and aggregate as well as their quality. It is agreed that there is a close relationship between mechanical and durability properties. For this reason, the durability properties of LWC examined in this study were correlated with compressive strength. The correlations are depicted in Figures 4.6 - 4.9.

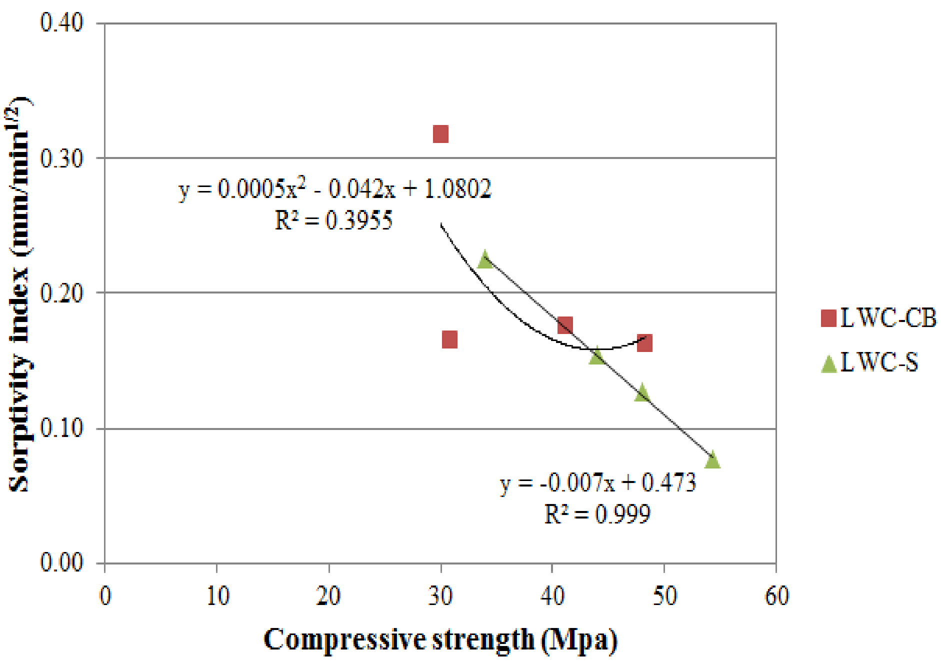


Figure 4.6 Correlating between compressive strength and sorptivity index

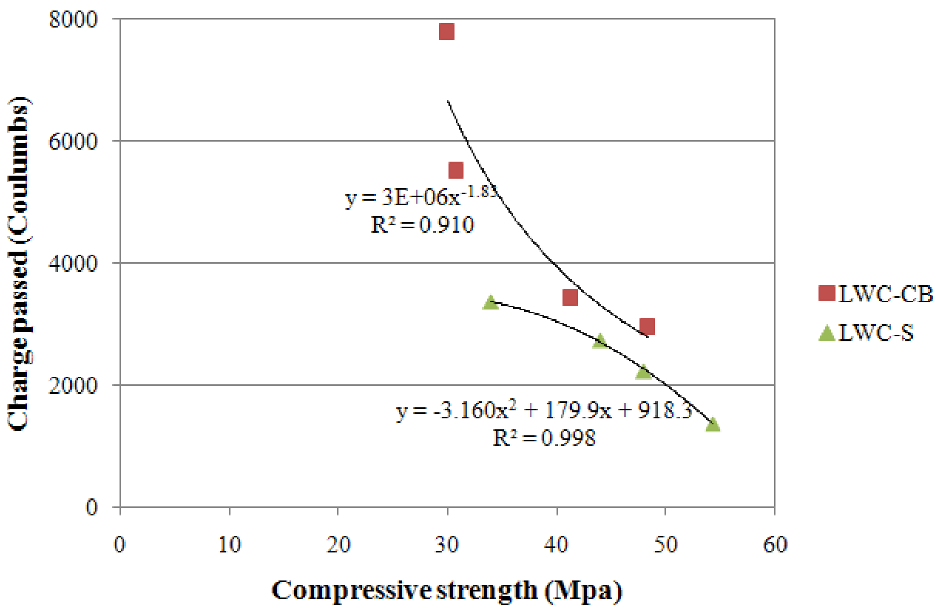


Figure.4.7 Correlating between compressive strength and total charge passed

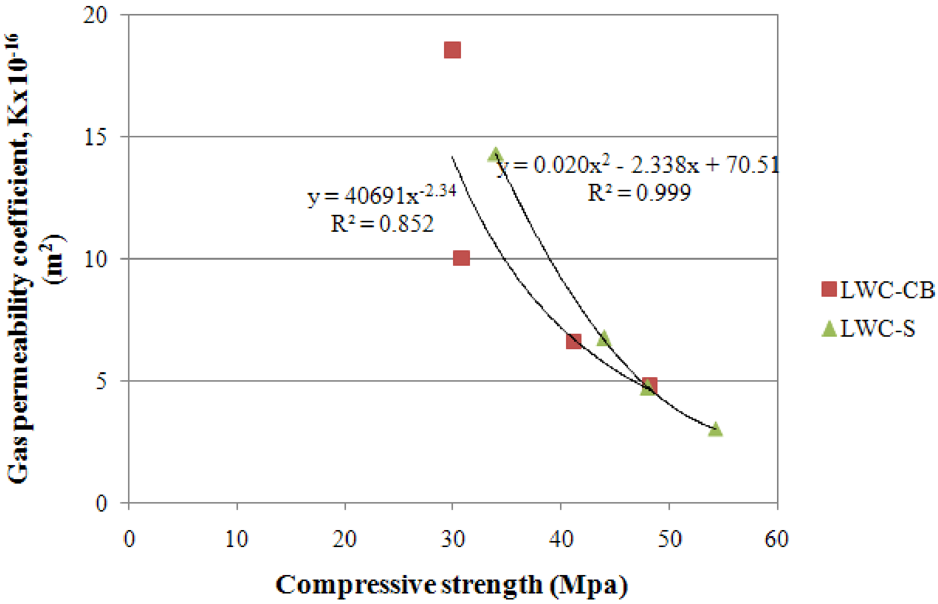


Figure 4.8 Correlating between compressive strength and gas permeability coefficient

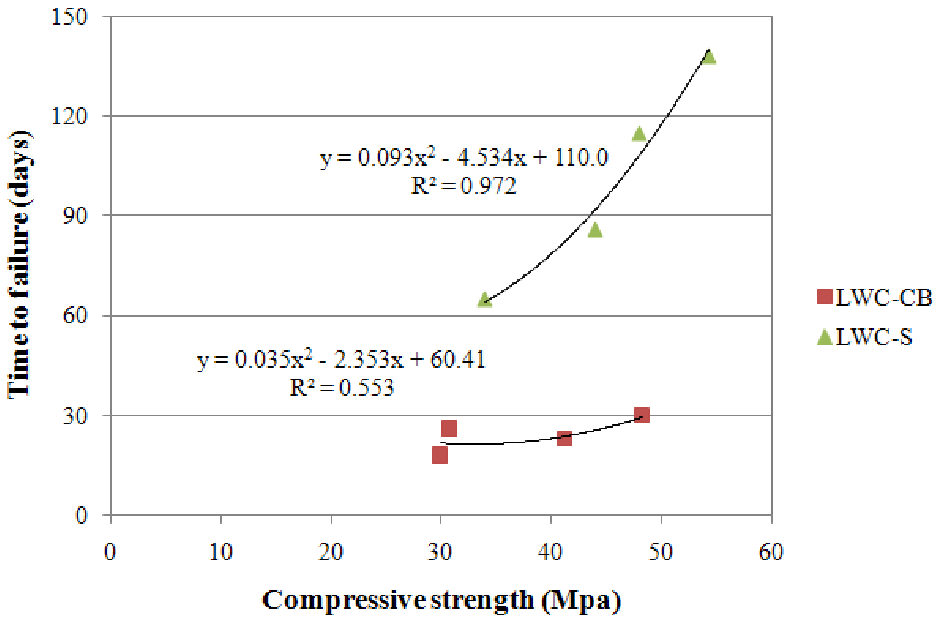


Figure 4.9 Correlating between compressive strength and time to failure due to corrosion of steel rebar

Based on the facts presented above to specify the possible analytical relation between compressive strength and the other properties, the correlation coefficients (R^2) as well as the mathematical expressions were presented on those figures as well. The data used for these figures cover the entire test results obtained. The strongest correlations were observed at LWC-S group for sorptivity and total charge passed (R^2=0.99) while the weakest were observed at LWC-CB group for sorptivity (R^2=0.39). R^2 values were ranged between 0.91 and 0.99 for LWC-S and 0.39 and 0.85 for LWC-CB. As a result of the noticeable differences and uniformity for the measured values for the LWC-S high correlations were observed to take place for this group. Low correlations observed for the LWC-CB group may be due to the irregularity of the scatter of the data.

CHAPTER 5
CONCLUSIONS

Based on the findings presented above, the following conclusions may be drawn.

- Cold bonded (CB) and sintered (S) aggregates were produced with water absorption values of 16.3% and 11.7%, respectively. The aggregate crushing strength of S aggregates was about 3-4 times greater than that of CB aggregates, depending on grain size. Higher strength aggregate provides opportunity for production of concrete with improved mechanical property.

- Inclusion of silica fume (SF) resulted in significant enhancement of compressive strength of the LWCs. The combined use of S aggregate and SF provided the compressive strength values of 54 MPa and 44 MPa for w/b ratios of 0.35 and 0.55, respectively.

- The improvement in water sorptivity due to pozzolanic and microfilling effect of SF was observed at both groups of LWCs. The aggregate type was also appeared to be influential on the improvement of capillary water penetration behavior of concretes.

- Reflecting the chloride penetrability into concrete, total charge values were significantly reduced in LWCs due to incorporation of SF. However, the utilization of S aggregates seemed to be more effective than inclusion of SF in diminishing the charge values. For example, addition of SF provided 14% decrease for LWC-CB concrete with w/b ratio of 0.35. However, for the same w/b ratio, LWC-S concrete had 34% less value than LWC-CB concrete.

- Gas permeability coefficients of the LWCs were ranged between 3.04-14.02 ($x10^{-16}$) m^2 and 4.78-18.54 ($x10^{-16}$) m^2 for LWC-S and LWC-CB groups, respectively. Due to enhancement in cement paste matrix, SF modified LWCs revealed less permeability. The significance of aggregate type on the gas permeability behavior of concretes were also observed in this test.

- The resistances of the LWCs against corrosion cracking were proved to be enhanced through incorporating SF and especially S aggregate. The crack time in the accelerated corrosion test was extended up to 5 times when S aggregate was used instead of CB aggregate. The highest failure time was measured as 138 days for SF modified LWC-S with 0.35 w/b ratio while the minimum crack initiation time was observed as 18 days for plain LWC-CB with w/b ratio of 0.55.

- The correlations between compressive strength and other properties of LWCs revealed that concretes with S aggregate had very high R^2 values between 0.91 and 0.99 while these values for CB aggregate incorporated ones ranged from 0.39 to 0.85.

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APPENDIX A. PHOTOGRAPHIC VIEWS

Figure A1 Photographic view of pelletization disc

Figure A2 Photographic view of CB aggregates

Figure A3 Photographic view of dried LWA in oven

Figure A4 Photographic view of vacuum