UNIVERSITY OF GAZİANTEP
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PROPERTIES OF STEAM CURED LIGHTWEIGHT CONCRETE MADE WITH FLY ASH LIGHTWEIGHT AGGREGATE

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Properties of Steam Cured Lightweight Concrete Made With Fly Ash Lightweight Aggregate

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Supervisor
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BarhamHaydarALI

ABSTRACT

PROPERTIES OF STEAM CURED LIGHTWEIGHT CONCRETE MADE WITH FLY ASH LIGHTWEIGHT AGGREGATE

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M.Sc. in Civil Engineering
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In this thesis, effects of steam and water curing on the compressive strength development and transport properties such as water sorptivity, rapid chloride ion permeability, and gas permeability of concretes containing various volumes of lightweight fly ash aggregate (LWA) were investigated. In production of concrete, a fixed amount of lightweight coarse (LWCA) aggregate plus varying amounts of lightweight fine aggregate (LWFA) were used. Utilization of LWFA was achieved by volumetric substitution of fine aggregate with 5 different replacement levels namely, 0%, 25%, 50%, 75%, and 100%. Therefore, five different concrete mixtures wereproducedfortheexperimental study. The produced concretes were divided into two parts one of which was initially steam cured while the other was directly exposed to water curing. After initial steam curing regime, the steam cured (SC) concretes were also transferred to water until testing. Mechanical properties of concretes were monitored through compressive strength development over 56 days while transport properties were measured by means of water sorptivity, gas permeability and rapid chloride permeability tests at the ages of 28 and 56 days.

Key words: Lightweight aggregate; Fly ash,Curing regime; Strength development; Transport properties

ÖZET

UÇUCU KÜL HAFİF AGREGASI İLE ÜRETİLEN BUHAR KÜRLÜ HAFİF BETONUN ÖZELLİKLERİ

Ali, Barham Haydar
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Tez Yöneticisi: Doç. Dr. MEHMET GESOĞLU
Ocak 2013, 94sayfa

Bu tezde, buhar ve su kürünün çeşitli oranlarda uçucu kül hafif agregası içeren ve içermeyen betonların, basınç dayanımı gelişimi, kılcal su geçirimliliği, hızlı klorür geçirimliliği, gaz geçirimliliği gibi özellikleri üzerindeki etkileri araştırılmıştır. Hafif beton üretiminde sabit miktarda hafif iri agrega kullanılırken, hafif ince agrega çeşitli hacimsel oranlarda kullanılmıştır.Hafif ince agrega kullanımı beş faklı değişim düzeyinde, yani %0, %25, %50, %75 ve %100 oranlarında gerçekleştirilmiştir. Böylece, deneysel çalışma için beş farklı beton karışımı elde edilmiştir. Üretilen betonlar iki kısma ayrılarak su ve buhar kürlerine tabi tutulmuşlardır. Başlangıçta buhar kürüne tabi tutulan betonlar daha sonra deney yaşları gelene kadar suda bekletilmişlerdir. Mekanik özellik olarak 56 günlük basınç dayanımı gelişimi incelenirken, geçirimlilik özellikleri 28 ve 56 günlük kür süreleri sonunda ölçülmüştür.

Anahtar kelimeler: Hafif agrega; Uçucu kül, Kür koşulları; Dayanım gelişimi; Geçirimlilik

To My Family, they should receive my greatest appreciation for their enormous love. They always respect what I want to do also give me their full support encouragement over the years.

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LIST OF SYMBOLS/ ABREVIATIONS

ACI	American concrete institute
AFA	Artificial cold-bonded fly ash aggregate
AFFA	Artificial fly ash fine aggregate
ASTM	American standard for testing material
B	Bentonite
BD	Bulk density
BFS	Blast furnace slag
BS	British standard
CLWC	Expanded clay lightweight concrete
C-S-H	Calcium-silica-hydrate (Gel)
DEF	Delayed ettringite formation
FA	Fly ash
FFA	Fly ash aggregate
G	Glass powder
H	Hour
ITZ	Interfacial transition zone
K_a	Gas permeability coefficient

LBD	Loose bulk density
LWA	Lightweight aggregate
LWAC	Lightweight aggregate concrete
LWBC	Lightweight bottom ash concrete
LWC	Lightweight concrete
LWFA	Lightweight fine aggregate
LWGC	Lightweight granular blast furnace slag concrete
MIP	Mercury intrusion porosimetry
MK	Metakoalin
NWC	Normal weight concrete
OD	Oven dry
OPC	Ordinary portland cement
PUR	Polyurethane
RBD	Rodded bulk density
RCPT	Rapid chloride permeability test
RV	Rodded bulk density
LV	Loose void
SC	Steam curing
SEM	Scanning electron microscopy
SEM-BSE	Scanning electron microscope-backscattered electron
SF	Silica fume

SFA	Sintered fly ash aggregate
SLWAC	Sintered fly ash lightweight aggregate concrete
SMF	Sulfonated melamine formaldehyde
SNF	Sulfonated naphthalene formaldehyde
SP	Super plasticizer
SSD	Saturated Surface dry aggregate
UFA	Ultrafine fly ash
V	Void
W/B	water/binder ratio
W/C	water/cement ratio
WC	Water curing

CHAPTER 1

INTRODUCTION

1.1 General

Coal-fired thermal power plants fabricate large quantities of fly ash, but unfortunately till now only a small amount can be used in concrete. Nowadays, a big quantity of fly ash is thrown off in landfills and storage ponds. One of the huge issues of causing air and water pollution is fly ash which drives to problems of disposal such as environmental damage. It is right to mention that a few years ago, usage of fly ash and sintering aid powders are developed in the improvement of new lightweight building materials. Previous investigations were done on physical features and strength of artificial lightweight sintered aggregates generated from different industrial by products [1–4]. Observation was done by Ramamurthy and Harikrishnan [5] on the features of aggregates relay on the sort and quantity of the binder that did not change the chemical composition but the microstructure of the aggregate. Thechangesof heat and polymer treatments causes the structure and features of sintered fly ash lightweight aggregate (Lytag) to gain different in their strength, absorption, and pozzolanic activity [6]. Production of lightweight aggregates is used as financial source for some of the countries such as UK, USA, Germany, Poland, and Russia [7]. Many researchers used lightweight aggregates in concrete for the aim of commercialas well as Strength, stiffness and durability of concrete [8–13]. The permeability of concrete identifies its long-term durability. Permeable concrete is vulnerable and precision to water and harmful substances it comprises and this causes deterioration of concrete and reinforcement. The interfacial zone between aggregate and the cement matrix affects the features of concrete such as strength, stiffness, and durability [14].

Curing in live steam at atmospheric pressure dramatically increases the rate strength development of concrete for that is used primarily for precast concrete products like masonry block, pipe, pre-stressed beams, and wall panels, but can also be used for enclosed cast-in-place structures. In the precast concrete industry, steam curing allows increased production by a more rapid turnover of molds and formwork shorter curing periods before shipment or pre-stressing, and less damage to the product during handling. When the steam is fabricated at atmospheric pressure, temperature should be kept below 100^{o}C, [15–17] to get rid of delay ettringite formation which characterized by the development of “gaps” around some aggregate particle. These gaps often contain densely compacted ettringite so thatoccurs primarily when cement is used that have a ratio of SO_3 to Al_2O_3>0.5 [18]. The pozzolanic reaction thermo-activated by a high curing temperature, provided the development of C–S–H and assimilated the phases to the detriment of calcium hydroxide. The detrimental impacts of steam curing may be due to the coarser pore structure, improved micro-cracking and delayed ettringite formation [19–21].The effect of curing temperature on the features of cement mortars and concretes has been the topic of several researches. It is widely clarified that a high curing temperature directly after casting supports the development of mechanical features at early ages but adversely influences the strength at later ages. Mouret et al. refers that [22] the concrete cured at 35^{o}C 10% had less 28-day compressive strength when compared with the similar concrete cured at 20^{o}C. According to Verbeck and Helmuth’s study [23], a 28% strength reduction was realized when curing temperature was increased from 20^{o}C and 50^{o}C. This reduction at later age strength was referred to the rapid initial rate of hydration at higher temperature which retarded the subsequent hydration and produced a non uniform distribution of the hydration products [23]. Topcu and Toprak [24] investigated the influence of curing temperature and the type of fine aggregate on the compressive strength of concretes. Concretes containing river sand or crush stone sand were generated and exposed to 20^0C, 40^0C, and 60^0C curing temperatures. The study recommended that increase in the curing temperature improve the strength at early ages but affected negatively the 28- day results.

Liu et al. [25] investigated the influence of steam curing on the compressive strength of concrete containing ultrafine fly ash with or without slag. They deduced that the concrete containing ultrafine fly ash (UFA) had much lower early strength after 13 h steam curing and the difference between the 28-day compressive strength of the 13 h cured steam concrete and that of the moist-cured concrete was large. This finding indicated that the steam curing adaptability of UFA seemed to be rather poor. In another study of Liu et al. [26], however, ultrafine fly ash composite was developed by adding some mineral powders into UFA. It was observed that concrete containing ultrafine fly ash composite and ground blast furnace slag gave the desired early compressive strength. Yazıcı et al. [27] showed the usability of the fly ash in mixtures for precast concrete industry. They revealed that steam curing enhance the 1-day strength values of high volume fly ash concretes from about 10 to 20 MPa. However, the ultimate compressive strength of steam-cured fly ash concrete was much lower than that of the standard-cured concrete. However, there is limited research on the durability performance of the steam-cured concrete. According to Ho and Lewis [28], and Ho [29], steam-cured ordinary Portland cement concrete cover was poor in quality and equivalent to that achieved with only 2–3 days standard curing as indicated by the water sorptivity tests. Ho et al. [28] discovered the potential benefits of steam-curing on concrete mixes incorporating various combinations of fly ash, slag, and silica fume. It was explored that the steam-cured concretes were more porous as indicated by their higher sorptivity compared with the standard cured specimens. Mixes with silica fume appeared to have the best performance with high early strength and low sorptivity. Ho and Cao [30] reported that the quality of steam-cured concrete containing 20% fly ash was better than that with 28 days standard curing. Similar results were obtained for blended cements containing 35% blast furnace slag [31, 32].

In recent years, there has been a growing interest in the use of fly ash to produce lightweight aggregate. Under the light of the facts referred above, the main objective of this thesis is to investigate the influence of lightweight fly ash aggregate inclusion (fine and coarse) on the compressive strength, gas permeability, water sorptivity, and rapid chloride ion penetration of the steam cured lightweight concrete which was kept for 17 h under high temperature at about 70^{o}C, comparing to the water curing lightweight concretes at room temperature.

1.2 Research Objectives

The study presented herein investigates the properties of the steam curing lightweight concrete made with cold bonded fly ash aggregate. For this purpose, artificial fly ash aggregate was generated by means of cold bonding at room temperature. Natural fine crushed lime stone was replaced by lightweight fine aggregate fly ash at a different replacement level to observe the shape and mineralogical effects of rounded artificial fine lightweight aggregate on the fresh, mechanical and durability properties of lightweight concretes.

Experimentally, tenLWCs mixes were prepared with water binder ratio of 0.35 and total binder content of 450 kg/m^3, which was five mixes were exposed to steam curing and the other five mixes were exposed to water curing. Testing parameters relevant to cold bonded aggregate are mainly the fine aggregate volume fraction. The selected volume fractions of artificial aggregates were0, 25, 50, 75 and 100 percent of the total aggregate weight. Fresh properties of LWCs were observed through slump to control the workability. Hardened properties of LWCs were evaluated in terms of compressive strength, chloride ion permeability, sorptivity index and gas permeability.

1.3 Thesis Organization

This thesis consists of five chapters:

Chapter 1: contains introduction, thesis objective, and thesis organization.

Chapter 2:shows a literature review and general background information about LWCs, and effects of steam curing on both mechanical and durability behaviors of concretes as well as material behavior are explained. A brief definition and theory of the pelletization process are presented. Also includes summary information about the concrete aggregate-cement paste interface bond characteristicsthrough previous studies. Moreover, carrying out a brief introduction about the structure, formation, properties of mineral admixtures namely fly ash and its effects on the fresh, mechanical, and durability properties of LWCs are also discussed.

Chapter 3: covers the experimental program conducted throughout this study. Properties of cement, aggregates, mineral, and chemical admixtures used in the concrete production as well as the tests on fresh and hardened properties of LWCs are included.

Chapter 4: provides the test results of the testing program conducted in the task. Furthermore, how lightweight concrete made with a cold bonded fly ash aggregate affect the fresh, mechanical and durability properties of LWCs are explained in this chapter.

Chapter5: presents conclusion of the thesis and recommendation for future studies.

CHAPTER 2

LITERATURE REVIEW

2.1 General

This chapter presents the history and recent development of lightweight aggregate concrete, effects of LWFA on mechanical and durability properties of concrete, importance of concrete curing, comparing the method of curing such as steam curing and water curing, and effect of increasing temperature on LWCs features.

2.2Introduction

The main parameter making separation between conventional concrete and lightweight fly ash aggregate concrete is the weight. Ordinarily density of concrete is in the range of 2200 to 2600 kg/m^3. However, light self-weight of fly ash aggregate concrete makes an economical structural material compared to heavy self-weight of conventional concrete. In order to manufacture concrete of requested density to conform the demanded application, the self-weight of structural and non-structural members is to be decreased. Therefore, economy is acquired in the design of supporting structural elements which guide to the improvement of lightweight concrete. Lightweight aggregate concrete is the concrete made by replacing the usual material aggregate by lightweight aggregates. Though lightweight concrete can’t always replace normal concrete for its strength potential, it has its own benefits like reduced dead load, and thus economic structures and improved seismic resistance, high sound absorption and good fire resistance [33].

2.3 Lightweight aggregate concrete

Artificially, fly ash is used to produce the lightweight aggregate with low specific gravity. This lightweight aggregate used to produce lightweight concrete instead of ordinary concrete. Pumice, scoria and all of those of volcanic origin are belong to the natural lightweight aggregate and the expanded blast-furnace slag, vermiculite, clinker aggregate and fly ash aggregate are all classified as artificial aggregate.The most important feature of this lightweight aggregate is its high porosity which causes low specific gravity [1]. Two types of lightweight aggregate concrete exist according to its application. One of them is partially compacted lightweight aggregate concrete and the second one is the structural lightweight aggregate concrete. The main usage of the first one (partially compacted lightweight aggregate concrete) is for two purposes that is for precast concrete blocks or panels and cast in-situ roofs and walls. In order to confront cracking one of the most important requirements for this type of concrete is that it should have enough strength and a low density to obtain the best thermal insulation and a low drying shrinkage [2].

2.4 Difference between Normal Weight Concrete and Lightweight Aggregate Concrete

Differences between LWAC and NWC interest the mixing phase, hardening phase, tensile, failure modes et al. The workability of concrete is affected by the mixing phase, the porous water absorbing LWAs [34] and the efficient water/binder ratio [35]. In stage of hardening phase, the origin of higher hydration temperature is made by the proportionately inferiority specific heat and high isolating capability of LWAC. The water at first split second in the porous aggregate fragments may affect the phase of moisture in the hardening procedure to a great extent.

Volumefluctuations occur with the fluctuations in the phase of water in the pore technique in the early of hardening stage. The differences between LWAC and NWC in hardened stage are mostly anticipated to divergences in the elastic modulus and strength of the aggregate, and especially variation being in the matrix aggregate transition zone. Grade of heterogeneity of concrete is designated by these differences. The features of the interfacial zone are indicated by the surface features of the aggregate, in addition to the pore structure and the basic water content of the aggregates [36]. Some defiance products, e.g. CH, confidents on the pore structure of the aggregates, will even drill inside the pores of the aggregates. This is further agreeable in aggregates with higher absorption and larger pores [36]. The strength of many LWA is approximately the equal as the strength of the hardened paste.

The matrix aggregate transition zone is of a higher distinction compared to the condition of NWC. The bleeding affect on aggregate surfaces is as well decreased anticipated to the decreased reaction of the LWA to vibration-energy through the compaction process of the concrete. It is reached to a conclusion that in many LWAC, the transition zone is not the most strengthening connection, ordinarily; the LWA has even lower modulus of elasticity than the mortar stage, generating the mortar to pull further stress.

With equivalent modulus of elasticity for the mortar and LWA, the stress will be further evenly distributed in LWAC than in NWC. As an issue of reality, in this case, the transition zone will slightly be cramped by inclined compressive stress. The resulting limited inclined tensile stress will demonstrate in the mortar, and not in the transition zone [37]. The crack beginning of LWAC happens at a very high-stress degree anticipated at the phase of elastic suitability. The strength and rupture toughness of LWA is considerably 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 LWA [38, 39].

2.5 Lightweight aggregate

2.5.1Background

Enormous amounts of fly ash are produced from thermal coal-fired power plants and only a small amount is taken advantages of it. Fly ash guides to create such big environmental problems as polluting of air and water by a large scale [40,41]. In Turkey, about 15 million tones of fly ash is produced annually while a few amount of it is being used for many purposes [42]. Large amount of fly ash be left unutilized in most countries of the world, the generating of lightweight fly ash aggregates is a suitable step to greatly increase its usage. Newly, some enterprises have been made to use fly ash for the manufacture of lightweight aggregate by two different methods.

Sintering and cold bonding are the primary hardening processes for generating lightweight fly ash aggregates from fly ash pellets. However, very limited study has been done for the use of binders as sintering aids in aggregate generation whereas the input of binders in fly ash decreases the specific gravity and increases the strength of lightweight aggregate (LWA) particles by altering the microstructure of aggregates during sintering process [5, 44–46]. The appropriate of fly ash for the pelletization and sintering process, on the other hand, is difficult to estimate because many physico-chemical factors are included. Ramamurthy and Harikrishnan [5] investigated that the properties of aggregates relay on the type and amount of the binder which did not change the chemical composition but the microstructure of the aggregate. The structure and properties of sintered fly ash lightweight aggregate (Lytag) was remodeled by heat and polymer dealings to achieve aggregates vary in their strength, absorption and pozzolanic activity [6].Wasserman and Bentur [6] have also proved that the strength of the concrete could not be responsible for by the strength of the aggregates only and it was recommended that the absorption and pozzolanic activity of the aggregates could have an effect on the strength improvement. Commercially generated lightweight aggregates were utilized in concrete by many researchers to explore the strength, stiffness and durability of concrete[48–53].

2.5.2 Peletizetion process

The demand in grain size distribution of an artificial lightweight aggregate is provided either by crushing or by means of accumulation process. Lightweight coarse aggregate (LWCA) is generated by pelletization process; some of the factors need to take consideration for the performance of the manufacture of pellet such as speed of revolution of pelletizer disc, moisture content, angle of pelletizer disc and duration of pelletization[54].

Disc or pan type, drum type, cone type and mixer type are different types of pelletizer machineutilized to make pellet. Controlling size distribution is more effortless in disc type pelletizer than drum type pelletizer. With mixer type pelletizer, first of all the small granule particles are formed and afterward increased in particle size by disc type pelletization shown in Figure 2.1 [55]. Size of the disc pelletizer instrument is 570 mm diameter and side depth ofthe disc as 250 mm, it is fixed in a flexible frame with regulating the angle of the disc as 35 to 55° and to control for the rotate disc in vertically manner should varying speed as 35 to 55 rpm shown in

Figure 2.2 [56]. Strength of pellet increases in cold bonding method as to increase the fly ash/cement ratio as 0.2 and above (by weight) [57].Moisture content and angle of the disc parameter affect the size enlargement of pellets [54]. The dosage of binding agent is more significant for making fly ash balls and the optimum range was obtained to be around 20% to 25% by the total weight of binders [55]. At first the addition of some percentage of water is done in the binder and then spilled in a disc; while it rotates remaining water is sprayed because during rotation if water is not spread in to the disc the fly ash powder tends to form lumps and does not increase the distribution of particle size. During 20 min. the pellets are going to be form.

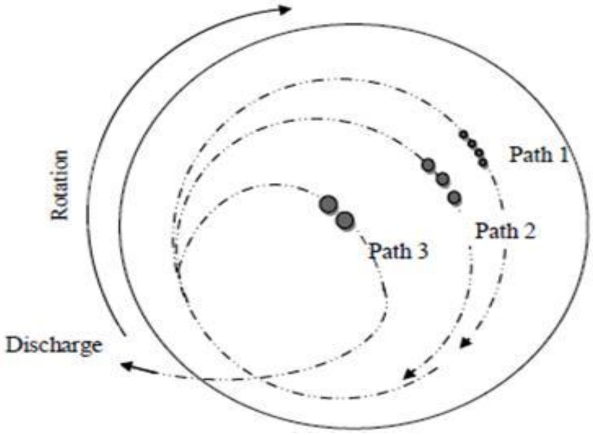


Figure 2.1 Enlarging path of pellets [55]

2.5.3 Hardening process of LWA

According to ASTM C 618 specification there are two major classes of fly ash which are class-C and class-F and their classification depend on the chemical composition resulting from the different types of coal burning. Class-C fly ash is ordinarily generated from the burning of sub-bituminous coal and lignite.

Figure 2.2 Disc pelletizer machine [55]

The fly ash aggregates are porous material and to develop the strength of the pellet the following binder material such as cement, lime, bentonite, metakaolin, kaolinite, glass powder and ceramic powders are put in. Higher fines value is obtained by clay binders like metakaolin and kaolinite [59]. The percentage of binder content is taken by the weight of fly ash. Cold bonding, sintering and autoclaving are different processes which make the pellets hard.

Water curing, steam curing and autoclaving are various curing processes which make cold-bonded flyash aggregates hard. Autoclave and steam curing technique is less influential to develop the features of aggregate as checked against to normal water curing method. Between accelerated cured class C fly ash aggregate, autoclaved aggregates has features near to the normal water cured aggregate because of the dense microstructure formation. The curing system is further significant to improve the aggregate strength. Consequently, for high early strength, a standard water curing system can be adopted and autoclaving may be adopted [60]. A higher strength of the aggregate can be gained at 8 to 10 h in autoclave curing [61].Sintering process can be described as burning the cold bonded pellet in a muffle furnace at temperature range of 800°C to 1200°C. The mineral particles in the binder integrate together to form the crystalline structure (CSH) and results in higher strength of the aggregate. Therefore, sintered fly ash lightweight aggregate production is more eligible while replacing the normal weight aggregate to lightweight aggregate [62].

2.5.4 Mix design of LWAC

The mix design of lightweight aggregate concrete differs from the conventional concrete mix design since the aggregates are porous and results in indemnity of extra water for gaining more workability. The mix design notions are usually depend on the generation of higher strength matrix to low water cement ratio for the weaker aggregate. Hence, in conventional concrete, the number of batches that are necessary to specify the best composition can be reduced to a minimum. But in a lightweight aggregate concrete mix design is more complex for incorporating of water; since LWA is a porous aggregate therefore we need additional water in the concrete [63].

The gradation of aggregate with variant aggregate grading size distributions are required to enhance the engineering properties in the concrete mix [64].There are two methods to design lightweight aggregate; loose volume calculation and absolute solid volume calculation [65].

In mix proportion, the LWA are mixed in different case in the form of fully saturated condition, partially saturation condition and dry condition. Before adding, lightweight aggregate to concrete, mix is wetted. The Polyurethane (PUR) foam waste as a lightweight aggregate were formulated before mixing in a concrete mix while LWA were soaked in water of 24 h to enhance the workability of concrete [66]. The choice of sand-aggregate ratio is 28 to 42% in the mix proportion, which can affect the compressive strength and coordinate the workability of concrete [65]. The strength of concrete is equal to the effective water to binder ratio which is selected as 0.26. The amount of the constituents can be chosen the volume of coarse aggregate to total volume of aggregate ratio as 0.6; depend on the cold-bonded fly ash aggregate the amount of cement ingredient as 551 kg/m^3 greater than sintered fly ash aggregate as about 548 kg/m^3. Both sort of lightweight aggregate concrete had demonstrated the higher compressive strength [67].

Lightweight concrete combining the bottom ash and the sintered fly ash in the concrete should raise the permeability; by replacing 30% of OPC with fly ash, to develop the permeability of LWC [68]. Affiliation of admixture in the lightweight concrete is to raise the strength and elastic modulus. The affiliation of silica fume at 5 to 15% in the LWC can enhance the strength features while replacements of 10% fly ash in place of cement in concrete can reduce strength as contrasted to without fly ash [69]. An exacted mix proportion of lightweight aggregate concrete accepted in variant studies is given in Table2.1.

2.5.5 Physical properties of LWAC

The physical features of the lightweight aggregate generated by pelletization are given in Table 2.2 [55]. The moisture ingredient and quantity of binder can influence the size of fly ash aggregates thus formed.

The fineness of the fly ash (414 m^2/kg) gives the better pelletization performance confronted to the coarser fly ash (257 m^2/kg). Hence finer fly ash requires the extra of the binder material and the excess of clay binder in the coarser fly ash will raises the pelletizing performance [56]. The specific gravity of fly ash lightweight aggregate is raised without incorporating binder and it's a denser structure. The supplementation of bentonite and glass powder in fly ash is to decrease the specific gravity as confront to lime and cement binder in fly ash [54].

2.5.6 Pozzolanic reactivity of LWA made with fly ash

A pozzolanic reaction takes place between dissolved minerals from glass and calcium from portlandite. Hydroxyl ions split the silica in the glass which in turn react with the calcium in the portlandite to form CSH paste. This reaction raises the bond strength between the aggregate and the cement matrix. Since an artificial fly ash lightweight aggregate are porous structure and it composed of glass phase, pozzolanic reaction is expected on the surrounding of this aggregate.

2.5.7 Strength features

The cement, lime and bentonitemay beutilized as a binder in 10, 20 and 30% by weight of fly ash for pelletization. It is also investigated that the enhancements in the 10% fines value and declining in water absorption of sintered fly ash aggregate. For 10% fineness is utilized to test strength of lightweight aggregate. The supplementation of bentonite is to improve the aggregate strength, cement is to grant minimum strength and the lime is for enhancing the ballability. Therefore, the supplementation of 20% bentonite grants an optimal strength [5].

The strength of the LWAC with different binder ingredient develops the strength features of aggregate and shown in Table 2.3. The compressive strength of polypropylene fiber reinforced SLWC is higher than the steel fiber reinforced by 7 MPa [71]. Fiber reinforced concrete raises the tensile strength with nominal modulus of elasticity as well as decreasing the shrinkage cracking in LWAC [72]. The lightweight aggregate produced using pelletizing process grants a soft surface after sintering process. The sintered fly ash aggregate (SFA) were crushed that is not enclose pelletizing, thestructure grants a harsh surface and improving the compressive strength as 66.76 MPa. [73].Expanded clay lightweight aggregate has higher porosity in the transition zonewhich may demonstrate important influence on the permeability of lightweight concrete. The pre-wetting time of expanded clay lightweight aggregate were sensitively influenced the strength and slump of the concrete [74]. The pore structure of the sintered pulverized fuel ash lightweight aggregate is approach range of the pore size from 200 μm down to less than 1μm with all the size had been evenly propagated throughout the pellet and grants the better bond between the pellets and cement matrix [75].

The high resolution optical microscope and image analysissoftware were handled to show the pore area percentage and pore size distribution in thecement paste and the interfacial zone of concrete cured at 28 days. The transition zone is a thin zone of more porousin nature between the aggregate and cement matrix. Theexperimental results of lightweight aggregate demonstrate large water absorption range from 8.9 to 11% which generate bigger pore percentage as 14.4 and 21.7% at the interfacial zone [76]. Hence, lightweight aggregate is more porous from the outer layer and it presents dense interfacial zone for the aggregate without any outer layer. Thus the aggregate givespreferable bond seemed due to the mechanical interlocking between aggregate and the cement paste [77]. The utilization of silica fume for supplementing in LWC is to develop the mechanical features, but deficit of shrinkage efficiency is lower compared to normal weight concrete [78].

Table 2.1 Mix proportion of LWAC ingredients studied from various literatures

Author	Concrete type	W/B ratio	Cement content (kg/m^3)	Fine aggregate content (kg/m^3)	Fine aggregate content (kg/m^3)	V_{CA}/V_{TA} ratio	Light weight aggregate content (kg/m^3)	AEA (%)	Admixture (%)	Admixture (%)
				Natural sand	Crushed sand				FA-F	SP
Yannick et al. [58]	LWAC	0.27	475.6	674.4	-		546.6	-	158.7	
		0.34	335.3	728.9	-	0.6	612.5		110.6	-
		0.28	391.2	734	-		540		107	
Koçkal and Özturan [14]	CLWC	0.26	551	318	318		592			
	LWBC		548	316	317	0.6	567	0.2	-	1.1
	LWGC		549	317	317		580			
Wasserman and Bentur [6]	SLWAC	0.4	440	49%	49%	0.51	51%	-	-	-

2.5.8 Micro-structural properties of fly ash lightweight aggregate

The mechanical attitude and durability prospect of concrete are influenced by its aggregate and cement paste as well as the interfacial zone between them. For normal weight concrete, the aggregate-cement paste interface is the weakest item of the micro-structural system and the place where cracks start, strongest constituent that is normal aggregate [77]. But, the lightweight aggregate concrete is various to the interaction between the cement paste-aggregate is complicated and it’s different to the normal aggregate concrete. This sort of aggregate are porous in nature, the grains are capable of absorbing water which yielded to the encircling matrix.

The porosity of Lytag aggregate are different, between 25to 75% based on the generating process utilized [76]. Many investigationsare done to study on specifying the internal and external structure of lightweight aggregate, especially cement matrix aggregate interface zone [79]. For performing, micromechanical method takes into account as precise bonding between the aggregate and mortar [80]. Ordinarily sintered fly ash lightweight aggregate were generated by heat and polymer procedure sothat to enhance their strength, absorption and pozzolanic activity with respect to theirfeatures of aggregate by alter to the microstructure. SEM analysis observes the higher amplification to see more identical distribution of small pore size in the sintered fly ash aggregate at the recommended temperature of aggregate like 1200°C to 1300°C [6]. Mechanical interlocking takes part a significant act for strengthening the interface [79].The impact of aggregate utilization is dry and pre-wetting lightweight aggregates on the ITZ microstructure.The thickness of ITZ around the dry aggregate is 10 μ less than the other pre-wetted and normal aggregate as 15 μ and beyond 35 μ respectively [81].

Table 2.2 Physical characteristics of pelletized aggregate from various literatures

Author	Type of LWA used	Specific gravity of LWA		BD (Kg/m^3)		Voids (%)		Water absorption (%)		Crushed strength of pellet (MPa)
		SSD	OD	LBD	RBD	LV	RV	24	48	
Koçkal and Öturan [141]	CLWA	1.63	1.3	789	842	39.2	35.1		25.5	3.7
	SFA+1200+10B	1.57	1.56	933	993	40.1	36.2		0.7	12
	SFA+1200+10G	1.6	1.59	936	936	41	37		0.7	9.6
Ramamurthy [5]	SFA+20B		1.83	850				15.8		
Amor et al. [43]	Polyurethane foam waste LWA	45		21		13.9				
Chi et al. [142]	CLWA	1.76	1.44	972				20.8		8.57

2.6 Curing

Curing is a system of governing the rate and degree of moisture loss from concrete during cement hydration. It may be either after it has been placed in position (or during the manufacture of concrete products), thereby providing time for the hydration of the cement to occur. Since the hydration of cement does take time-days, and even weeks rather than hours-curing must be undertaken for a reasonable period of time if the concrete is to obtain its potential strength and durability. Curing may also include the control of temperature since this affects the rate at which cement hydrates. The curing period may relay on the features demanded of the concrete, the aim for which it is to be utilized, and the surrounding situations, for example the temperature and relative humidity of the ambient atmosphere. First of all, curing is designed to protect the concrete moist, by preventing the loss of moisture from the concrete duringthe period in which it is gaining strength. Curing may be applied in a number of ways and the most appropriate means of curing may be identified by the site or the construction method [70]. The strength developed by concrete resulting from the setting of the cement. A complex involving hydrolysis and hydration exposure of the freshly made concrete to conditions of temperature and humidity which are favorable to these reactions is termed curing.

The forms of curing practiced in the industry are air-curing, in which the goods are kept moist for a period, usually 28 days at normal temperature, low pressure steam curing, in which the concrete exposed to steam at atmospheric pressure, and high pressure steam curing or autoclaving, in which the concrete units are subjected for some hours to steam.The rate of development of strength in concrete is much enhanced by elevated temperatures, particularly at early ages.

With low pressure steam curing, a high early strength are obtained, but the gain at later ages is somewhat is reduced, so that the strength which is ultimately attained is rather less than that would have been obtained by curing at ordinarytemperature[82].

2.6.1 Importance of concrete curing

Concrete features and durability are considerably affected by curing since it mainly influences the hydration of cement. The hydration of cement actually halts when the relative humidity while capillaries falls down below 80% [83]. Under an effective curing method such as water curing, the relative humidity is preserved above 80% to precede the hydration of cement. Inversely, the concrete specimens forfeit water or moisture through evaporation and become dry in none-existence of a suitable curing. The evaporation reduces the relative humidity by decreasing the quantity of existing moisture, and thereby delays the hydration of cement. In intense condition, the hydration is finally halted. When the hydration is halted, adequate calcium silicate hydrate (CSH) cannot improve from the reaction of cement compounds and water. Calcium silicate hydrate is the significant strength-providing reaction product of cement hydration. It also plays as a porosity reducer and thereby results in a dense microstructure in concrete.

Without sufficient calcium silicate hydrate, the improvement of dense microstructure and fine pore structure is interrupted. A more uninterrupted pore structure may be created in cover concrete, since it is very susceptible to drying. The uninterrupted pore structure constituted in cover concrete may permit the login of deleterious agents, and consequently would cause different durability issues. Also, the drying of concrete appearances results in shrinkage cracks that may worsen the durability issues. Therefore, a productive curing is inevitable to avoid the moisture action or evaporation of water from concrete surface. It can be achieved by preserving the concrete element fully saturated or as much saturated as possible until the water-filled spaces are pretty decreased by hydration products [84,85]. For this, an addition quantity of water must be incorporated to fill the loss ofwater due to evaporation. As an alternative, some evaluations must be taken to avoid the loss of moisture from concrete surface.

A convenient curing preserves a proper warm and moist environment for the improvement of hydration products, and consequently decreases the porosity in hydrated cement paste and raises the density of microstructure in concrete. The hydration products prolong from the surfaces of cement grains, and the volume of pores reduces due to suitable curing under eligible temperature and moisture. If a concrete is not fine cured, especially at the early age, it will not achieve the features and durability at demanded grade due to an inferior degree of hydration, and would endure from irremediable loss [86,87].

For any concrete, curing roles just like feeding to a newborn infant. If a concrete is not fed with water at the early age, it cannot acquire the features and durability for its long service life. A convenient curing tremendously subscribes to decrease the porosity and drying shrinkage of concrete, and subsequently to gain higher strength and greater resistance to physical or chemical attacks in aggressive environments. For this reason, a suitable curing method like water pooling, spraying of water, or covering with wet burlap and plastic sheet is constitutional in order to generate powerful and durable concrete [88]. This research offers the impact of various curing ways on diverse hardened properties such as compressive strength, ultrasonic pulse velocity, dynamic modulus of elasticity, initial surface absorption, and rate of moisture movement of micro silica concrete In addition, this investigation debates the influence of moisture movement on the compressive strength, ultrasonic pulse velocity, dynamic modulus of elasticity and initial surface absorption, and eventually determines the most influential curing process for micro silica concrete.

2.6.2 Steam curing

Live steam at atmospheric pressure (for enclosed cast-in place structures and large precast concrete units) and high-pressure steam in autoclaves (for small manufactured units) are two different methods of steam curing. Figure 2.3 shows the steam-curing cycle that composes of (1) preset period before applying steaming, (2) a term for raising the temperature, (3) a term for keeping the maximum temperature constant, and (4) a term for reduction the temperature. Atmospheric pressure method of steam curing is generally applied infield practice,in an enclosure to reduce moisture and heat loss. The desired maximum temperature within the enclosure and the concrete is approximately 66^0C. It has been shown that strength will not increase significantly if the maximum steam temperature is raised from 66^0C to 79^0C. Steam temperatures more than 82^0C should be prevented because of wasted energy and potential reduction in ultimate concrete strength.

The benefit of steam curing can be advantageously utilized to save time of curing of concrete for convey of pre-stress. The optimum steam curing cycle for a specific case can only be assigned by trial and error. In any case, it has been found convincing to utilize a pre steaming period of 4 to 5 hour or rate of temperature increase between $(22\text{-}33)^0$C per hour and a maximum curing temperature of $(66\text{-}82)^0$C for a period such that whole curing cycle does not pass 18 hour. Rapid temperature alters during the cooling period should be prevented and decrease in middle temperature in the covering is not sharper than 20^0C per hour. The reuse of casting beds and forms along with 18 hour steam curing makes it a total 24 hour cycle.

Pre-stress to members in pretension beds should be transferred instantly after the finishing of steam curing while the concrete and forms are still warm, otherwise the temperature within the covering shall be preserved at over 15^0C until the pre-stress is transferred to the concrete. The steam curing will be taken into account when the concrete has achieved the minimum strength at 'Strength at Stress transfer' or handling strength [90].

Strength of concrete products is developed by applying atmospheric steam curing which is a heat transaction that has been used for many years because the hydration rate ofcement increases with the raise in temperature, the gaining of strength can be hastened by curing concrete in steam.When steam is generated in atmospheric pressure, the temperature is below 100^0C; the treatment can be designed as a private case of moist curing in which the vapor-saturated atmospheres procure a supply of water [89, 91]. Maximum field of curing temperatures may be about 40^0C to 100^0C whenthe optimum temperature has been discovered in the range of 65^0C to 85^0C.

Table 2.3 Mechanical features of LWAC from various study available in the literature

Author	Concrete Type	Compressive strength (MPa)		Split tensile strength (MPa)		Modulus of elasticity (MPa)	
		28 d	56 d	28 d	56 d	28 d	56 d
Byung-Wan et al. [143]	AFLAC[1]	26.7				25	
Kayali et al. [72]	SFAC[2]	68		6.6			
Santish and Leif	LWAC	20.4					
Koçkal and Özturan [141]	(SFA+1200+10G)[3]	55.8	60.4	4.9	5.1	25.7	25.9
	(SFA+1200+10B)[4]	53.5	59.5	4.8	5.1	26	26.3
	LWCC[5]	42.3	44.6	3.7	3.9	19.6	19.7
Grubl [145]	FAA[6]	66.75		3.75		25.5	

1: Alkali-activated fly ash lightweight aggregate concrete;
2: Sintered fly ash aggregate concrete;
3: Sintered fly ash aggregate with 10% glass powder at 1200°C temperature;
4: Sintered fly ash aggregate with 10% bentonite at 1200°C temperature;
5: Cold-bonded fly ash lightweight aggregate concrete;
6: Fly ash aggregate manufacture by using sintering without pelletizing aggregate and the procedure is same. That aggregate are crushed in briquette and fired in a kiln.

When the optimum temperature has been discovered in the range of 65^0C to 85^0C the curing temperature will be a correlate between rate of strength achieve and ultimate strength, because the higher the curing temperature, the lower the ultimate strength [92].

In order to minimize times, the concrete utilized to make structural precast beams and slabs must have good mechanical characteristics at both early and later ages. For example, a high compressive strength at early age such as 1 day is demanded for pre-stressed concrete so that the pre tensioned strands can be relaxed. To gain such mechanical features, two solutions are suggested. First, CEMI-52.5R cements (OPC) complying with European standard EN 197-1 [19] should be used because they incorporate high clinker ingredient (at least 95% by weight, notation CEMI), high fineness (notation R), which enables high reactivity at an early age [92] and 28- day minimum compressive strength of 52.5 MPa (notation 52.5) measured on normalized mortars according to European Standard EN 196-1 [93]. Second, a high curing temperature (steam curing) should be used to speed up the maturation of precast products. It is widely informed that a high curing temperature promotes the improvement of mechanical features at early ages but can inversely impact the strength at later ages [94,95].

Since the rate of hydration of cement increases with a rise in curing temperature, the strength gain of concrete can be accelerated by steam curing. The influence of curing temperature on the features of cement mortars and concretes has been the expose of several investigations. It is widely described that a high curing temperature immediately after casting promotes the improvement of mechanical features at early ages but inversely impacts the strength at later ages. In the research of Mouret et al.

[97], for instance, the concrete cured at 35^0C had 10% lower 28-day compressive strength in comparison with the same concrete cured at 20^0C. According to Verbeck and Helmuth [98], a 28% strength reduction was considered when curing temperature was increased from 20^0C and 50^0C. This reduction at later age strength was based on to the rapid initial rate of hydration at higher temperature which postponed the following hydration and generated a non-uniform spreading of the hydration products [98].

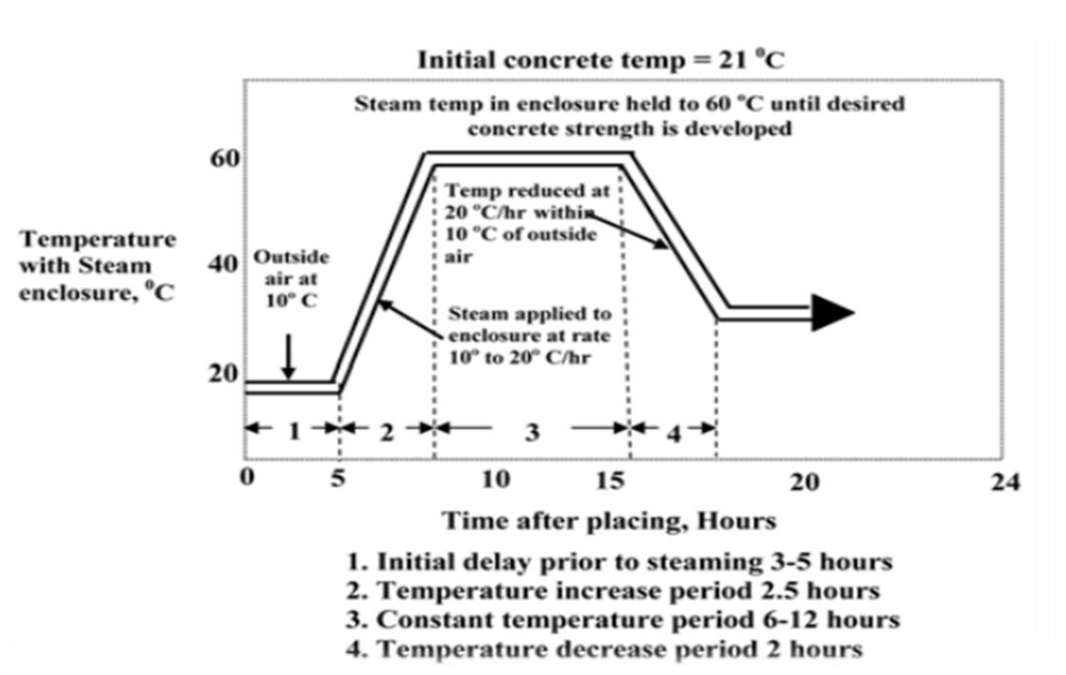


Figure 2.3 a typical atmospheric steam curing cycle [146]

Topcu and Toprak [99] studied the effect of curing temperature and the sort of fine aggregate on the compressive strength of concretes. Concretes including river sand or crush stone sand were generated and exposed to 20^0C, 40^0C, and 60^0C curing temperatures. The investigation recommended that increase in the curing temperature improved the strength at early ages but influenced negatively the 28- day results Liu et al. [100].

2.6.3 Importance of time control on steam curing

To speed up the production rate steam curing is applied for precast concrete plants directly after casting. Many investigators have denoted that the early applying steam curing is quite harmful and in order to get good concrete features, such as strength and durability it is better to have some delay prior (preset time) to applying steam curing [101–105]. Soroka et al. [101] arrived at a decision that applying of steam curing after preset time of (30-60 min.)wasdetrimental to compressive strength. Shideler and Chamberlin [102] believed that a delay of 2-6 h prior to steam curing based on the temperature, generated 15-40% higher strengths at 24 h than when steam curing was started directly after the concrete was placed.

Hanson [103] demonstrated that the compressive strength increase at all ages when delay period of applying steam curing raised from 1 to 5 h. In addition of delay 1 h exposure to steam curing horizontal cracking was mentioned in all specimens. Mironov[104] deduced that the delay period should be specified in such a way that the steam curing process should not cause expansions. It was specified that this period complies to the time needed for the concrete to have a compressive strength of 7–8 kgf/cm^2. Alexanderson [105] monitored that the expansions can be ignored for delay periods of 4–7 h (depending on water–cement ratio) and no strength loss was monitored at late ages. According to Alexanderson [105], lower quality of concrete due to shorter delay periods is the result of increased porosity and cracks caused by the tensile stresses formed by the internal pressure in the pores. Thus, it was finalized that the concrete should have a critical tensile strength before the start of the steam curing operation. Heinz and Ludwig [106] informed the importance of secondary ettringite formation on the deterioration of high temperature (>75^{o}C) steam-curedprecast concrete. Delayed expansion in the concrete was attributed to the transformation of metastable monosulfate to ettringite when steam curing was followed by normal temperature moist curing at later ages [107]. If curing temperature, heating and cooling rates, and delay periods are not picked fairly, thermal stresses can cause micro-cracks, and influence not only the strength, but also the responsibility of the concrete to all kinds of damaging processes such as DEF. Different delay periods were explored in the previous studies [101–105]. In this investigation, the delay periods were chosen depending on the setting time. The reason for this and the advantages of delay periods that are equal to the setting time can be described as follows: during the temperature increment, the concrete temperature delays behind that of the curing chamber due to the time needed for the heat transfer to the inner parts. Hence, if the steam application starts before the setting time of the concrete, the outer portions (or the faces) of a concrete specimen harden earlier while the inner concrete is still plastic.

In other words, a rigid skeleton (or a hardened shell) is formed around the inner plastic concrete. As the internal temperature increases (due to steam application and heat of hydration), the inner fresh concrete will try to expand. Hence, the exterior rigid shell can be damaged due to the tensile stresses provoked by this expansion. Moreover, during the heating phase, the variations in the thermal expansion coefficient of the concrete contents can lead to microcracking and increased porosity [105], while the steam curing of the concrete begins after a delay period equal to its setting time.

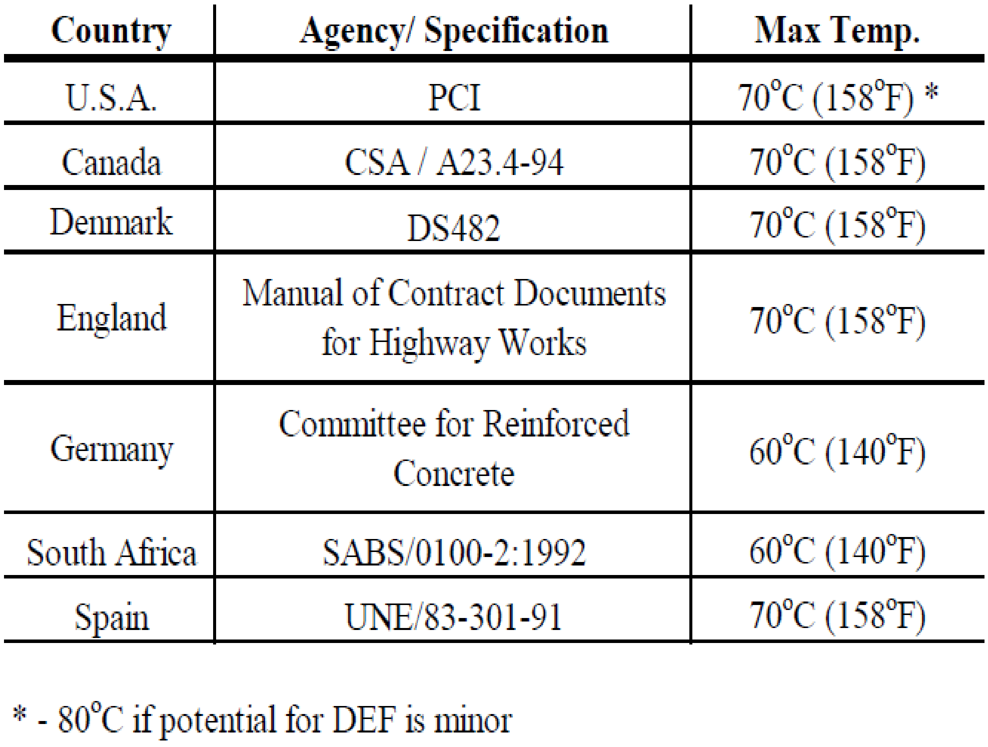
2.6.4 Effect of maximum temperature

Basically, the chemical reaction of cement hydration takes place rapidly under higher curing temperatures. This results in greater early strength and faster turnover of precast products. The necessity to control curing temperature exists for the following reasons: early heat application and high rate of temperature rise can adversely influence the strength and pore structural properties of concrete. Always an optimum maximum curing temperature exists.

Homogenous temperature within the product and form day-to-day production is necessary to prevent differential shrinkage. In general, an increase in the maximum chamber temperature can lead to an increase of the 18-hour compressive strength. However, a limit to maximum temperature is set to secure compressive strength at later ages and thus, to enhance durability [103]. Compressive strength curves rise at uniform rate approximately to 65^0C maximum temperature. Beyond this temperature, the increase in relative strength is shown to slow down. This indicates that 18-hour compressive strength improves rapidly as the maximum temperature increases to approximately 65^0C, with only a moderateadditional advantage gained by using temperatures greater than 65^0C. The limit of maximum temperature to have a constant rate of strength gain for type III cement is lower than that for type I cement [103].

In many cases, the early strength seems to be optimum at about 65^0C with little apparent gain at temperatures above that limit. The curing temperature can be compromised between the rate of strength gain and ultimate strength because higher curing temperature lowers the ultimate strength [108]. The study on the accelerated curing conducted by the concrete technology text bookreveals that the reduction of strength at later ages due to an accelerate curing occurs when an impermeable coating forms around the cement grains and restricted further hydration [43]. The coating develops from an early hydration of C_3A compound in the cement. A premature “honeycomb-like” structure occurs when insufficient gypsum (SO_3) is present in order to fully retard C_3A hydration. Higher temperatures accelerate the hydration of C_3A and with higher than normal optimum SO_3 content tend to perform better under accelerated curing conditions than those of cements that are higher in C_3A (greater than 8%) and low SO_3 content. However, this must be concluded after careful investigation because excess gypsum can lead to expansion and disruption of paste set.Table 2.4 summarizes some international accelerated curing temperatures [109].

Table 2.4 International heat curing specifications [96]



Country	Agency/ Specification	Max Temp.
U.S.A.	PCI	70°C (158°F) *
Canada	CSA / A23.4-94	70°C (158°F)
Denmark	DS482	70°C (158°F)
England	Manual of Contract Documents for Highway Works	70°C (158°F)
Germany	Committee for Reinforced Concrete	60°C (140°F)
South Africa	SABS/0100-2:1992	60°C (140°F)
Spain	UNE/83-301-91	70°C (158°F)

* - 80°C if potential for DEF is minor

2.7 Durability of steam cured concrete

2.7.1 Effects of steam curing on porous structure of concrete

Pore system of concrete is categorized as gel pores with features dimension of 0.5–

10 nm, capillary pores with average radius ranging from 5 to 5000 nm and macro-pores due to insufficient compaction or intentionally entrained air [110]. The association ofgel pores to compressive strength can be ignored, although these pores are directly attached to creep and shrinkage. Capillary pores and other larger pores, on the other hand, are accountable for reduction in strength and elasticity [111,112]. MIP method and SEM-BSE analysis technique were selected to evaluate the porous features of high performance concrete with various duration of initial steam curing. Pore structures importantly impact the strength of concrete.

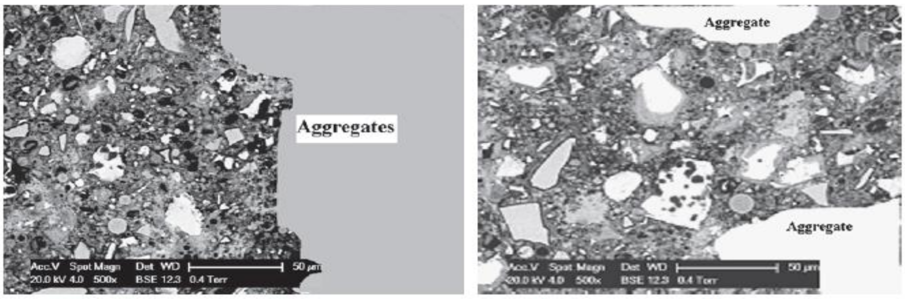
Particularly, the coarseness of pore size could result in a strength reduction [113]. Figure 2.5 gave the variations of porosity of steam cured concrete evaluated by SEM-BSE analysis. The coarse pore sizes evaluated by SEM-BSE were all larger than 500 nm. From Figure 2.5 it could be observed that the increasing duration of steam curing up to 14h caused the decreased coarse porosity. However the 24h duration induced an increase of coarse porosity. These variations of coarse porosity with increasing duration of initial steam curing could be also seen from the SEM-BSE images in Figure 2.4.

The fraction of pores (black pixels) in Figure 2.4a–c reduced with the rising duration up to 14 h. A further rising in duration up to 24 h leaded to an increased coarse porosity (Figure 2.4d). The variations of coarse porosity with increasing duration of initial steam curing were in better conformity with those of the compressive strength. It was recording that the changes of flexural strength would not be analyzed here. Figure 2.6 shows the porosity achieved by MIP method. It could be monitored that most of the pores measured by MIP are ranging from 10 nm to 1000 nm, and the volume of pores larger than 500 µm hardly displayed any variations. From Figure 2.6

it was seen that the variations in total porosity were unrelated with the changes of compressive strength in Figure 2.7. This finding displayed that the coarse pores subscribed more to the corresponding compressive strength.

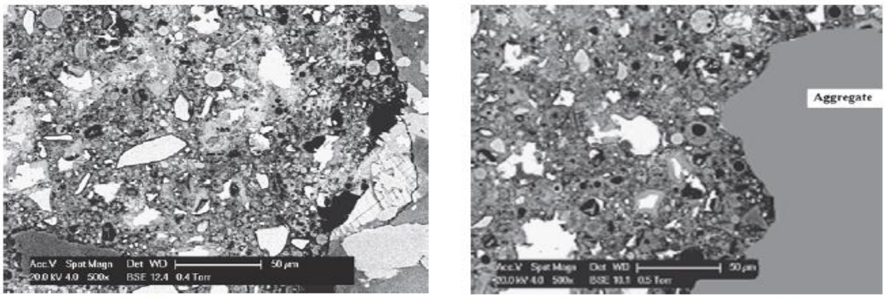
In order to measure the effect of pore size propagating on the compressive strength, the evaluated capillary pores and macro-pores were segmented into three types: fine capillary pores (diameter < 0.5 µm), larger capillary pores (diameter > 0.5 µm) and macro-pores (diameter > 50 µm). Depended on above pore assortment, an empirical statement was suggested to compute the effects of altered pore size spreading on the compressive strength.

By regression of the measured results of pores and compressive strength, the contributing coefficients of three type pores were determined to be 0.0082, 0.03284 and 0.2235 respectively. For precast concrete element with low water/binder ratio and high mineral admixture replacement, there existed a critical duration of steam curing at medium temperature regime as 50^0C. This extra curing duration could make the pore coarser, which was not able to be healed even after water curing at common temperature of 20^0C for 90 days [114].



(a) 0-hour duration of initial steam curing (500×)

(b) 5-hour duration of initial steam curing (500×)



(c) 14-h duration of initial steam curing (500×)

(d) 24-h duration of initial steam curing(500×)

Figure 2.4 steam cured concrete with diverse duration by SEM-BSE micrographs: (a) 0-h period of inceptive steam curing (500x); (b) 5-h duration of inceptive steam curing (500x); (c) 14- h duration of initial steam curing (500x) ; (d) 24-h duration of initial steam curing (500x) [97].

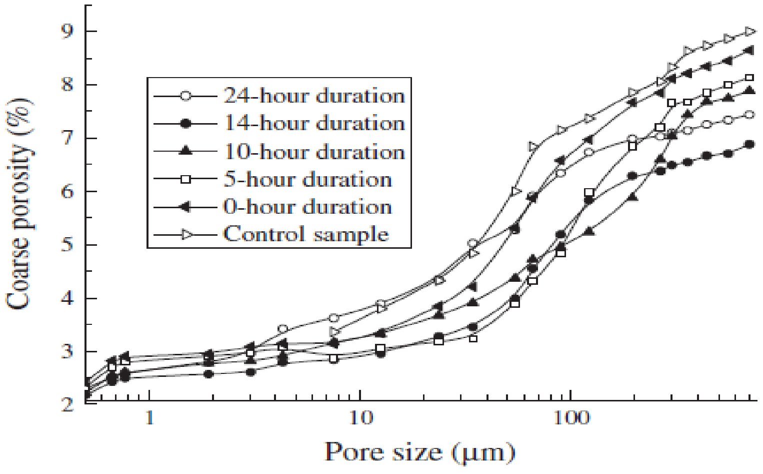


Figure 2.5 Coarse porosity by SEM-BSE analysis [97]

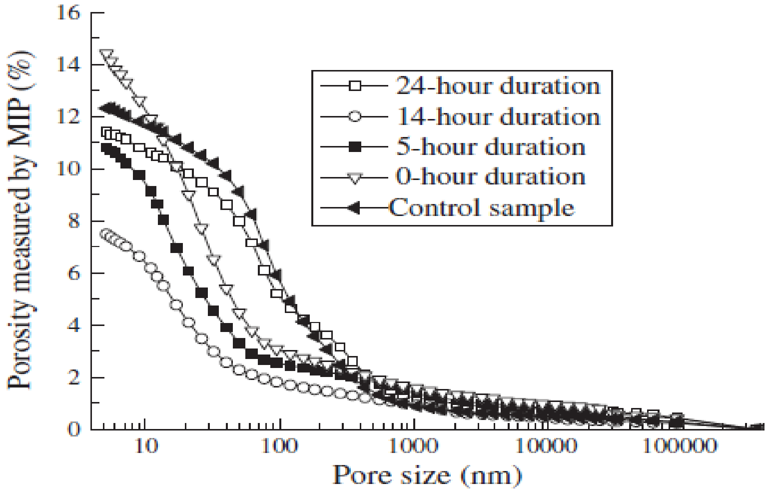


Figure 2.6 Porous characteristics measured by MIP [97].

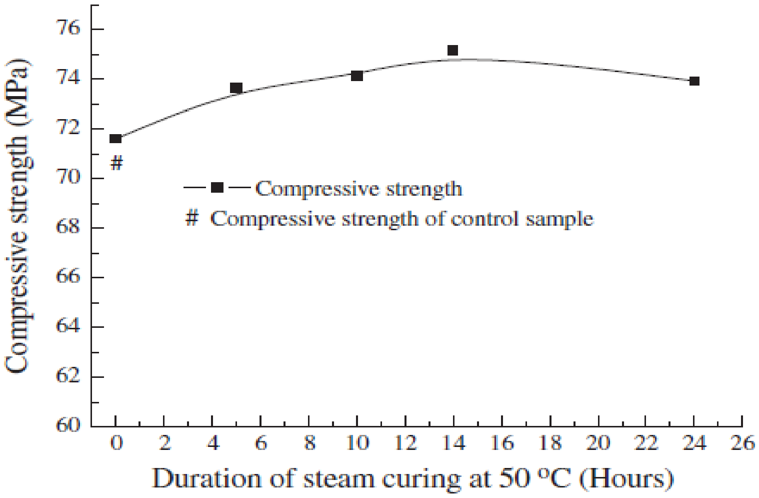


Figure 2.7 Influence of period of inceptive steam curing at 50^{0}C on compressive strength of concrete with low water/binder ratio at later curing of 90 days [97].

2.7.2 Influence of steam curing on sorptivity

Since the depth of water penetration, D, and weight gained were extracted from the same transport mechanism of capillary absorption, investigations on results of sorptivity depth were supposed to be similar to those of weight. Actually, for strength under 40 MPasorptivity depths raisedquickly; the porous with sorptivity depths of steam-cured concretes from OPC, FA and BFS mixes were more,approximatelytwicethose of samples having 3 days of water curing; there were clear profits in the use of SF in developingthe pore structure of concrete under steam or standard curing case[115].

Steam cured plain concrete had higher sorptivity than the water cured one. Increase in the sorptivity of steam cured concretes may be attributed to the negative impact of steam curing on the pore size distribution. According to Erdogdu and Kurbetci [116] heat treatment affects the pore structure of cement paste by increasing the proportion of large pores in the cement paste. Similarly, Reinhardt and Stegmaier [117] declared that, with increasing curing temperature, the quantity of bigger pores increased associated with the increase in the mean pore radius. Steam curing application significantly increased the sorptivity coefficient of concretes [118].

2.7.3 Resistance to chloride ion penetration of steam cured concrete

Effects of curing condition and the sort and amount of the mineral admixtures on rapid chloride ion permeability are displayed in Figure 2.14. In steam curing condition, however, the former and the latter were 1050 and 4872 C, respectively. As obviously seen in Figure 2.8 steam-cured concretes had higher chloride ion permeability than the water cured concretes. The adverse impact of steam curing on the chloride ion permeability seemed to be lower for MK and SF concretes than for the control concrete. While the control concrete had chloride ion permeability of 3465 and 4872 C, respectively, for water and steam curing conditions, permeabilities of the concrete containing 5% MK were 3110 and 3604 C, respectively. Chloride ion permeability resistance of steam cured concretesis clearly higher than those of the water-cured concretes. The difference of chloride ion permeability of the water andsteam cured concretes seemed to be very high for the plain concrete; however, these distinctions markedly diminished for the MK or SF concretes [118](See Figure 2.8.).

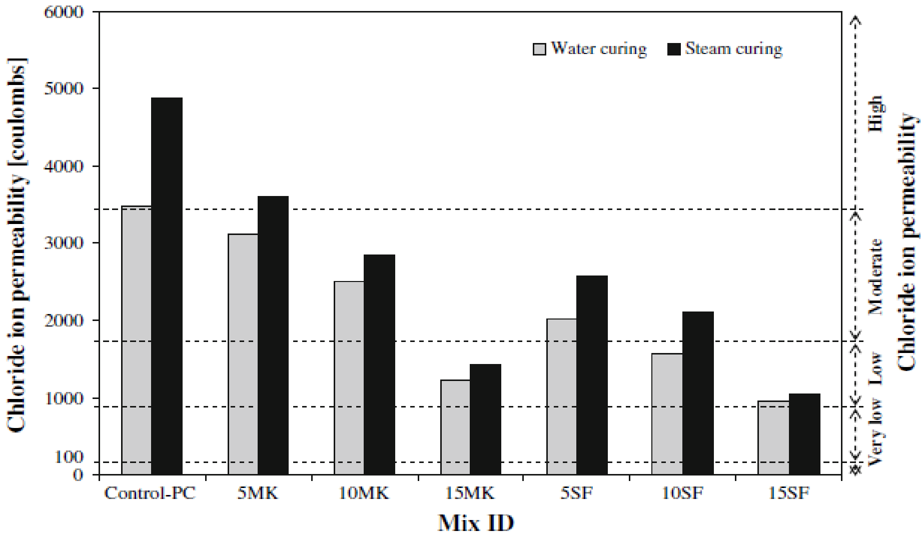


Figure 2.8 Influence of curing condition and mineral admixture on the chloride ion permeability of concrete [115]

2.8 Mechanical features of steam cured concrete

2.8.1 Compressive strength

Figure 2.9 illustrates the changes of compressive strength of the concretes subjected to water and steam curing. Compressive strengths for water cured plain concretes were 20.4, 50.2, and 60.2 MPa at 1, 7, and 28 days, respectively. Compressive strengths for steam cured plain concretes, however, were 40.1, 43.7, and 46.4 MPa at 1, 7, and 28 days, respectively. The experimental results defined that the steam curing application improving the 1-day compressive strength of concretes drastically compared to the 1-day water cured concretes in line with the literature [19, 23]. Steam cured MK and SF concretes had approximately 10% greater strengths than the control concrete at 28 days of age. Moreover, at 15% replacement level of MK, the

28 day strength ratio of the steam cured concrete to that of the standard cured onewasabout 87% which diminished to as low as 75% for the plain concretes. Therefore, no important change was seen in the 28-day compressive strength of the steam cured MK and water cured plain concretes.

Figure 2.9 also displays that there was no remarkable difference in the compressive strength of concretes due to the containment of MK and SF at 1-day for both curing conditions. In fact, 1-day compressive strength of the water and steam cured plain concretes were about 20.4 and 40.1 MPa, respectively, while the concrete with 15% MK had 66.7 and 54.4 MPa compressive strengths under water and steam curing conditions, respectively. As seen in Figure 2.9, the ratio of the 1-day compressive strength of the steam cured concrete to that of the water cured concrete was approximately twice, irrespective of the type of mineral admixture and replacement level. At 7 and 28 days, however, compressive strength improvement of steam cured concretes was so slow that the compressive strength of water cured concretes passed those of the steam cured concretes, even in the case of concretes with MK or SF.

The reduction in the strength at later ages lies in the fact that despite a higher temperature during placing and setting increases the very early strength, it may adversely affect the strength from about 7 days onwards in line with the literature [19, 23]. Compressive strength of the concrete mixtures increased with the increasing curing period. Although, the steam cured concretes had higher compressive strength at the very early ages, the strength at 7 days onwards appeared to be lower [118].

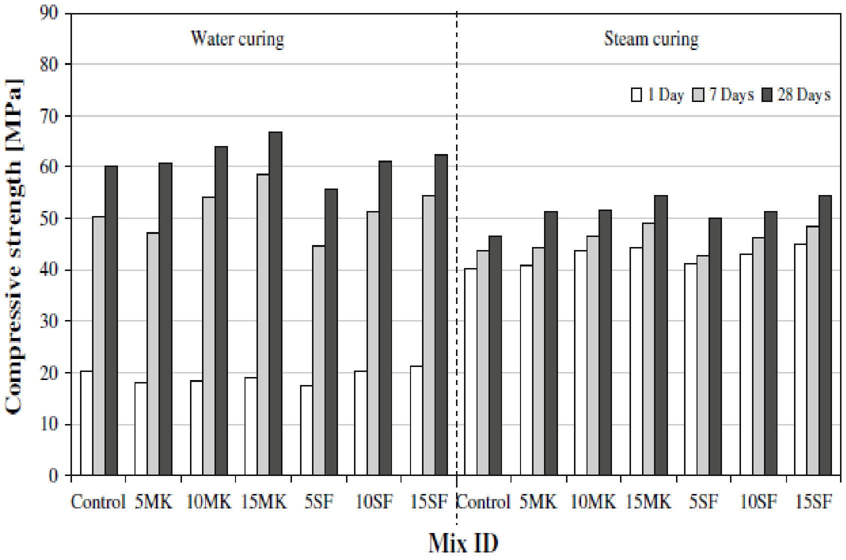


Figure 2.9 Compressive strength of the concretes normalized to corresponding strength of the control concrete cured in water at 20^0C [115]

CHAPTER 3

EXPERIMENTAL PROGRAM AND METHODOLGY

3.1. Introduction

The properties of steam cured and water cured lightweight concrete made with artificial cold-bonded fly ash aggregates (AFA) was investigated through an experimental program which involves mainly two parts. Firstly, AFA was produced through the pelletization of fly ash and cement at ambient temperature. Thereafter, the manufactured AFA was used in the production of LWCs. The slump testwas carried out to identify required properties, improving workability and characteristics of fresh LWCs. The hardened concretes were tested for the compressive strength at 1, 3, 28 and 56 days for the evaluation of mechanical properties. Moreover, the durability tests were governed to explore the resistance to chloride ion penetration, sorptivity index and gas permeability at the ages of 28 and 56 days.

3.2. Materials

3.2.1. Cement

Ordinary Portland cement (PC CEM, I 42.5R) conforming to the TS EN 197-1 [19] (which mainly based on the European EN 197-1)was used in this study. It had a specific gravity of 3.15 g/cm^3 and Blaine fineness of 326 m^2/ kg. It was utilized in the production of both artificial aggregates and concretes. Physical and chemical properties of the cement are given in Table 3.1

3.2.2. Fly Ash

Fly ash used in the manufacture of AFA was obtained from Zonguldak fire coal power plant factory. It had a specific gravity of 2.25 g/cm^3 and the Blaine fineness of 287 m^2/ kg. Physical and chemical properties of the fly ash are given in Table 3.2.

3.2.3. Superplasticizer

Naphthaline-sulphonatedformaldehy basedsuperplasticizer (SP) with a specific gravity of 1.19 g /cm^3 was used to achieve the target workability. The properties of superplasticizer are given in Table 3.3.

3.2.4 Aggregate

3.2.4.1 Artificial cold-bonded aggregates (AFA)

AFAproduced through a cold bonding process was used in manufacturing of LWCs. During the cold bonding process a dry mixture of cement/ fly ash in particular amount were pelletized through moisturizing in a rotating inclined pan at an ambient temperature. The pelletizer used has a pan diameter and a depth of 80 cm and 35 cm respectivelyas shown in Figure 3.1.

Firstly, some percentage of water was added to the mixture and then poured in a disc; remaining water is sprayed during the rotating period because while rotating without water in the disc the fly ash powder tends to form lumps anddoes not increase the distribution of particle size.The amount of sprayed water was about 18-20 % by weight of the dry powder mixture. The pellets were formed approximately in duration of 10 min. After formation the second step was going on with pelletizing to more stiffening of the fresh pellets that would takes approximately 10 min. So the characteristic production period held about 20 min.Afterward, the produced fresh aggregates were kept in sealed plastic bags and stored for hardening in a curing room at a temperature of 20^0C and a relative humidity of 70% for 28 days. Thereafter the hardened AFA was sieved into fractions of 4-12 mm sizes. Aggregates passing through 4mm are used in LWCs production as coarse aggregate and retaining on sieve 4 mm was considered as fine aggregate as shown inFigure 3.2. The specific gravity and the water absorption tests were carried out as per ASTM C127 [119] while crushing strength test was performed as per BS 812, part 110 [120].

Table 3.1 Properties of plain portland cement (CEM I 42.5R)

Composition		Percentage(%)
SiO_2 (%)		19.79
Al_2O_3 (%)		3.85
Fe_2O_3 (%)		4.15
CaO (%)		63.84
MgO (%)		3.22
SO_3 (%)		2.75
Na_2O (%)		-
K_2O (%)		-
Cl^- (%)		0.0063
Insoluble residue (%)		0.34
Loss on ignition (%)		0.87
Free lime (%)		1.28
Specific gravity (gr/cm^3)		3.12
Vicat time	Start	2:42
(h:min)	Stop	3:44
Le chatelier (mm)		1
Fineness	45 µm	15.3
(%)	90 µm	1.47
Specific surface (cm^2/gr)		3349

Table 3.2 Properties of fly ash

Composition	Percentage(%)
SiO_2 (%)	56.2
Al_2O_3 (%)	20.17
Fe_2O_3 (%)	6.69
CaO (%)	4.24
MgO (%)	1.92
SO_3 (%)	0.49
Na_2O (%)	0.58
K_2O (%)	1.89
Loss on ignition (%)	1.78
Specific gravity (gr/cm^3)	2.25
Blaine fineness(m^2 /kg)	287

Table 3.3 Properties of superplasticizer

Property	Superplasticizer
Name	Daracem 200
Colour	Dark brown
State	Liquid
Specificgravity [g/cm^3]	1.19
Chemical description	Sulfonatednaphtaline formaldehyde
Freezing point ^{0}C	-4

Crushing strength of the produced aggregate is shown in Figure 3.3. The specific gravity of coarse fly ash aggregate and fine fly ash aggregate were 1.71 and 1.67 gm/cm^3, respectively.

3.2.4.2 Natural fine aggregate

As fine aggregate, a crushed limestone was used with a maximum size of 4 mm. the specific gravity of crushed limestone was 2.45 g/cm^3

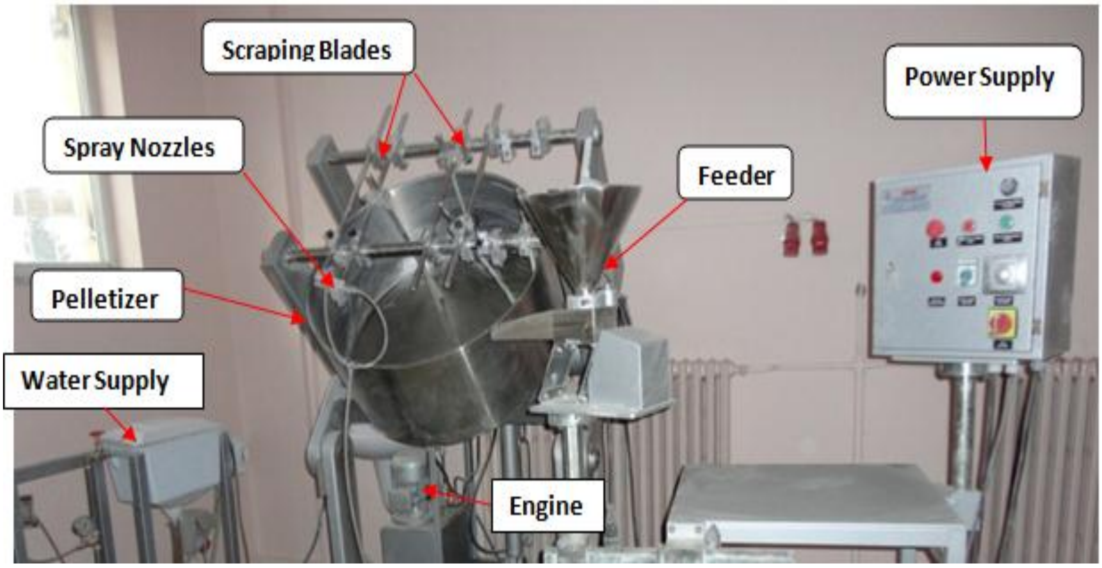


Figure 3.1 General view of the pelletization disc

Figure 3.2 Aggregate size

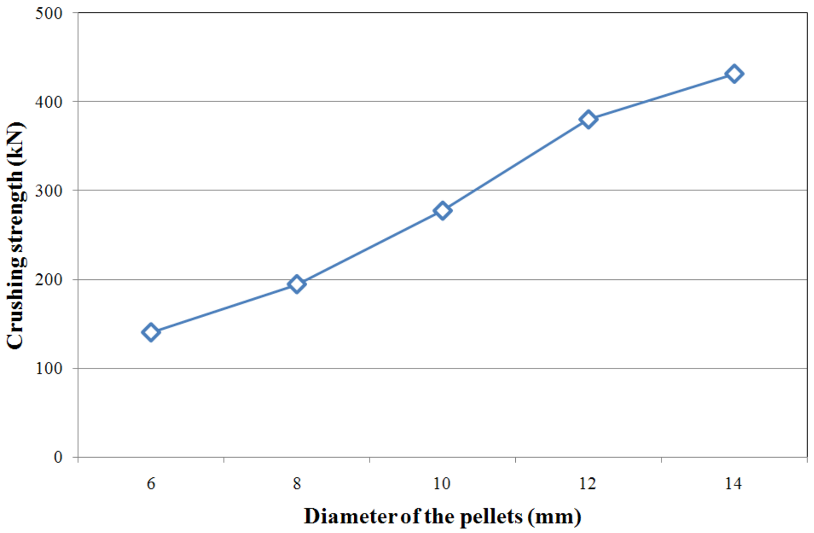


Figure 3.3 Crushing strength of the produced AFA

3.3 Concrete Mixture Details

Two series of control mixtures with same w/c ratios of 0.35 with 450 kg/m^2 were designed. For Series 1 method of steam curing was used (Steam cured lightweight concrete: SC-LWC), while for Series 2 standard water curing method was adopted (Water cured lightweight concrete: WC-LWC). In order to investigate the effect of lightweight fine aggregate (LWFA), it was replaced with 0%, 25%, 50%, 75%, and 100% of crushed limestone sand by volume. Thus, totally 5 different mixtures to be tendered under two different curing regimes were prepared in this study. (See Table 3.4).

3.4 Concrete Casting, Test Specimens, and Curing

In manufacturing of LWCs, the mixing sequence and duration are very important. All concretes were mixed in accordance with ASTM C192 [121] standard in a power driven rotating pan mixer.

Table 3.4 Details of mix proportions (in kg/m^3) and unit weights (in kg/m^3) of concretes.

Description of mix	w/c	Cement	water	Coarse aggregate	Fine aggregate		SP	Unitweight
				LWCA[a]	NWA[b]	LWFA[c]		
0% LWFA	0.35	450	157.5	589.6	837.9	0.0	4.09	2035.1
25% LWFA	0.35	450	157.5	589.6	628.4	144.0	3.17	1969.5
50% LWFA	0.35	450	157.5	589.6	419.0	287.9	2.00	1904.0
75% LWFA	0.35	450	157.5	589.6	209.5	431.9	0.90	1838.5
100% LWFA	0.35	450	157.5	589.6	0.0	575.9	0.50	1773.0

a: Lightweight coarse aggregate, b: Normal weight fine aggregate (crushed limestone sand) c: Lightweight fine aggregate

The same procedure for batching and mixing was followed to supply the same homogeneity and uniformity in all mixtures [122]. Before mixing, the cold bonded aggregates are immersed in water for 30 minutes to ensure saturated surface dry condition of aggregate [123,124,125].

The batching sequence consisted of homogenizing cement then adding the cold bonded aggregate into the mixer and continuing to mix for 30 s. Thereafter, the fine aggregates were added and mixing was resumed for 30 s. then the natural fine crushed limestone aggregate was added and mixing for 30 s. Finally, SP and water was added in two parts to avoid the segregation and getting the required workability. The concrete was mixed for 3 min. and then left for 2 minutes rest. Eventually, the concrete was mixed for additional 2 min. to complete the mixing sequence. The workability of the LWCs was controlled through the slump test. Trial batches were produced for each mixture until the desired slump of 14±2 was obtained by adjusting the dosage of the SP. From each concrete mixture, eight 150 mm cubes, four Ø100 x 200 mm cylinders and two Ø150 x 300 mm were also cast in two parts each of which vibrated for a couple of second. After casting five of the mixes with the molds were put in curing chamber for 17 h to supply steam curing and then cooling the chamber to normal room temperature. Then, the samples were removed and demouldedand cured in water until the testing ages. The other remaining five mixes were casted and maintained for 24 hours then demoulded and water cured were applied until the testing date

3.4.1 Steam curing chamber

A chamber in the shape of a rectangular box with a height of 90 cm, width of 80 cm, and length of 120 cm were used. The bottom of the chamber is furnished with heating wires connected to an electric source by a cable. Also a cap exists to close and open the top part of the chamber. When electric source switch on, the heating wires starts to heat the chamber internally. A valve is exist which control the temperature degree of the chamber internally. Since steam curing application is implemented, there should be asmall amount of water at the bottom of the chamber which can cover just the bottom of the moulds. The water is evaporated during heating of the chamber. Since the top of chamber is closed by a cap, the evaporated water remains inside the chamber. Sothe samples were cured by the evaporated water of which temperature is equal to70±1 ^{0}C for 17 hours. (See Figure 3.4)

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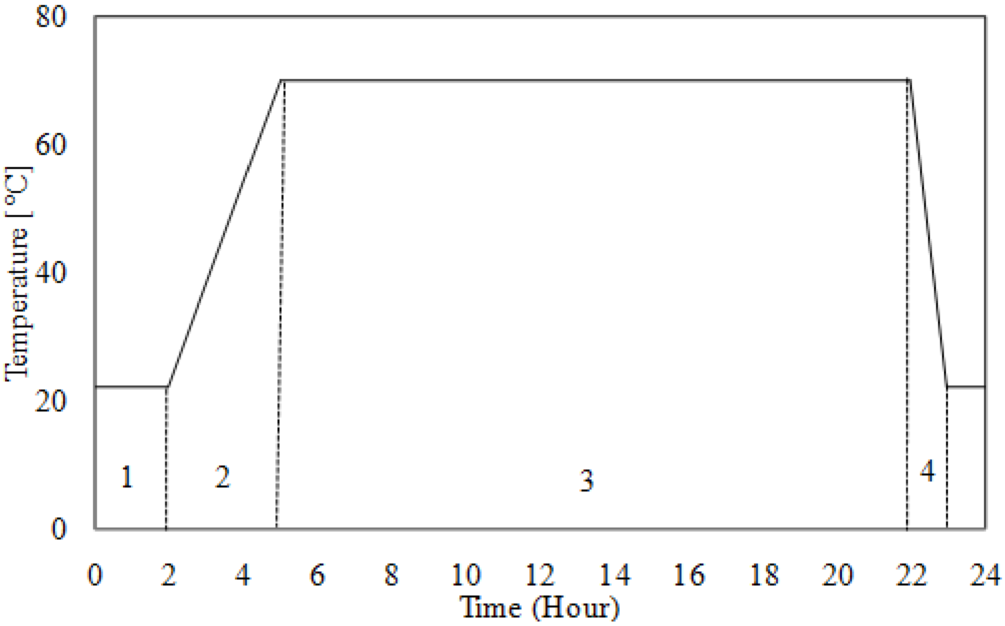

1. Preset time prior to steaming about 2 hours
2. Temperature increase period 3 hours
3. Constant temperature period 17 hours
4. Temperature decrease period 1 hours

Figure 3.4 Schematic representation of steam curing procedure

3.5 Tests for Mechanical Properties

3.5.1 Compressive strength

The concrete cubes (150X150X150 mm) were tested under compression at 1, 3, 28, and 56 days after casting. The test was conducted by means of a 2000 kN capacity testing device in conformity with ASTM C39 [126]. Three specimens from each mixture of different series were tested at each testing age and then comparison were done between (Series 1) and (Series 2).

3.6 Determination of Concrete Durability Performance

3.6.1 Water sorptivity

According to ASTM C 1585 water absorption evaluated by the water uptake from the concrete per unit cross-sectional area with time, is referred to as the sorptivity [127]. The test was conducted on the surface of concrete which is in contact with a thin water layer while the sides of the specimens were coated by paraffin, capillary suction was considered as dominant invasion mechanism.This test was performed on two cylinders specimens of 100 mm in diameter and 50 mm in height, which aresupported by rods immersed in water of 3~5 mm as shown in Figure 3.4. Prior the sorptivity test the specimens were dried in at temperature of 100±5 °C to prevent micro cracking, thus leading to relatively realistic values and then allowed to cool to ambient temperature in a sealed container. The initial weight of the specimen was measured before contacting water. Specimens were removed from the tray and weighed at different time intervals up to 1 H to evaluate the mass gain. By dividing the mass gained by the supposed surface area of the specimen the volume of water absorbed was calculated and the density of water then plotted with respect to square root of time. Sorptivity coefficient was represented as the slope of most excellent fit line.

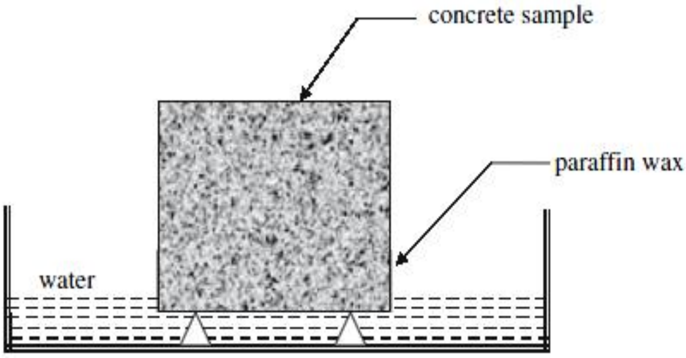

Figure 3.5 Measurement of concrete sorptivity

3.6.2 Rapid chloride permeability

In order to determine the penetration resistance of the concrete to chloride ions, rapid chloride permeability test (RCPT) was performed according to AASHTO T277 [128]. RCPT is based on the electrical conductivity of the concrete. Concrete discs of 100 mm in diameter and 50 mm in height were used for the test. Before the test, a standard vacuum saturation procedure was applied to the specimens. Then, specimens were put between test cells as seen in Figure 3.5 one of which containing NaCl solution and the other NaOH solution. Then the concrete sample was subjected to a potential difference of 60 V and the total charge was measured by data logger registered the current passing through concrete over six hours period and expressed in terms of coulombs as a basis for the evaluation of the concrete chloride permeability. The test is terminated after 6 hours. AASHTO T277 had a classification to chloride permeability in concrete which consist of five classes starting from ‘High’ to ‘Negligible’ on the basis of the coulomb as shown in Table 3.5. Figure 3.6 shows graphic arrangement of the test set up for RCPT.

Table 3.5 Analysis of results obtained using RCPT Test [139]

Charge Passed (Coulombs)	Chloride Permeability	Typical of -
>4000	High	High W/C ratio (>0.60) conventional PCC
2000–4000	Moderate	Moderate W/C ratio (0.40–0.50) conventional PCC
1000–2000	Low	Low W/C ratio (<0.40) conventional PCC
100–1000	Very low	Latex-modified concrete internally-sealed concrete
<100	Negligible	Polymer-impregnated concrete, Polymer concrete

3.6.3 Gas permeability

The gas permeability of the concrete mixtures was performed by using a CEMBUREAU method recommended by RILEM TC 116 [129]. The graphic view and line diagram of the apparatus as well as the detail of the testing cell are shown in Figures 3.7-3.9. Two specimens were taken simultaneously for each concrete mixture after curing period of 28 and 56 days was ended. Both specimens should have a diameter of 150 mm and a thickness of 50 mm such that concrete disc specimens cut from the mid portion of Φ150x300 mm cylinder. Oxygen gas was used as passing through medium. The gas was applied to the specimens at disparity pressures changeable from 150 to 500 KPa in pressure cells, which were secured by a strongly fitting rubber pressuring under high pressure next to the curved surface. Before testing, the pre-conditioning of the specimens is necessary to obtain meaningful results.

Figure 3.6 Rapid chloride permeability test

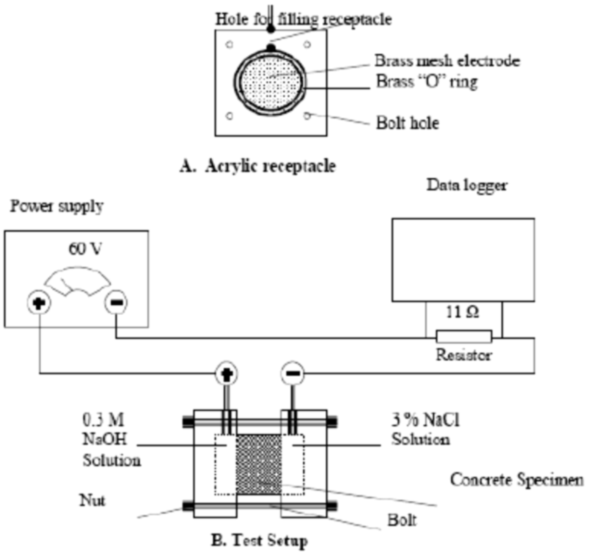

Figure 3.7 Schematic presentation of the test set up for RCPT

For this the specimens would be dried at 100±5 °C in oven to guarantee maximum 1% weight change within the specimens. After oven drying process, specimens were kept in a sealed envelope till test began. The average of two specimens was reported as a test result. Underlying principle was Hagen- Poiseuille relationship [130] for laminar flow of a compressible fluid through a porous body with small capillaries under steady-state conditions. The relationship solved for the specific permeability coefficient K_A can be written as follows:

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

Where, K_A is the gas permeability coefficient in m^2, P_1 is the inlet gas pressure in N/m^2, P_2 is the outlet gas pressure in N/m^2, A is the cross-sectional area of the sample in m^2, L is the height of sample in m, μ is the viscosity of oxygen ($2.02\text{x}10^{-5.12}$ Ns/m^2), and Q is the volume flow rate in m^3/s.

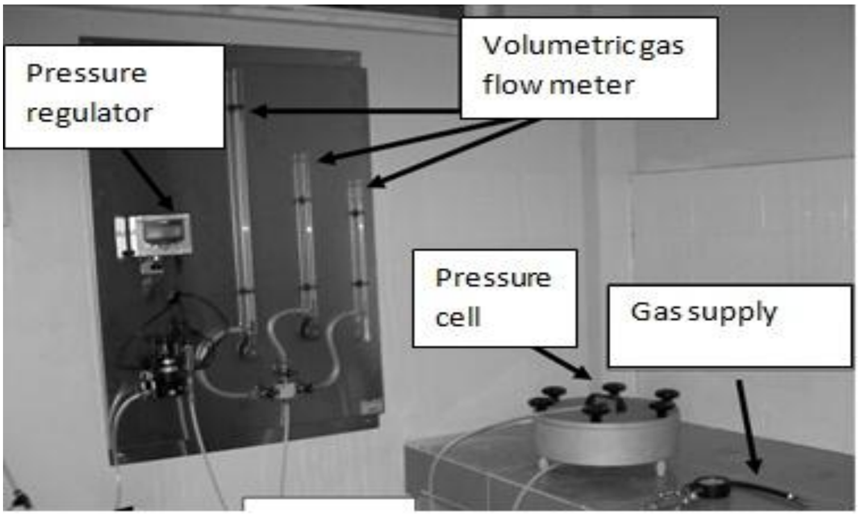

Figure 3.8 Photographic view of the gas permeability test set up and details

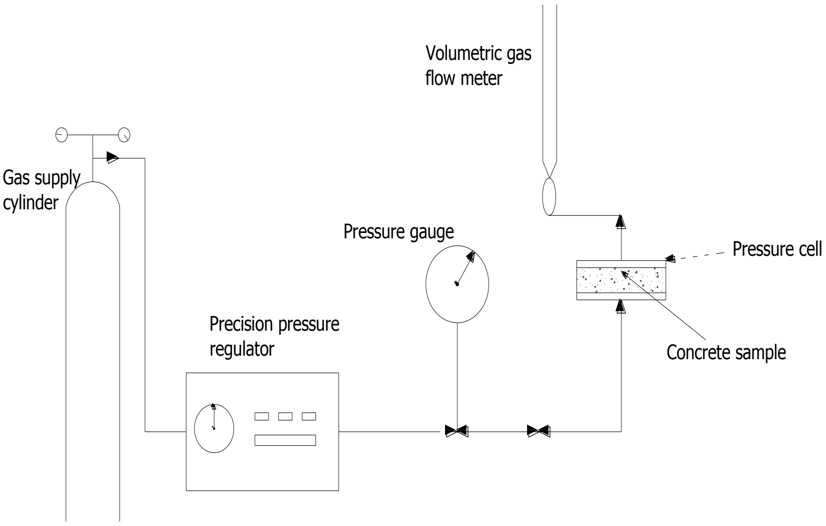

Figure 3.9 Schematic presentation of the gas permeability test set up

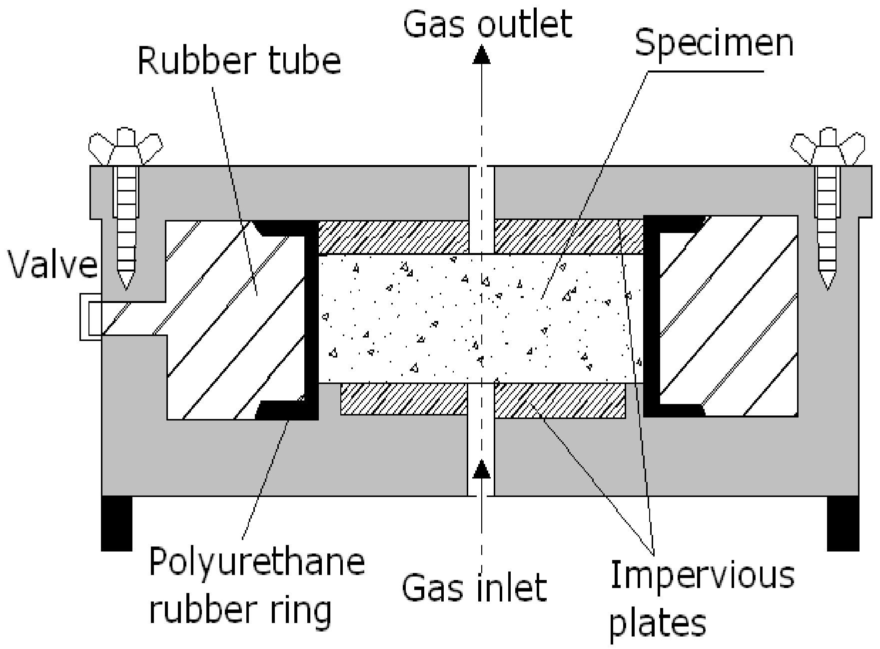

Figure 3.10 Schematic presentation of the pressure cell and test specimen

CHAPTER 4

TEST RESULTS AND DISCUSSIONS

4.1. Mechanical Properties

4.1.1 Compressive strength

It was reported that early compressive strength of concrete which exposed to steam curing is much higher than the compressive strength of concrete subjected to WC [16, 131]. But the later age compressive strength of concretes which is subjected to water curing is higher than the steam cured one at the mentioned age. The explanation reported by Verbeck and Helmuth [131] suggests that the rapid initial hydration produces a non-uniform distribution of the hydration products. They explain the uneven distribution of the hydration products by insufficient time being available for the diffusion of the constitutive species away from the cement particles and for uniform precipitation in the interstitial space at the high initial rate of hydration.

Figures 4.1 and Figure 4.2 show the values of compressive strength of the lightweight concretes subjected to SC and WC, respectively. As illustrated in Figure 4.1 considerable decrease in compressive strength occurred with increasing the level of replacement of LWFA. Early age (1 and 3 days) and later age (28 and 56 days) compressive strength values of SC concretes were very close to each other, while significant differences were observed for WC cured ones. The highest 1 day compressive strength of 32.60 MPa was observed for SC-LWC at 0% LWFA. While the lowest was observed at WC-LWC at 0% LWFA replacement as 24.44 MPa. SC-

LWC showed lower enhancement in compressive strength development than WC-LWC as the time passed. For instance, for 25% LWFA replacement SC-LWC had 24.5% increase in compressive strength at the age of 56 days while WC-LWC had 103.1% increase at that age. Although SC provided high early strength, for 75% and 100% replacement levels 3 day compressive strength was not significantly higher than that of WC-LWC. Such that, SC-LWC with 75% LWFA replacement, had 3 day compressive strength of 24.66 MPa being very close to that of WC-LWC which is 24.05 MPa. (See Table 4.1)

Based on the similar results carried on normal weight concretes were reported by Yazıcı et al. [27], it was revealed that steam curing enhance the 1-day strength values of high volume fly ash concretes from about 10 to 20 MPa. However, the ultimate compressive strength of steam-cured fly ash concrete was much lower than that of the standard-cured concrete. They also concluded that the amount of bigger pores increased with increasing curing temperature associated with a rise in the mean pore radius, which was the reason for the difference in compressive strength at elevated temperatures compared to the storage at 20^{o}C.

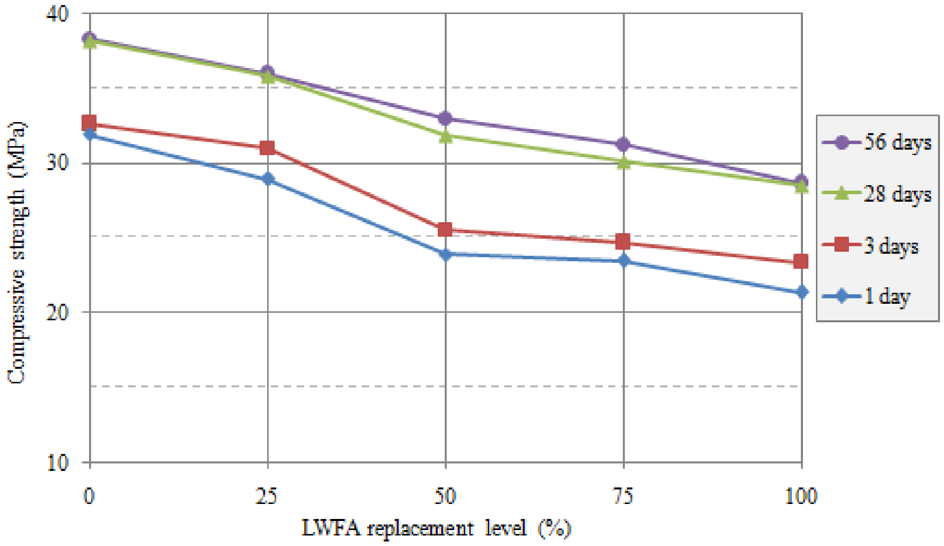

Figure 4.1 Compressive strength of steam cured LWCs verses LWFA at different ages

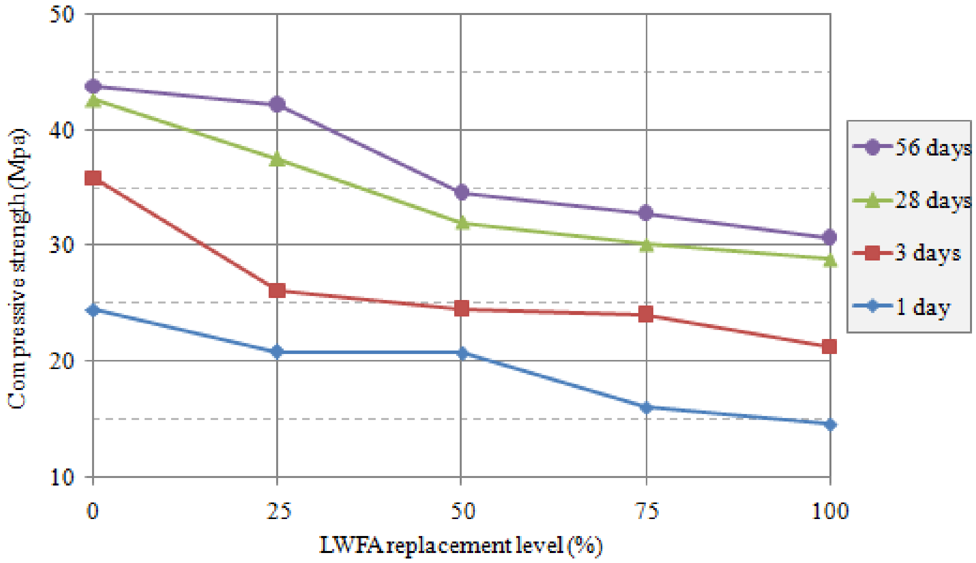

Figure 4.2 Compressive strength of watercuredLWCs verses to LWFA at different ages

4.2. Determination of Concrete Durability Performance

4.2.1 Water Sorptivity

The variations of sorptivity of concretes with the curing condition and the amount of

LWFA are given in Figure4.3. SC-LWCs had higher sorptivity than WC-LWCs at both ages. Increasing the amount of LWFA caused a systematic increase in sorptivity of the concretes, irrespective of the curing condition. Replacing crushed limestone sand with LWFA resulted in 8-119% increase for SC-LWFA and 35-120% increase for WC-LWFA at 28 days. However, for 56 days these intervals were measured as 35-119% for the former and 35-155% for the latter. When comparing 28 and 56 days sorptivity values at the same LWFA replacement levels, the change in sorptivity values were appeared to be insignificant for SC-LWC, while comparable variations were observed for WC-LWC. For example for 50% LWFA replacement level 1.15% change was observed at SC-LWC while 14.08% enhancement was observed for WC-LWC.

Increase in the sorptivity of steam cured concretes may be attributed to the adverse effect of steam curing on the pore size distribution. According to Erdogdu and Kurbetci [114] heat treatment influences the pore structure of cement paste by increasing the proportion of large pores in the cement paste. Similarly, Reinhardt and Stegmaier [117] stated that, with increasing curing temperature, the amount of bigger pores increased associated with the rise in the mean pore radius.

Rising in sorptivity of steam cured concrete seemed to be more, when the LWFA has been used at 100% replacement level as seen inFigure4.3. Moreover, increasing the amount of replacement of LWFA contents increased the sorptivity associated with the reduction in strength of the concretes for both curing conditions as a result of the finer pore structure [133, 134, 135]. (See Table 4.2)

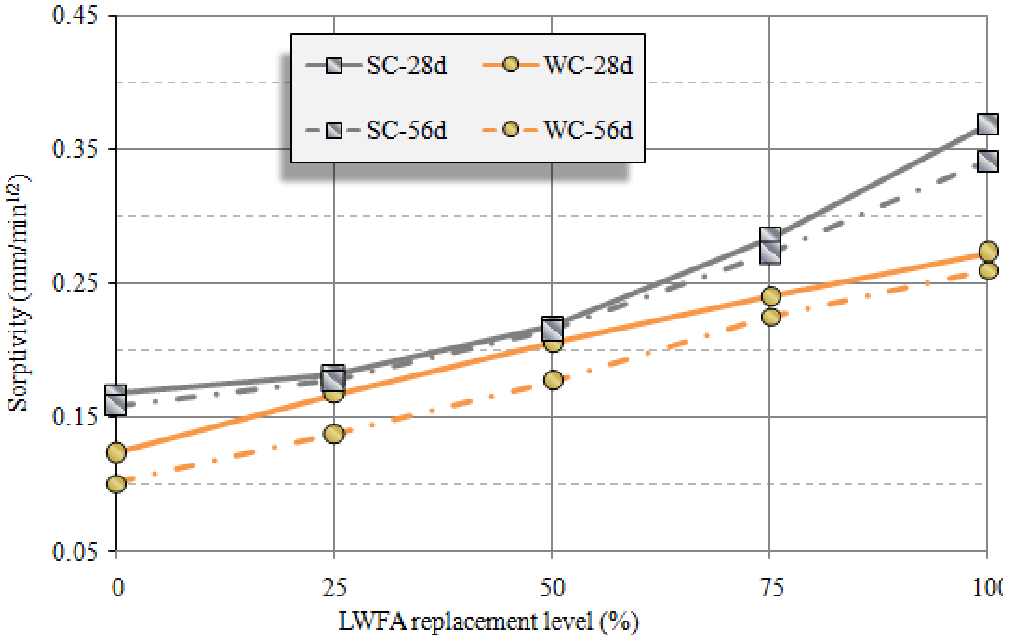

Figure 4.3 Sorptivity coefficient versus to LWFA, subjected to SC and WC at different age

Table 4.1 Compressive strength of both curing methods of LWCs

Amount of LWFA (%)	Compressive strength (steam curing)-(Mpa)			
	1 day	3 days	28 days	56 days
0	31.9	32.6	38	38
25	28.9	30.9	35.7	35.9
50	23.9	25.5	31.8	32.9
75	23.5	24.7	30	31
100	21	23	28.4	28.6

Amount of LWFA (%)	Compressive strenght (water curing)-(Mpa)			
	1 day	3 days	28 days	56 days
0	24	35.8	42.6	43.7
25	20.8	26	37	42
50	20.7	24.5	32	34.6
75	16	24	30	32.8
100	14.6	21	28.8	30.7

Table 4.2 Sorptivity coefficient of LWC

LWFA Replacement(%)	28 days		56 days	
	SC	WC	SC	WC
0	0.168	0.124	0.159	0.1015
25	0.1815	0.1675	0.1775	0.138
50	0.2175	0.206	0.215	0.1772
75	0.284	0.241	0.2725	0.225
100	0.3685	0.2725	0.341	0.2595

4.2.2 Resistance to chloride ion penetration

Curing condition and the type and source of aggregate are factors that should be considered for the resistance to chloride ion penetration of concretes. The use LWFA with increasing content resulted in increasing the RCPT values for both curing conditions. The total charge passed through the LWCs with respect to replacement levels of LWFA was shown in Figure 4.4. As it can be clearly detected from Fig. 4.4, SC-LWC had higher chloride ion permeability than WC-LWC. The negative effect of steam curing on the chloride ion permeability appeared to be more clear as replacement of LWFA increases. The lowest 28 day total charge values of 4974 C and 3951 C were measured for SC-LWC and WC-LWC, respectively. Based on the classification of concretes for chloride permeability, SC-LWC can be considered as "high" while WC-LWC is classified as "moderate" chloride permeability concrete. (See Table 4.3).However, 56 day results indicated that both of the concretes were in "moderate" chloride permeability class. Although, increasing the amount of LWFA caused sharp increases in SC-LWC, WC-LWC concretes, especially at 56 days, had insignificant variations up to 75% replacement level. The negative effect of SC is because of the increasing the pore size in the paste and also between the interfacial transition zone. Steam curing participates in developing of voids and continuing pore structure developments between cement paste and aggregate particles.

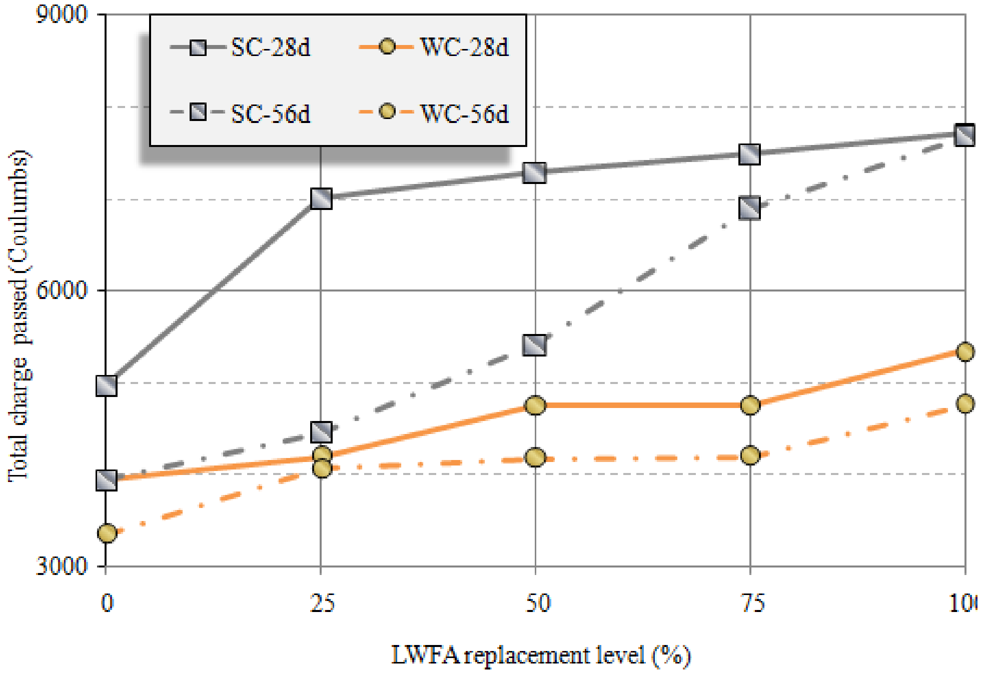

Figure 4.4 Chloride Ion value with respect to LWFA replacement, exposing to SC and WC at different ages

4.2.3 Gas permeability

The apparent gas permeability coefficients of the concretes was shown in Figure 4.5. By increasing amount of LWFA, gas permeability coefficient of concretes increased significantly irrespective of curing condition. SC concretes seemed to be more liable to have increase in gas permeability coefficient due to LWFA replacement than that of WC concretes, at 28 days. However, the tendency of the variation became lower for 56 days age. Significant enhancement in gas permeability coefficients of SC concretes was observed at 56 days.

For example, considering 50% LWFA replacement WC concretes demonstrated 13.6% enhancement while SC cured ones had 60.6% decrease in gas permeability coefficient. Moreover, 56 days gas permeability results indicated that RCPT values of SC-LWC concretes revealed very close trend to that of WC-LWC measured at 28 days.Since the transport properties of concrete are strongly depending on its pore structure [137, 132, 133], the raising of gas permeability of concrete can be attributed to the increasing pore structures in concrete due to LWFA addition.

Moreover, steam curing were effected the mechanism hydration, which cause the cement paste to be insufficient to fill the voids through aggregates and this effects the interfacial transition zone (ITZ). ITZ characteristically includes a high concentration of large, joined CH crystals, which may cause to localized regions of increased porosity and lower mechanical property.

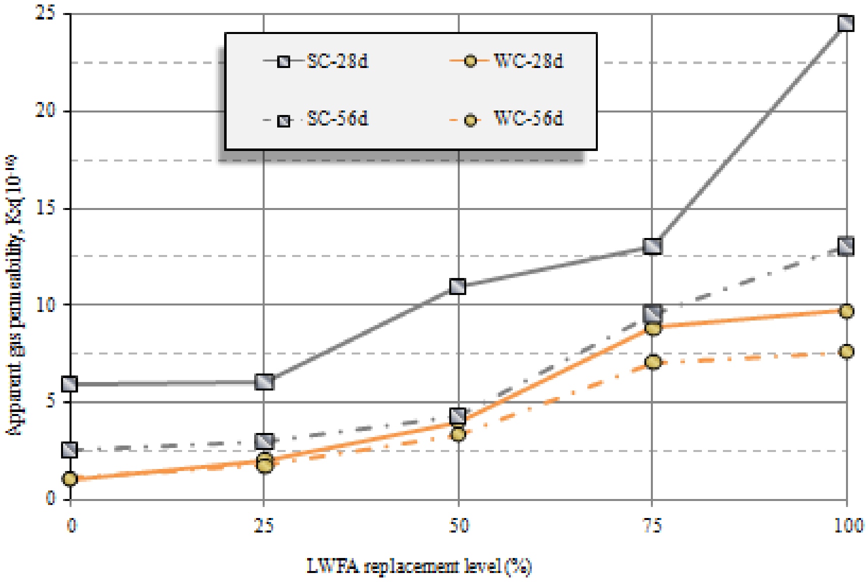

Figure 4.5 Gas permeability value with respect to LWFA, Exposing to SC and WC at different ages

Table 4.3 Values of rapid chloride permeability

Percent of LWFA replacement (%)	Age (day)							
	28				56			
	Steam Curing		Water Curing		Steam Curing		Water Curing	
	Charged passed (Coulombs)	Penetrability level	Charged passed (Coulombs)	Penetrability level	Charged passed (Coulombs)	Penetrability level	Charged passed (Coulombs)	Penetrability level
0	4974	high	3951.5	Moderate	3943.6	moderate	3354.5	Moderate
25	7000	high	4199.7	High	4459	High	4066	high
50	7279.5	high	4743.9	High	5414.9	High	4178	high
75	7485.7	high	4752.9	High	6887.5	High	4199	high
100	7704.8	high	5349	High	7678.8	High	4762.5	high

4.3Correlations between features of concrete

Acommon method for evaluation of tendencies of the experimental results is correlation, which is generally used bythe investigators for interpretation of thedata.Relative volume fractions of paste and aggregate with pore structure of the matrix and the interfacial transition zone around the aggregate particles are the principle elements for controlling the mechanical and transport features of LWC. The correlation coefficients (R) between the investigated properties were calculated and presented in Figures 4.6 through 4.11. The data used for these figures cover the entire test results for transport and mechanical properties. Figure 4.6 shows that the correlation between RCPT results and water soprtivity data of WC was better than the SC. Correlating gas permeability data with sorptivity test results had the highest correlation coefficient (R^2= 0.950) among permeability properties (See Figure 4.8) , while the weakest correlation among transport features of LWCs was observed between gas permeability and RCPTresult of water cured as shown in figure 4.7. It can be concluded from Figures 4.6 to 4.8, a strong correlation takes place among the transport properties of water cured LWCs.

The best correlation was observed between compressive strength and sorptivity test which yielded R^2 of 0.964 (See Figure 4.9). Figure 4.10 demonstrates the good correlation of water cured LWCs which was taken place between compressive strengthandgas permeability test results. The weakest correlation as shown in Figure 4.11 was between compressive strength and RCPT of LWCs.

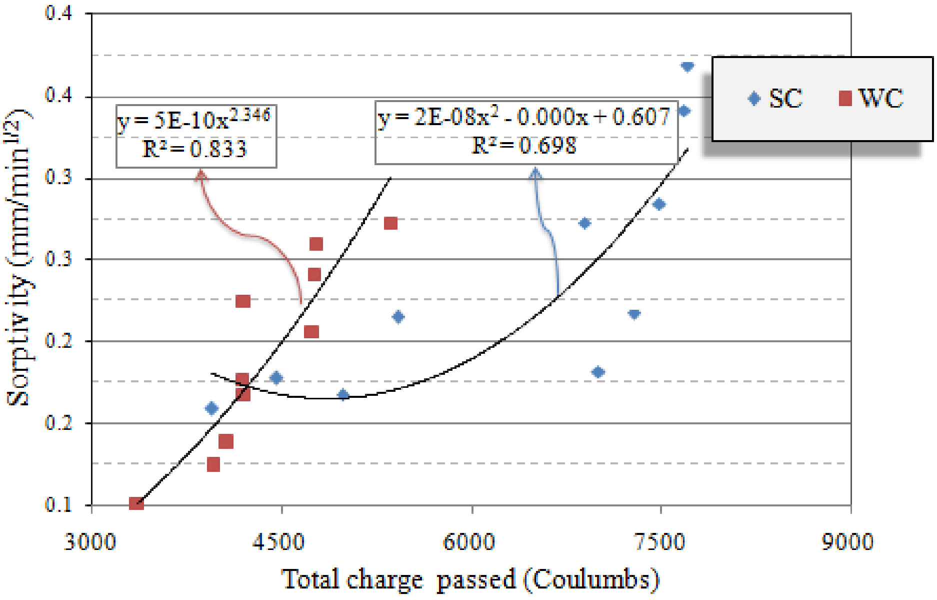

Figure 4.6 Correlation between water sorptivity and RCPT values of LWCs

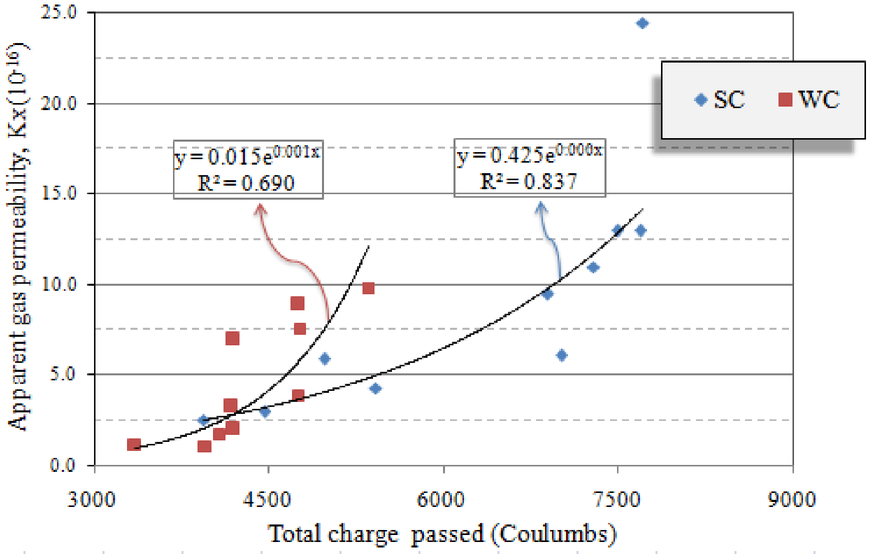

Figure 4.7 Correlation between water gas permeability and RCPT values of LWCs

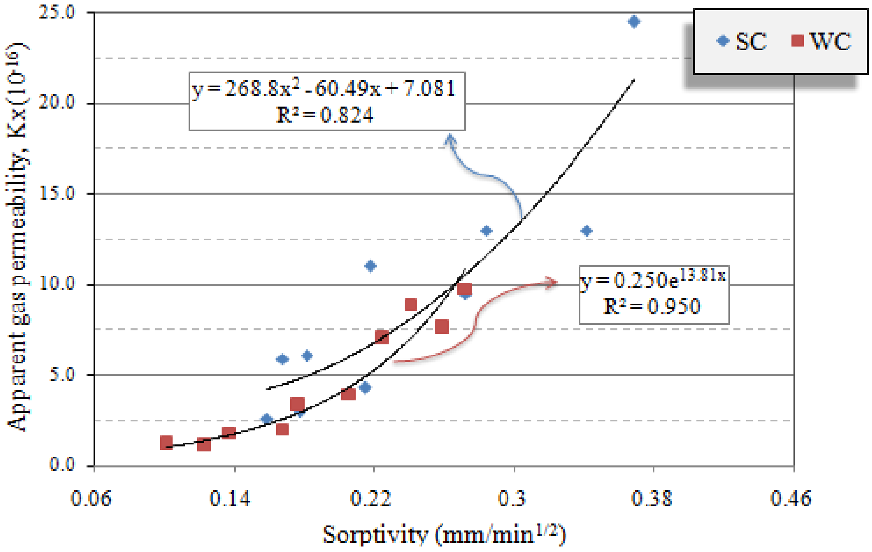

Figure 4.8 Correlation between gas permeability and water sorptivity values of LWCs

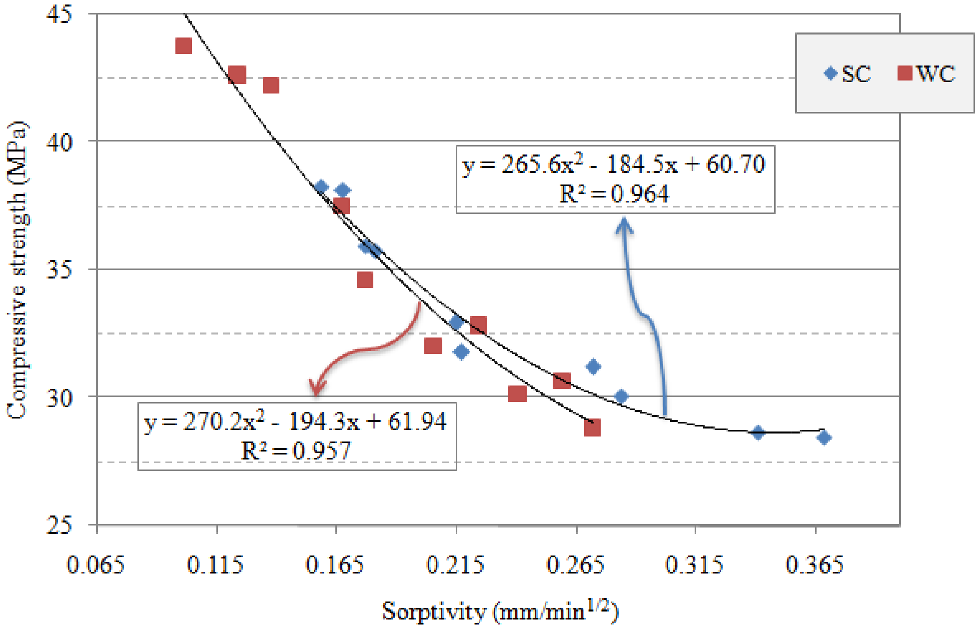

Figure 4.9 Correlation between compressive strength and water sorptivity values of LWCs

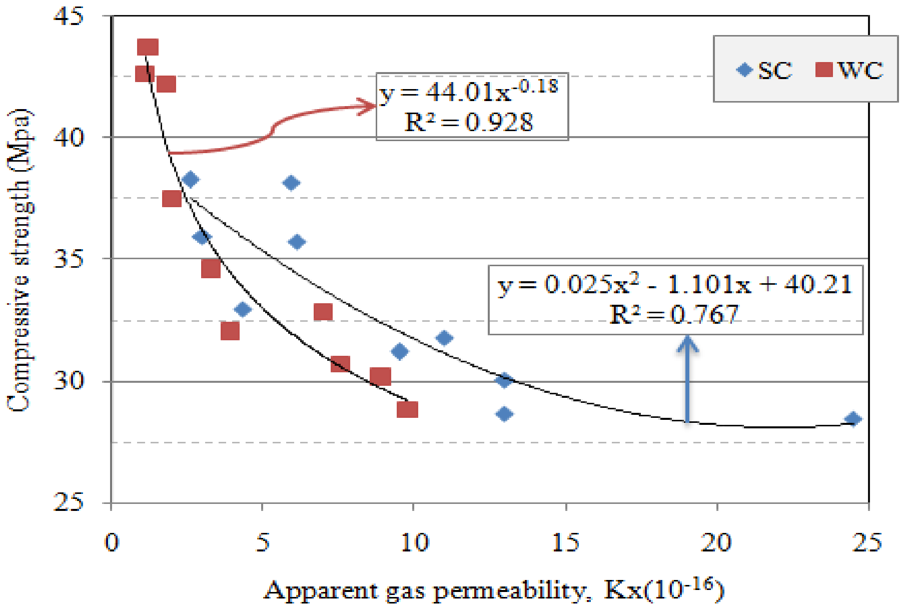

Figure 4.10 Correlation between compressive strength and gas permeability values of LWCs

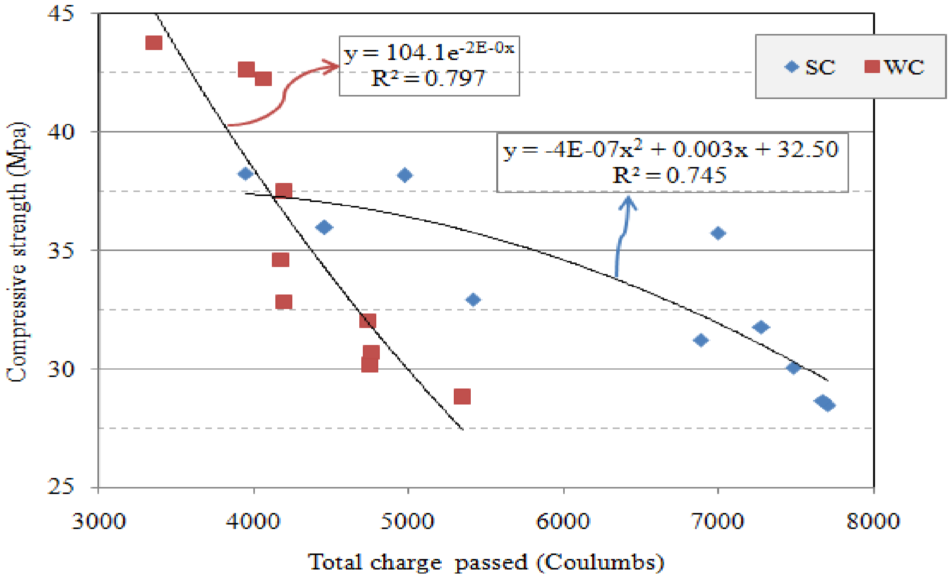

Figure 4.11 Correlation between compressive strength and RCPT values of LWCs

4.4. Statistical analysis

In order to assess the statistical significance of the experimental test parameters, general linear model analysis of variance (GLM-ANOVA) was performed at 0.05

level of significance. GLM-ANOVA is an important statistical analysis and diagnostic tool which helps in reducing the error variance and quantifies the dominance of a control factor.

To determine statistical significance of level of LWFA replacement, age of LWCs, and curing regime GLM-ANOVA was applied and the results were presented in Table 4.4. In the analysis, aforementioned factors were assigned as the independent variables while transport properties and compressive strength development were considered as the dependent variables. The general linear model analysis of variance was performed and the effective test parameters on the above mentioned properties were determined.

GLM-ANOVA results sown in Table 4.4 revealed that all of the independent factors except curing regime are statistically significant on the variation of the entire dependent variables. However, curing regime was proved to be statistically significant only on transport properties. In other words LWFA replacement level, age of LWCs, and curingregimeare statistically significant parameters affecting the variations of the RCPT test, sorptivity, and gas permeability at 28 and 56 days. Neverthless,statistical analysis revealed that the variation o compressive strength data were not affected from the curing regime adopted. The reason may be due to the limited number of data samples in the population.

Table 4.4 Statistical evaluation of the test results for LWC properties

Dependent Variable	Independent variable	Sequential sum of squares	Mean square	Computed F	P value	Significance
Compressive strength (MPa)	Replacement LWFA (%)	664.82	166.21	26.30	0.000	YES
	Age of LWCs	1022.83	340.94	53.94	0.000	YES
	Curing regime	5.15	5.15	0.81	0.374	NO
	Error	195.94	6.32	-	-	-
	Total	1888.74	-	-	-	-
Gas permeability (10^{-16})	Replacement LWFA (%)	346.079	86.520	93.013	0.000	YES
	Age of LWCs	54.417	54.417	7.61	0.016	YES
	Curing regime	106.768	106.768	14.92	0.002	YES
	Error	93.013	7.155	-	-	-
	Total	600.278	-	-	-	-
RCPT (Coulumbs)	Replacement LWFA (%)	12512359	3128090	7.79	0.002	YES
	Age of LWCs	3610015	3610015	8.99	0.01	YES
	Curing regime	18567485	18567485	46.21	0.000	YES
	Error	5223109	401778	-	-	-
	Total	39912969	-	-	-	-
Sorptivity ($mm/min^{1/2}$)	Replacement LWFA (%)	0.07667	0.019168	79.58	0.000	YES
	Age of LWCs	0.001350	0.001350	5.60	0.034	YES
	Curing regime	0.011153	0.011153	46.31	0.000	YES
	Error	0.003131	0.000241	-	-	-
	Total	0.092306	-	-	-	-

CHAPTER 5

CONCLUSIONS

The following outcomes can be got through the experiment works:

1. Lightweight concretes (LWCs) with unit weights between 1773 kg/m^3 and 2035 kg/m^3 were produced by using different combinations of coarse and fine lightweight fly ash aggregates.

2. Utilization of LWFA with increasing amount resulted in reduction of the amount of chemical admixture to provide 14±2 cm slump value. In addition to provision of recycling high amount fly ash as concrete making material, this may also be considered as one of the important advantage of utilizing LWFA due to cost saving.

3. As a result of steam curing LWCs had significant high early strength especially at 1 day. However, when compared to later age compressive strength development of the concretes, it was observed that water cured concretes had considerably higher rate of strength development. Although SC-LWC revealed lower performance than WC-LWC in terms of later age compressive strength, it was proved that LWC with 100% lightweight aggregate having unit weight of 1773 kg/m^3 can be utilized as structural concrete within 24 h. Because, ACI states that the lowest limit for compressive strength of LWC is 17 MPa. However, SC-LWC with 100% LWFA had 1 day compressive strength of 21.3 MPa.

4. Due to highly permeable and porous structure of LWFA, increasing thevolume of utilization resulted in systematic decrease in transport properties without depending on curing type. However, by adjusting mix design parameters such as water-to-binder ratio, total binder content, using of pozzolanic materials etc., lightweight concretes of desired performance can be produced. Moreover, steam curing caused to deterioration of transport properties of LWCs, especially at 28 days. However, at 56 days of curing the differences between SC and WC concretes were not as distinct as 28 days.

5. Using of AFFA as a replacement for normal fine aggregate adversely influence the resistance to chloride penetration and effective in improvement of the pore structure of the concretes. The reduction in permeability and the resistance to chloride intrusion increases as the level of AFFA increases in the concrete mixture.

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APPENDIX

APPENDIX A: Photographic Views

Figure A.1 preparation fly ash and cement to make AFA

Figure A.2 General views of pelletization disc

Figure A.3 AFA production

Figure A.4 preparation for sieving after keeping at least 28 days in plastic bags

Figure A.5 Immersing aggregate for 30 min in water. to get SSD aggregate

Figure A.6 Immersing aggregate for 30 min in water. To get SSD aggregate

Figure A.7 Photographic view of mixture

Figure A.8 Photographic view of slump test

Figure A.9 Samples inside chamber before exposing to steam curing

Figure A.10 The required temperature of the steam curing cahmber reached

Figure A.11 Samples inside chamber after exposing to steam curing

Figure A.12Photographic view of steam curing chamber

Figure A.13Photographic view of compressive strength specimens

Figure A.14Photographic view of gas permeability specimens

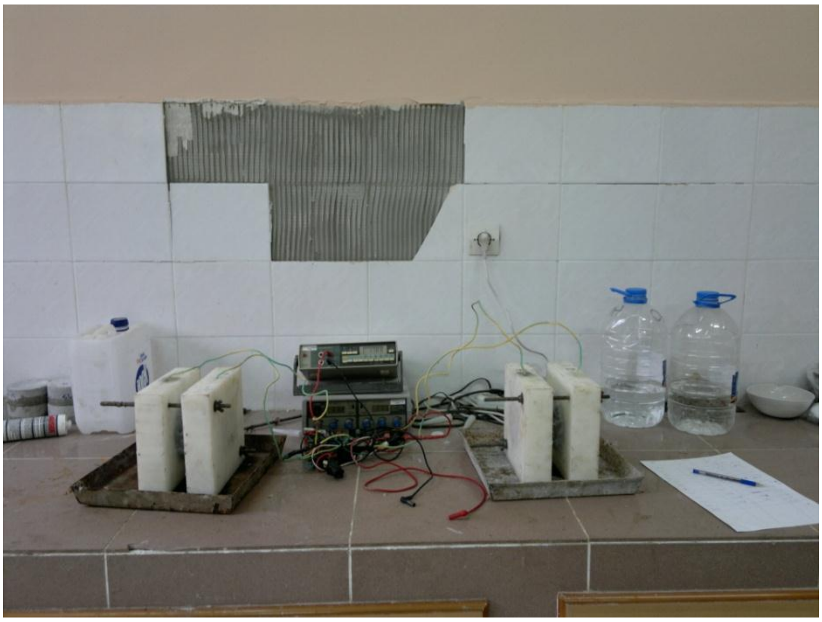

Figure A.15Photographic view of Rapid Chloride ion Penetration specimens

Figure A.16Photographic view of Water Sorptivity of specimens