UNIVERSITY OF GAZIANTEP
GRADUATE SCHOOL OF
NATURAL & APPLIED SCIENCES

# THE EFFECT OF NANO-SILICA ON THE GAS PERMEABILITY, DURABILITY AND MECHANICAL PROPERTIES OF HIGH STRENGTH LIGHTWEIGHT AGGREGATE CONCRETE

M.Sc. THESIS
IN
CIVIL ENGINEERING

BY
MOHAMMED LAYTH ABBAS
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# The Effect of Nano-Silica on the Gas Permeability, Durability and Mechanical Properties of High Strength Lightweight Aggregate Concrete

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

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Mohammed Layth ABBAS

# ABSTRACT

## THE EFFECT OF NANO-SILICA ON THE GAS PERMEABILITY, DURABILITY AND MECHANICAL PROPERTIES OF HIGH STRENGTH LIGHTWEIGHT AGGREGATE CONCRETE

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**January 2017, 80 pages**

In this current study, we carried out an experimental investigation on the effect of nano-silica on the gas permeability, durability and mechanical properties of high strength lightweight concrete. The experimental analysis consists of two parts. The first part is the production of lightweight aggregate by using cold bonded method and the second part is the design of different mixes of concrete samples. The lightweight aggregate through cold bonded method is produced after three processes. The first process is started with by mixing 90% of cement replacement material fly ash class (F) with 10% Portland cement by weight. The second process is pelletization of lightweight aggregates by moisturing in pelletized machine at ambient temperature and final stage is the curing process at 28 days. Utilization of light weight aggregate has been finished off by volumetric substitution of normal coarse aggregate with 5 different percentages (0%, 10%, 20%, 30% and 40%) with and without nano-silica ($SiO_2$). It has been used with a constant water/binder and fly ash (FA) ratios as 0.35 and 0.2, respectively. By the way, the properties of concrete has been investigated independently for each different percentages of lightweight aggregate. All mechanical properties; compressive strength and splitting tensile strength were monitored and physical properties like sorptivity and gas permeability were measured at the ages of 28 and 90 days. The results indicates that the negative results of LWAs can be remedied by addition 3% of nS particles that leads to increase the efficiency.

**Keywords:** Nano-silica; Lightweight aggregate; Cold-bonded; Fly ash; Mechanical properties; Physical properties.

# ÖZET

## NANO-SİLİKANIN, YÜKSEK DAYANIMLI HAFİF AGREGALI BETONLAR ÜZERİNDE, GAZ GEÇİRGENLİĞİ, IŞLENEBİLİRLİK VE MEKANİK ÖZELLİĞİ ETKİLERİ

**ABBAS, Mohammed Layth**
**Yüksek Lisans Tezi, İnşaat Mühendisliği Bölümü**
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**Ocak 2017, 80 sayfa**

Bu çalışmada, nano-silisin yüksek mukavemetli hafif betonun geçirgenliği, dayanıklılığı ve mekanik özellikleri üzerine etkisini deneysel olarak araştırılmıştır. Deneysel çalışma iki kısımdan oluşmaktadır. İlk kısımda soğuk bağlama yöntemi ile hafif agrega üretimi ve ikinci kısımda ise farklı karışım oranlarında beton numunelerin üretimi gerçekleştirilmiştir. Soğuk bağlama yöntemi ile hafif agrega üretimi üç süreç içerisinde tamamlanmıştır. İlk süreç 90% F sınıfı uçucu kül ile ağırlıkça 10% Portland çimentosu karışımı ile başlamıştır. Sürecin ikinci aşamasında peletleme makinası ile ortam sıcaklığında nemlendirme yolu ile hafif agregaların peletizasyonu ve son olarak 28 günlük kür işlemi gerçekleştirilmiştir. Hafif agrega içerisinde kaba agregaların yerine 5 farklı oranda nano Silika ($SiO_2$) kullanılmıştır (0%, 10%, 20%, 30% and 40%). Bu karışımlarda sırasıyla 0.35 ve 0.2 sabit oranlarında su/bağlayıcı ve uçucu kül kullanılmıştır. Bu yolla farklı yüzdelerde hafif agregalı betonların özellikleri ayrı ayrı incelenebilmiştir. 28 ve 90 günlük kür koşullarında, tüm mekanik özellikler, basınç dayanımı ve yarmada çekme dayanımı izlenmiş ve sorptivite ve gaz geçirgenliği gibi fiziksel özellikler ölçülmüştür. Sonuçlar, 3% oranında eklenen nS parçacıklarının hafif agregaların neden olduğu negatif etkileri iyileştirdiğini göstermiştir.

**Anahtar Kelimeler:** Nano-silika; Hafif agrega; Soğuk bağlama; Uçucu kül; Mekanik özellikler; Fiziksel özellikler.

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# LIST OF SYMBOLS

| | |
|---|---|
| AA | Artificial aggregate |
| ACI | American concrete institute |
| AFA | Artificial fly ash aggregate |
| ASA | Artificial slag aggregate |
| ASTM | American standard for testing material |
| BSI | British Standards Institution |
| $Ca(OH)_2$ | Calcium hydroxide |
| CaO | Calcium oxide |
| C-S-H | Calcium-Silica-Hydrated (Gel) |
| EPS | Electrostatic precipitators |
| FA | Fly ash |
| $F$c | Compressive strength |
| $F$st | Splitting tensile strength |
| $F$t | Tensile strength |
| G.s | Specific gravity |
| GGBFS | Ground granulated blast-furnace slag |
| HPC | High performance concrete |
| HRWRA | High range water reducer admixtures |
| HSC | High strength concrete |
| HSLC | High strength lightweight concrete |
| HVFA | High volume fly ash |
| ITZ | Interfacial transition zone |
| K | Gas permeability coefficient |

| | |
|---|---|
| LOI | loss of ignition |
| LWA | Lightweight aggregate |
| LWAFA | Lightweight aggregate fly ash |
| LWC | Lightweight concrete |
| LWCA | Lightweight coarse aggregate |
| MK | Metakaolin |
| NCA | Natural coarse aggregate |
| NFA | Natural fine aggregate |
| NS | Nano silica |
| NSC | Normal strength concrete |
| NWA | Normal weight aggregate |
| NWC | Normal weight concrete |
| OD | Oven dry |
| OPC | Ordinary Portland cement |
| PC | Portland cement |
| RCC | Roller compacted concrete |
| RCPT | Rapid chloride permeability test |
| RVE | Representative volume element |
| SEM | Scanning electron microscope |
| SP | Superplasticizer |
| SSD | Saturated surface dry |
| *T*s | Turkish standard |
| W/b | Water/binder ratio |
| W/C | Water/cement ratio |

# CHAPTER 1

# INTRODUCTION

## 1.1. General

Environment pollution controlling management is a most confrontation matter in view of the increasingly huge amount of solid waste and lack of landfills in existence. To reduce this problem and looking for environmental contamination, it is important to employ and recycle destruction waste. For example in Turkey, very small amount of Fly ash (FA) can be used in construction industry, in spite of 19 million tons is being in this country approximately (Güneyisi et al., 2013; Gesoğlu et al., 2013; Güneyisi et al., 2015). FA disposal leads to problems as well as environmental damage that air and water pollution caused widespread. For this reason, the expansion of the growing demand for reducing aspects of environmental damage and many of the investigations involved to control harmful of these related to learn different ways to the consumption of materials or substances in a good way and less harmful way (Sočo and Kalembkiewicz, 2007; Babbitt and Lindner, 2005).

These materials are considered as raw material for the manufacture of rubble best way to the goal of reducing the environmental impacts of the problems during the production of artificial aggregate, which can arise from these materials, known waste and pollutants to the environment. Therefore, the production of artificial aggregates solves two problems, maintains a safe environment from pollution and prevents the depletion of natural resources through the creation of a lack of natural aggregates in infrastructure growing industry. Many studies has been developed different methods to target the production of various artificial aggregates from a variety of sources. Basically the goal of each method for agglomeration of powder waste materials which are raw materials and separated into different specific desired size that can be used in the aggregate in the design work needed (Majeed, 2015).

Many applied technologies has been commonly used for artificial aggregates manufacturing such as Cold bonding, autoclaving or sintering. The agglomeration of fine particles that has cementitious properties either by them or by blending those with a mineral additive it is called Cold-bonding or pelletization method. This method need to use up minimum energy in order to making pellets by agglomeration fine particles with water acting as a coagulant in a pelletization disc (Baykal and Döven, 2000; Gesoğlu, 2004; Arslan and Baykal, 2006).

The use of high-strength concrete (HSC) term for concrete with a compressive strength of over than 41 MPa, as defined by the ACI Committee 363 (ACI committee 363, 1987). It can also defined as occupying a uniaxial compressive strength higher than that which is normally obtained in a region; because from region to region the maximum concrete strength is being varies. High-strength concrete usage leads to small cross-sections and therefore, it will reduce a structure dead load. This enables engineers to build multistory buildings and bridges with longer spans. The ultimate strength of concrete can be controlled by mineralogy and the strength of coarse aggregate, but the researchers observed that the hardened cement paste and transition zone are no longer strength limiting. Overall, it is observed that the HSC cracking is more localized and approach a homogeneous material behavior in comparison with NSC. More than that, HSC exhibits more brittle and more linear elastic behavior than NSC (Beshr et al., 2003).

Premature deterioration of concrete structures in aggressive environments in the development led to appear high strength concrete and high performance concrete. The mainly features of the high-strength concrete and high-performance concrete are low porosity, discontinuous structure of pore capillaries (fine pore structure) for cement paste and impermeable which they are most important properties of concrete. it can be obtained by using low w/b and high content of cement with addition of superplasticizers to achieve the workability and reduction in the mixing water Therefore, the volume of water in the concrete needed to complete the hydration process is sufficient, while the entry will be hampered due to water impermeability of concrete. One by one these enhance the resistance of concrete to penetrate harmful substances such as chloride, sulfate ions, carbon dioxide, water and oxygen, and thus improved the durability performance. Using of mineral and chemical admixtures can enhance the pore structure of high-performance concrete. Mineral admixtures, such as fly ash (FA) and silica fume (SF), supply additional reduction in the porosity of the mortar matrix and able to enhance the interface with aggregate . Curing also, will effect the quality of high-performance concrete (Mehta, 1990; Hassan et al., 1998; Hassan and Cabrera, 2009).

There are many advantages of integrating nanotechnology in to cement and concrete, such as enhance the manufacture of cement, improve the properties of concrete, and revolutionize the ability to monitor performance. The ability of using marginal material and recycled material is nanotechnology benefits to cement and concrete, and it will become usable when its provide systems to coat or modify problem systems. Furthermore, the other advantage of nS to concrete and cement is the ability to reduce permeability. It also leads to longer-lasting concrete structures or concrete pavements if a way can be developed to lead a concrete approach to the point of being impermeable (Grove et al., 2010; Birgisson et al., 2010). It can also enhance the concrete hardened properties and the aggregate paste bond that's leads to increase the compressive strength of concrete (Metaxa et al., 2009). Improving the construction proses another thing of nanotechnology benefits to use it out of the mechanical properties. It will be able to ease support the construction process by producing more uniform concrete products through diminish construction related problems. The new assembly ways and improvements in the ability to monitor changes in the constituent materials will improve the process and result in better concrete structures. Nanotechnology can reduce the emission of gasses by reducing the amount of carbon dioxide ($CO_2$) loading on the environment. The cement production process involves the production of a large amount of carbon dioxide ($CO_2$) as a by-product (Grove et al., 2010).

## 1.2. Research significance

In this current study, we carried out an experimental investigation on the effect of nano-silica on the gas permeability, durability and mechanical properties of high strength lightweight concrete. The experimental analysis consists of two parts. The first part is the production of lightweight aggregate by using cold bonded method and the second part is the design of different mixes of concrete samples. The lightweight aggregate through cold bonded method is produced after three processes. The first process is started with by mixing 90% of cement replacement material fly ash class (F) with 10% Portland cement by weight. The second process is pelletization of lightweight aggregates by moisturing in pelletized machine at ambient temperature and final stage is the curing process at 28 days. Utilization of lightweight aggregate has been finished off by volumetric substitution of normal coarse aggregate with 5 different percentages (0%, 10%, 20%, 30% and 40%) with and without nano-silica ($SiO_2$). It has been used with a constant water/binder and fly ash (FA) ratios as 0.35 and 0.2, respectively. By the way, the properties of concrete has been investigated independently for each different percentages of lightweight aggregate. All mechanical properties; compressive strength and splitting tensile strength were monitored and physical properties like sorptivity and gas permeability were measured at the ages of 28 and 90 days.

## 1.3. Outline of the thesis

Chapter 1-Introduction: The main objective and the aim of the thesis.

Chapter 2-Literature review: Presents general background and literature review on the fly ash, lightweight aggregate, pelletization process, and previous studies using lightweight aggregate in concrete, high strength concrete and high performance concrete, add to this properties of nano-silica and use it in concrete.

Chapter 3-Experimental study: The experimental program followed in the study like material properties (Cement, Aggregate, Chemical admixtures, Fly ash, and nano-silica), mixtures casting, curing and described test methods.

Chapter 4-Test results and discussion: The results, figures, and tables of the tests.

Chapter 5-Conclusions: Conclusion of the thesis and recommendation for relevant future studies

# CHAPTER 2

# LITERATURE REVIEW AND BACKGROUND

## 2.1. Fly Ash (FA)

Fly ash called pulverized fuel ash (PFA) is a solid waste fine particles produced from process of burning coal in power generation. FA is collected in dry condition by different ways like electrostatic precipitator. When transporting of fine coal particles, the pulverization process will start to procreate the steam in power generation. This process is called a combustion process. Consequently, the carbon and volatile mater are burned off. Two types of mineral components found in the coal gangue, first is the coarser ash collected in the bottom of the furnace such as, clays, feldspars melt and fuse droplets as spherical glassy particles . Second is the finer ash in flue gases removed by cyclone precipitators termed as pulverized fly ash (Luke, 2002). The schematic representation of coal-fired generation plant can be seen in Figure 2.1.

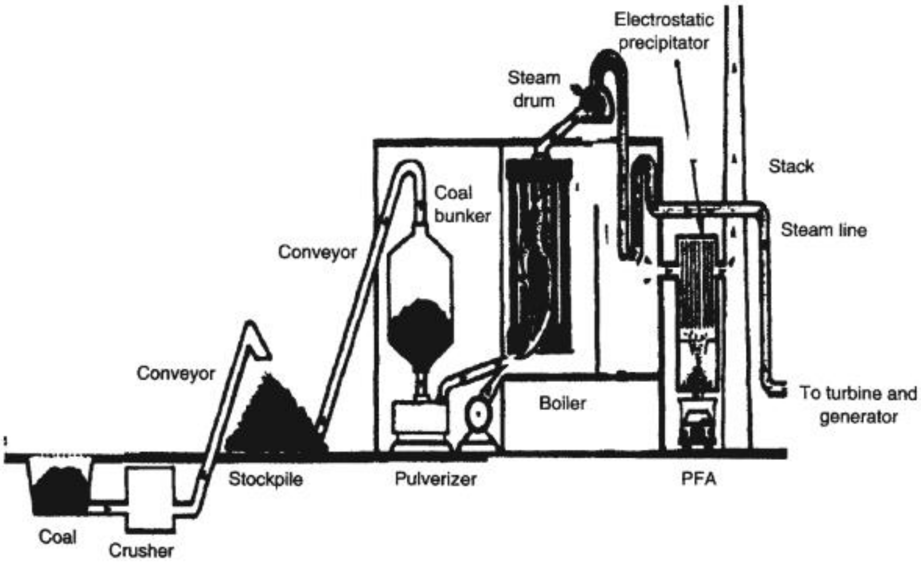


**Figure 2.1** Schematic of coal-fired generation plant emphasising PFA generation (Luke, 2002)

### 2.1.1. Types and Classes of Fly Ash

Fly ash recognized as class C and class F types according to chemical composition, origin, and reflecting their combustion with respect to ASTM (C618) and Canadian Standards Association (CSA).

Class F FA found lignite of subbituminous coals has a pozzolanic properties and contain ($SiO_2$+$Al_2O_3$+$Fe_2O_3$) total amount more than 70% and less than 10% CaO. Class C FA can be found from bituminous coals have pozzolanic properties and cementitious properties but contained ($SiO_2$+$Al_2O_3$+$Fe_2O_3$) more than 50% of total amount and more than 10% CaO.

### 2.1.2. Mineralogical Properties of Fly Ash; Fineness, Specific Gravity and Specific Surface Area

FA fineness can be measured using dry and wet sieving methods. Specify standard for fineness recommends that maximum percentage fineness residue on 45 µm sieve as established in (Malhotra and Vallace, 1993). Rounded and spherical fly ashes changing between 1.0 to 150 µm according to particle size analysis. Almost, angular and irregular shapes of fly ashes are larger, in most cases, its particles >1 µm in diameter. When Mehta (1984) used X-ray technique, he was found that high CaO fly ashes were finer than low CaO fly ashes cause of the higher amount of alkali sulphates in high CaO fly ash. Figure 2.2 shows SEM of typical FA shape.

The specific surface area of FA can be explained by area of a unit of mass. It can be measured by different ways such as; Lazer particle size analyzer, particle size analysis, Blain and the Best technique which measures compacted particles resistance for air flow (Carette and Malhotra, 1987). It is found that the specific area differ from 130 $m^2$/kg to 581 $m^2$/kg for bituminous ash and lignite ash, respectively. Furthermore, surface areas of fly ashes collected in (EPS) electrostatic precipitators have surface area between 400-700 $m^2$/kg but ranges between 150 and 200 $m^2$/kg for that cyclone collected.

The specific gravity of FA and hydraulic cement can be calculated as stated in ASTM C188. The specific gravity differs from 1.90 to 2.96 for subbituminous ash and iron-rich bituminous ash, respectively (Carette and Malhotra, 1987).

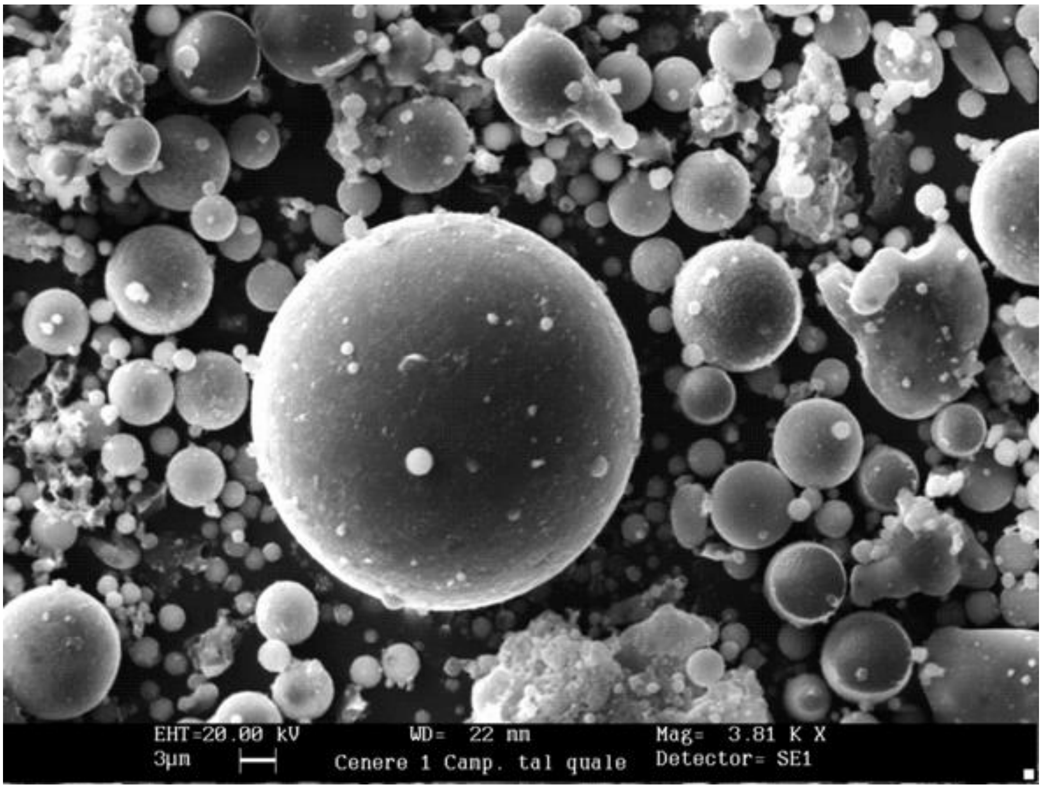


**Figure 2.2** SEM of typical fly ash shape (Belviso et al., 2011)

### 2.1.3. Physical Properties

FA is a very tiny- grained material, which mostly consists of spherical particles. Some of them contain angular and irregular particles. The size of particles may be coarser or finer than Portland cement depending on the ash sources (Carette and Malhotra, 1987). Its colors change from light gray to dark gray depending on the burning and coal properties. The black color in FA appears due to the unburned carbon as a result of incomplete burning. Better combustion leads to get lighter ash. Comparatively, more iron in ash gives light gray color but more carbon gives dark gray color (Ipek, 2013).

### 2.1.4. Chemical Properties

The FA chemical composition can be influenced by composition and the characteristics of the coal pulverized in power stations. The chemical analysis of fly ash shows that silicon dioxide ($SiO_2$), aluminum oxide ($Al_2O_3$), iron oxide ($Fe_2O_3$), calcium oxide (CaO) are the major components of FA. Other components like, MgO, $Na_2O$, $K_2O$, $SO_3$, MnO, $TiO_2$, and C are minor components. When Mehta (1983); Mehta (1984) examined the chemical analysis for two types of FA (C and F) they found that low lime fly ash (<10 % CaO), usually formed by the combustion of bituminous coal, shows 45–65 wt% $SiO_2$, 20–30 wt% $Al_2O_3$, 4–20 wt% $Fe_2O_3$, 1–2 wt% MgO, ≤ wt% alkalis, and ≤ wt% loss on ignition (LOI). The high-calcium fly ashes (≥10 % CaO) formed by the combustion of subbitummious and lignite coal typically contain 20–50 wt% $SiO_2$, 15–20 wt% $Al_2O_3$, 15–30 wt% CaO, 5–10 wt% $Fe_2O_3$, 3–5 wt% MgO, ≤8 wt% alkalis, and <1 wt% LOI.

A comparison between low and high calcium fly ashes shows that high-calcium usually include a smaller amount of unburned carbon (<1 %). The truth of low-calcium fly ashes is the complete removal of carbon dioxide is rare. Indeed, the carbon will be exemplified in glass, but a major portion appears to take place as cellular particles which may have a very large specific surface and are, therefore, able to drink up significant quantities not only of water but the chemical admixtures in concrete, like retarders, water-reducing admixtures, and air-entraining admixtures (AEA).

### 2.1.5. Influence of Fly Ash to Cement and Concrete

Because of its fines, pozzolanic status, and spherical form FA can be recycled in engineering construction. FA applications are important in cement as, firstly can use a replacement cement material in concrete, secondly as FA is a pozzolanic material, it can contribute to product a pozzolanic cement and finally as an inhibitor element in concrete. Using of FA in concrete have many benefits; enhance the workability, partial replacement of cement that reduces the cost. Remarkably, concrete FA gives the concrete much more strong and enables concrete to against weathering action. Furthermore, it gives concrete low permeability as a result of spherical particles and denser paste results from pozzolanic reaction. For high percentage of FA replacement gives lower heat of hydration. Also, enhance the concrete to corrosion, sulphate resistance, good durability, excellent mechanical properties, and very low penetration to chloride ions (Ahmaruzzaman, 2010). When Ravina and Mehta (1986) replaced (35-50) % cement with FA gives (5-7) % reduction in water mix design for designed slump.

## 2.2. Lightweight Aggregate ( LWA)

Lightweight aggregate are a course-grained materials that have bulk density and particle density not exceeding 1200 kg/m$^3$ and 200 kg/m$^3$, respectively. In general, LWA can be classified with reference to production and process methods. Therefore, LWA can divided by two types; natural and artificial (Gonzalez-Corrochano et al., 2009).

Natural lightweight aggregate can be found from igneous rocks like pumice or from sedimentary rocks like clay stone and shale (Conley et al., 1948; Dahab, 1980; Decleer and Viaene, 1993). Artificial lightweight aggregate can be fabricated from industrial and waste material such as FA, glass and slag (Baykal and Döven, 2000; Videla and Matinez, 2002; Kim et al., 2005; Mahmood, 2012). The two types of LWAs should meet the requirements of ASTM C 330 (2014).

### 2.2.1. Lightweight Aggregate Production with Fly Ash

Approximately, 450 million tons of FA is generated in the world every year. But very little reach 6% of the total amount is available for used in cement and concrete mixtures (Baker, 1984). In Turkey, 19 million tons which represent 3% of total world production from twelve active thermal power plants has been produced. Only 10% of this total amount of percentage can be used in cement and construction industry as recycling of waste materials. Sintering, autoclaving and cold bonded are the manufacturing methods of production LWAFA.

### 2.2.2. Cold Bonding Method

Cold bonding method is a type of bonding which clarify the capacity and ability of FA and other waste materials to react with calcium hydroxides $Ca(OH)_2$ at a room temperature. Pelletization or agglomeration process of manufacturing artificial aggregate considers the main technology which pelletizing FA with PC and water at limited value for specific periods to product the lightweight aggregate. This process considered most economical and superior one than others because of lowest amount of energy exhaustion during the process period of manufacturing artificial aggregate (Döven, 1996; Gesoğlu, 2004; Koçkal, 2008; Booya, 2012; Güneyisi et al., 2012).

### 2.2.3. Autoclaving Method

It’s a hardening process of pellets of waste materials like FA through the use of pressurized saturated steam and this method also known as hydrothermal treating. Autoclaving includes addition by weight some chemical materials in the agglomeration stage like, 47% FA, 45% quartz sand, 4.5% lime, 2% additives and 1.5% water are used in fly ash manufacturing in order to get required bonding properties in the materials. The green pellets with all the admixtures heated in high humidity environment then fired up for 6.5 hours at 200 °C in order to fabricate LWA for varies usage (Bremner and Thomas, 2004; Koçkal, 2008).

### 2.2.4. Sintering Method

Sintering method is vitrification process by burning aggregate in industrial furnace with high temperature. Sintered process starts by using production of artificial aggregate from FA and other waste materials. At the beginning, the FA and clay mixed together after that with water then pelletized. Later, it's followed by firing with high temperature reach 1100 °C applied at travelling grate and on a sintering strand. FA lightweight aggregate is ending up when the pellets passed through processes of drying, grinding, sintering, and cooling. Cold bonding method doesn’t need energy for curing after production of LWA but sintered method generates aggregate much more strength compared to cold bonded.

### 2.2.5. Pelletization Theory

Pelletization process is a famous worldwide technique to product artificial aggregate by moisture treatment under atmospheric conditions. Pelletization can be influenced by size, moisture content, and distribution of particles. The technique was improved in 1940s'. Material pelletized properties, moisture content in the medium and mechanical parameters of the process such as angle of rotation disk and the rotation speed are the affected functions in the performance of pelletization process (Baykal and Döven, 2000).

There are different types of pelletizer machines used in making pellets; cone type, drum type, pan type and mixer type. Using disk type is very useful because of easier controlling drum type pelletizer. In contrast, the type pellet mixer formation grains with increasing particle size by the shape of the disk as shown in Figure 2.3 (Bijen, 1986). In cold bonded method, increase the pellets with respect binder/cement ratio by weight of 0.2 onwards (Yang and Huang, 1998). Disk angle and the amount of humidity are two parameters that plays a great role in enlargements of the pellets (Ramamurthy and Harikrishnan, 2006). The optimum range of dosage binding agents from 20% to 25% by total binders' weight is vital for making balls (Bijen, 1986).

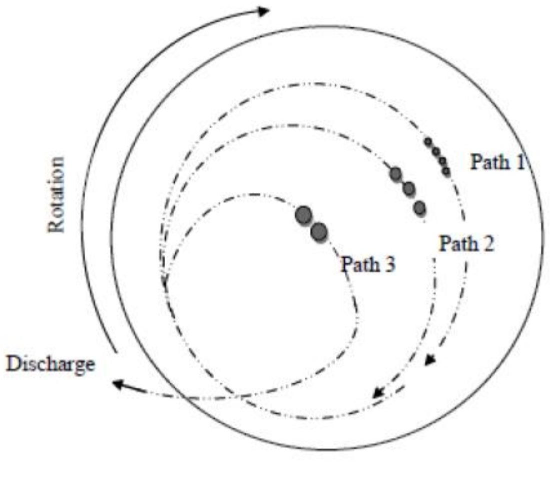


**Figure 2.3** Growing paths of pellets (Bijen, 1986)

The theory mainly states that fine-grained materials humidified, a slim moist film is created on the surface of these particles and structures behaves same as the bridges in shape meniscus among fragments by this film. In the case of rounding the particles in pelletization disk, a sphere shaped structures is being appeared and formed by bonding forces between the particles and developed due to gravitated and centrifugal forces as shown in Figure 2.4.

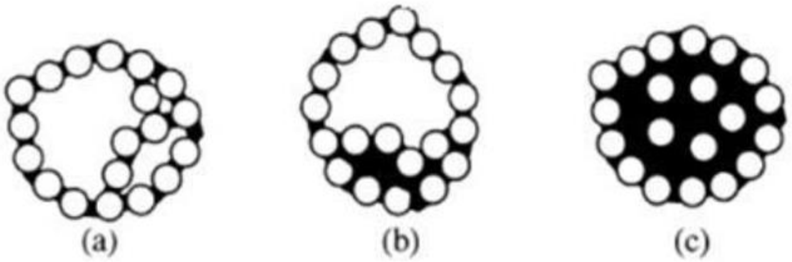


**Figure 2.4** Mechanism of pellets formation (Baykal and Döven, 2000)

In a period of pelletization process, air between the grains are drive out by the grow force on the pellets to do a denser pellets structure by the free spaces with water together with grains'. Denser pellets’ refers to closer packed particles to improve the structure coherence in order to create a dense and strengthened fresh pellet for handling and storing (Pietsch, 1991). The magnitude of the cohesive forces stratified on the grains in pelletization process and interlocking are the two main factors that determine the strength of the fresh pellets. The previous studies showed that the pellets strength is directly proportional with capillary rise and inversely with the radius of capillaries taking into account angle of contact between solid phase and liquid. Also, the mechanical and capillary forces are directly proportional with coherence structure. Döven, (1996) and Gesoğlu, (2004) defined pelletization process in three stages depending on the degree of filling water the inter-granular spaces:

- The pendular state, only water is present in all point contacts of grain particles.
- The funicular state, in this state, in addition to occurred in pendular state, some of the pores are completely filled with water.

- The capillary state, in this state, all inter-granular spaces are completely filled with water and no water film on the pellets surfaces.

Granulometric distribution of pelletized material is also very important. The granulometric distribution of pellets can be organized and arrayed through water content and amount of binders controlling. The optimal water content for FA lightweight aggregate ranged between 20-25 % by weight. Figure 2.5 displays mechanism of pellets bellow optimum state, this state takes place because of moisture content is below optimum water content, and Figure 2.6 displays mechanism of pellets above optimum state which happens because of the moisture content is higher than the optimum water content (Jaroslav and Rurickova, 1987).

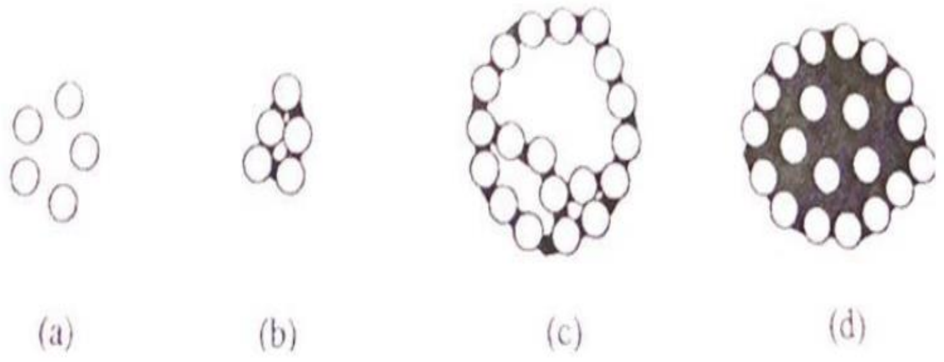


**Figure 2.5** Mechanism of ball nuclei formation (water content below optimum state) (Jaroslav and Rurickova, 1987)

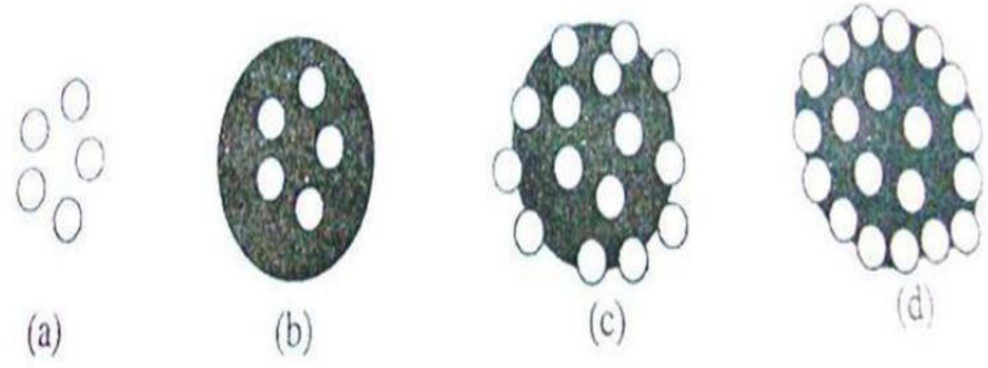


**Figure 2.6** Mechanism of ball nuclei formation (water content above optimum state) (Jaroslav and Rurickova, 1987)

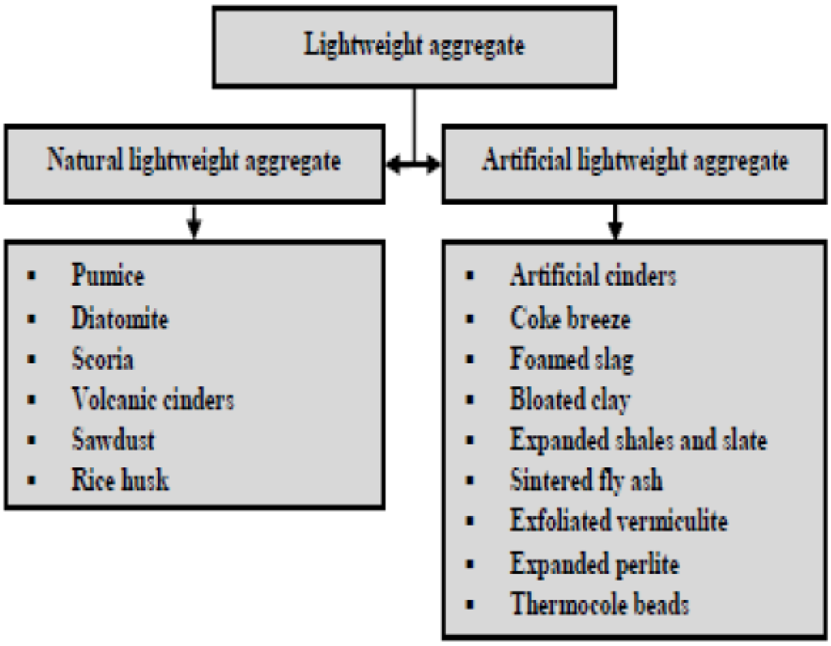


**Figure 2.7** Lightweight aggregate differentiations by (Shetty, 2006)

### 2.2.6. Lightweight Aggregate Concrete ( LWAC )

Structural lightweight concrete can be produced by totally or partially replacement of natural aggregate in concrete mixtures by lightweight aggregate containing great part of voids with respect to ACI committee 213 (2003). The details, qualities and characteristics of LWAs will change differently because it's produced in a different methods by great type of raw materials like; FA, shale, clay and blast-furnace slag possess. Productions of lightweight concrete can be summarized according to Choo, 2003) as;

- Wimpey process of no fine concrete process generates air-filled voids by neglecting the finer friction of NWC.
- Including gas-bubbles to cement paste to get a cellular structure comprises approximately 30-50% voids. This method called foamed or aerated concrete.
- Totally or partially replacement of the natural aggregate with LWAs including a large proportion of voids.

Many studies appeared to investigate the lightweight concrete mechanical properties and its characteristics. Zhang and Gjorv (1991a) studied surface texture, particle shape and pore structure of high strength lightweight concrete. They found that the more than half of 24 hour absorption happened in first 30 min and maximum water absorption took placed in the beginning of the first 2 minutes.

Nielsen et al. (1995) and Yang (1997) suggested a surface treatment to increase wear resistance and to decrease water absorption by coating LWA particles with polymer treatment, water glass, immersing the aggregate in cement slurry or silica fume and applying heat to aggregate surface more than sintering temperature.

Ramadan (1995) found that by addition of different low melting point metals or sintering process can be produce high performance FA lightweight aggregate and also he showed that without any heating process making LWA from high calcium fly ash is possible.

Manikandan and Ramamurthy (2007) noticed that the FA fineness influenced on the agglomeration method. Finer ash that has fineness of 414 $m^2$/ kg doesn't need any binder for pelletization efficiency. On the contrary to the coarser ash has fineness of 257 $m^2$/ kg that has lower pelletization efficiency. Pelletization efficiency can be improved by addition of clay binders such as kaolinite or bentonite. They also observed that pelletization process depend mostly on angle and speed of pelletized machine.

Manikandan and Ramamurthy (2008) discussed the effect of three kind of curing conditions like normal water curing, steam curing and autoclaving on the class C fly ash aggregate properties. The optimum limits of pelletization parameters (speed 55 rpm, angle 55º and moisture content 31% by weight of binder). Significantly, normal water curing had better effects when compared to autoclaving and steam curing because of intense of microstructure formation.

Baykal and Döven (2000) produced lightweight aggregate FA by cold bonded method. There were used three type mixtures proportions, fly ash only group, FC8( FA 92% by weight, cement 8% by weight) and FL8 ( FA 92% by weight , lime 8% by weight) . They observed that optimum angle and disk speed 43º and 45 rpm, respectively. Also, optimum period for pelletization process is 20 min and optimum moisture content ranged between 29 and 33% and internal friction angle of FA group, FC8 and FL8 are 29.4º, 45.4º and 44.4º, respectively.

Gesoğlu (2004) produced LWAFA with cement/ fly ash ratio of 0.1 by weight, then he favored to use surface treatment methods either cement silica fume slurry or water glass. LWAs surface treatments with glass water enhance water resistance and strength but cement silica fume slurry incorporation significantly decrease water absorption and slightly increase crushing strength of aggregate. But Koçkal (2008) after production LWAFA, he used sintering method to enhance the aggregate properties.

### 2.2.7. Mechanical properties of Lightweight Aggregate concrete

LWA has a similar characteristics' of NWC in plastic state. LWA is a porous structure for that reason it absorbs a large amount of water resulting in slump loss after mixing. This problem can be solved when using air-entraining agents in order to reduce the water absorption by reaching aggregate to saturated surface dry (SSD) condition and mix design water balance. In this case to prevent segregation of coarser particles, the maximum value of slump test should be 100 mm (Mindness, 2003).

The engineering properties of LWC can be determined by the materials that are used in its mix design. Compressive strength is directly proportional to its density (Choo, 2003). Zhang and Gjorv (1991a) enable to generate HSLWC up to 100 MPa with density of 1865 kg/m$^3$ with unorthodox species if lightweight aggregate. The strength of the aggregates appears to be a main element to control the strength of the concrete produced. Clarke (1993) proposed a classification that determines the relationship between the compressive strength and density as displayed in Table 2.1.

**Table 2.1** Classification of lightweight concretes according to compressive strength-density relationship (Clarke, 1993)

| Property | Class and Type | | |
|---|---|---|---|
| | Structural | Structural/Insulating | Insulating |
| Compressive strength (MPa) | >15 | >3.5 | >0.5 |
| Density range (kg/m$^3$) | 1600-2000 | <1600 | «1450 |

Despite the high porosity and weakness inherent in the lightweight aggregate, 50-63 MPa compressive strength can be obtained for LWCs. To get higher strength lightweight concrete, it should be used the mineral admixtures and high cement content compared to the same strength of NWC. However, it is difficult to precisely calculate w/b ratio of the paste because of LWAs higher absorption. In general, compressive strength and tensile strength of LWAs have the same behavior and influenced by the same factors (Mindness, 2003).

Gesoğlu et al. (2004) showed that compressive strength is gradually decreased when increasing the amount of lightweight aggregate fly ash because the fly ash aggregate is weaker than the matrix. Also, when they decreased w/c ratio from 0.55 to 0.35 for coarse aggregate volumes 30%, 45% and 60% resulted in clear increase in compressive strength by 86%, 60% and 40%, respectively. But Koçkal and Özturan (2010) fabricated lightweight aggregate from cold bonded method and then used sintering temperature to treat the surface. They got compressive strength and splitting tensile strength for 28 days ranged in 42.3 to 55.8 and 3.7 to 4.9 MPa, respectively.

Güneyisi et al. (2015) investigated the physico-mechanical properties of LWAFA through cold bonded and treated with Sodium-Silicate and then used with nano-particles at three levels of w/b ratio on compressive strength, sorptivity, gas permeability and water permeability. They found that increase in w/b ratio decreases the compressive strength and other properties and treated LWA with water glass has better properties than natural cold bonded aggregate. Therefore, the combined usage of treating lightweight concrete and nano-Silica increased in 90 days compressive strength to 87.81, 77.28 and 59.97 for w/b ratio of 0.25, 0.37 and 0.50, respectively as shown in the Figure 2.8.

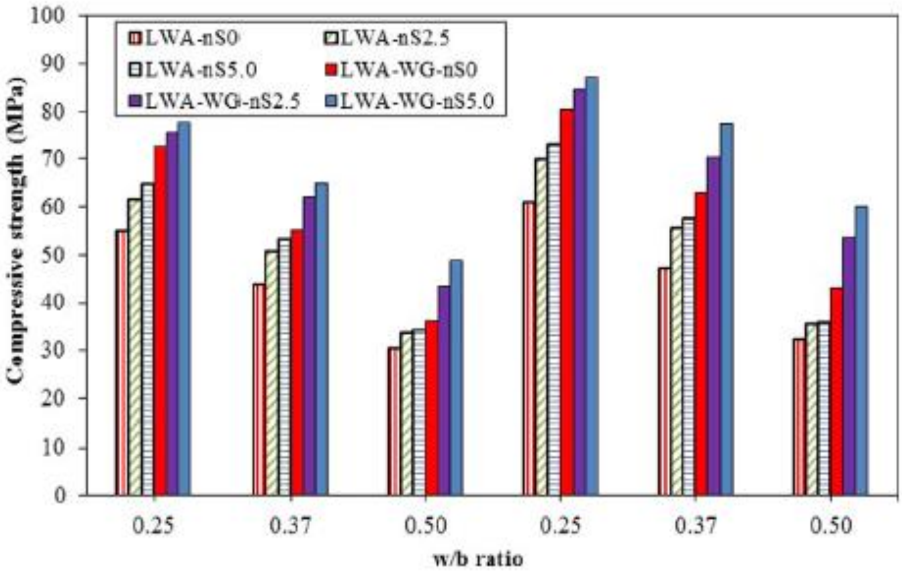


**Figure 2.8** The 28 and 90 days compressive strength values of SCLCs (Güneyisi et al., 2015)

### 2.2.8. Interface Between Lightweight Aggregate and Cement Paste

Interfacial transition zone (ITZ) which defined as a weakness region in concrete compounds, both in terms of strength and fluids permeability. Because of concrete is a three phase combination consists' of cement paste, coarse aggregate and ITZ between cement paste and coarse aggregate therefore, it's critically important. LWA is break down in LWA particles because the mortar is stronger than LWA (Mindness et al., 2003).

Hu et al. (2005) studied the combination structure and interface between LWA and cement paste by using scanning electron microscopy, micro hardness analysis, energy dispersive x-ray analysis and back scattered electrons image. They found the surface of HSLWA is denser than its core, depth of ITZ between 20-30 μm and boundary interlocks between cement paste and LWA. Also, addition of minerals like FA improved the interface combination and structure. They also reported that concrete performance and LWA particle strength are eventually improved due to reaction of calcium hydroxide with mineral additions to form hydrated calcium silicate gels to fill micro defects and cracks of LWA. Lo et al. (2007a) showed that pore size and surface characteristics of LWAs affected the adhesion between cement mortars and aggregate itself.

## 2.2.9. Durability of Lightweight Concrete

In general, better transition zone between aggregate and paste , less of cracking exist in LWA due to internal curing, higher value of inelastic strain capacity and lower elastic modulus are results' of using material selection, proper structural design and construction practices which are improve the durability in both of LWC and NWC (Ozyildirim, 2009).

Al-Khaiat et al. (2007) implemented an experimental program for research on long term development of strength and durability of LWA in hot marine exposure condition. They were casted 35 and 50 MPa compressive strength of LWA in 28 day with NWA 50 MPa in order to make comparison. The specimens applied to an initial curing ranged from 1 to 7 days and after that they exposed to hot dry and hot humid (seaside conditions). They found that 35 and 50 MPa of LWAs for 28 days were workable and cohesive with a unit weight 1800 kg/m$^3$. The better strength development for NWC 50 happened under a continuous water curing system. But for LWC 50 the best strength development occurred on seaside exposure after 7 days of primary curing. Moreover, at the age of 270 days the modulus of elasticity, modulus of rupture, and indirect tensile strength of NWC 50 was approximately 20, 50 and 30% more than LWC 50 when compared to its matching value, respectively.

## 2.3. High Strength Concrete (HSC)

High strength concrete is a term recently used with development in concrete technology. It can be made by high strength cementitious material and admixtures of efficient water reducing. In general, the term of HSC represent the concrete compressive strength of 41 MPa or more. But in UK, specified compressive strength of 60 MPa or more. In Norway it includes concrete with a compressive strength up to 150 MPa (Helland, 1997). The two terms of high strength concrete and high performance concrete are being synonym considered due to increasing tendency. HSC is one of the possible widely range of high performance concrete which includes LWC or high workability concrete with improved durability.

The main reason of using (HSC) is that it offers a cost effective solution to the many problems encountered in the design of a complex structure while at the same time supplying a higher strength and improved durability. The usage of HSC evident to decrease in member size results in aesthetically pleasing structure and more efficient floor plans. Furthermore, the use of HSLWC stretches the envelope design that gives engineers the ability to span longer distances and reduced the dead load of structural members. However, HSC exhibits brittle behavior under a heavy load (Mitchell and Marzouk 2007).

Hoff (1993) investigated the properties of HSLWC, these properties included modulus of elasticity, stress strain relationship, modulus of rupture, Poisson's ratio, tensile splitting strength, creep, shrinkage, and freezing and thawing. The strain at maximum stresses ranged from (0.0025-0.0035), modulus of elasticity at 40% of ultimate stresses ranged from 18 to 30 GPa. Compressive strength ranging between 55-82 MPa and also he was found that elasticity modulus lower than NWC.

Gesoğlu et al. (2015) investigated the internal curing of HSC using artificial aggregate as water reservoir by producing two types of artificial aggregate, the first one with FA and the second one with GGBFS with cold bonded method with 90% FA and 10% PC and 90% GGBFS and 10% PC and casted concrete mixes with partially substituted with artificial aggregate from 0 to 20% by 5% increment. They found the compressive strength ranged from 64.92 to 76.52 MPa, splitting tensile strength various from 4.25 to 4.74 MPa, losing weight from 1.14 to 1.03% and maximum crack ranged from 0.82 to 1.25. Significantly it is observed that compressive strength of HSC reduced with AFA and denser ITZ, higher crushing strength and slightly increase in compressive strength found in ASA.

### 2.3.1. Materials Technology of High Strength Concrete

#### 2.3.1.1. Cement

Productions of HSC with most available PC, but coarsely ground particles are usually unsuitable (Aïtcin and Mehta, 1990). In Norway, they developed special type of cement more lower $C_3A$ content and more finely ground particles for HSC (Helland, 1997). But in general normal commercial products are employed a high cement content 8-10 sacks has been required when product HSC without chemical admixture (Peterman and carrasquillo, 1986).

### 2.3.1.2. Water/Cement Ratio

Water cement ratio is an important variable in implementing of HSC (Peterman and carrasquillo1986). The percentage of w/c ranged between 0.22 - 0.4 is considered when focuses on the HSC production through conventional mixing technology. The results in compressive strength 60-130 MPa when normal density aggregate is used (Fib, Ce 1990). Greater strength and hardened paste comes from less capillary porosity that result from reduction in w/c which happen in cementitious particles are initially closer together in fresh mix concrete.

### 2.3.1.3. Admixtures Cement

Materials that are more significant use in high strength concrete rather than conventional concrete. Those materials are mineral admixtures, chemical and air entraining agents. The types of them will be chosen to improve workability, enhance durability, increase compressive strength, and accelerated strength gain. For production concrete of a high workability in very low levels of w/c (typically below 0.3) without high cement content unacceptably needed, its required to use the superplasicizer in order to get the required workability , the superplasticizer dosage rate will be very high up to 3% by cement weight (Newman and Choo, 2003).

The high range water reduces admixtures (HRWRA) main function is to decrease water 12-30% in concrete mixtures for kept recommended slump (Gagne et al., 1996).

Notably, compressive strength increases 25% than expectation in decrease w/c ratio, also, it's obvious from uniform microstructure enhancement in cement dispersal. (HRWRA) is also used to decrease the permeability of concrete by growing a uniform pore structure and decreasing of w/c with enhancing the durability (ozyildirim, 2003).

#### 2.3.1.4. Aggregate

HSC limiting factor depends on the capacity of aggregate and it's happen when the aggregate is weaker than the cement matrix. Also, it's not rigid enough strength and effects in relation to coarse aggregate. Minimum size aggregate consideration at 10-12 mm to accomplish optimum compressive strength with low water cement ratio and high cement content. Increasing in surface area of aggregate results in reduction in average bonding stress doing increase in the strength possibility. From previous studies, it's obvious that production of HSC is represented by crushed stones than rounded because of higher mechanical bond can be developed together with angular particles. The ideal requirements of coarse aggregate in HSC are cleanness, angular, cubical, 100% of crushed including minimum of flats excepting elongated particles (ACI 363R, 2010).

Fine aggregate in HSC must be selected to optimize the water demand. It must be circular in shape, smooth in texture, and slit, dust and clay should be kept as low as possible. The finest portion of fine aggregate is no longer essential to prevent segregation or increase workability.

## 2.4. Nano-Silica ($SiO_2$)

Nano-particles may be defined as any particle with average diameter ranged 1nm to 1000 nm in Nano scale. Nano-particles are created products by sol-gel method and not industrial by-products like silica fume and fly ash. Nano Silica and nano-$SiO_2$ are two types of spherical Nano-particles with average diameter approximately 5 to 70 nm for nano-$SiO_2$ and 100 nm for nano-silica. Also, there is another type obtained from highly purified clay is called nano-clays. All these types used as a nano filler when its addition to cement paste in order to stimulate hydration and as nano coatings. Two main forms of nano-silica are available, colloidal suspension and compacted dry grains (dry powder). Before mixing, a special preparation procedure of dry nano-silica has been required in order to insure that the nanoparticles dispersion in water mixing and uniformly distributed in concrete mixtures. But, colloidal nano-silica is a dispersive agent and ready to use form of nano-silica because of fabricated as a suspension stabilized (Said et al., 2012). Figure 2.9 shows the SEM photographs of nS.

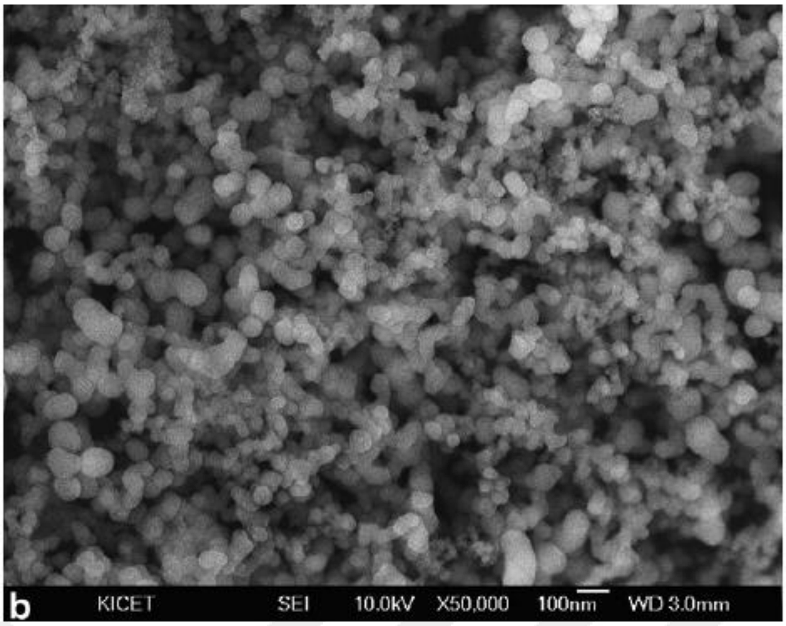


**Figure 2.9** SEM photographs of Nano-$SiO_2$ (Jo et al., 2005)

Li et al. (2004) studied experimentally the microstructures and properties of cement mortar with nanoparticles (Nano-$Fe_2o_3$ and Nano-$SiO_2$) and compared with plain cement mortar. The test results showed that at 7th day and 28th day of flexural and compressive strength of nano pastes were higher than normal cement paste with same w/c. Thus, it's possible to add nanoparticles to enhance the mechanical properties of concrete. Also, they investigated from SEM that cement mortar with nano-particles reduced $Ca(OH)_2$ and filled up the pores. Jo et al. (2005) studied the experimental investigation of cement mortar characteristics with nanoparticles. They used two types of additives silica fume and nano-$SiO_2$ particles. The results showed that at the same w/c ratio the compressive strength of all cement mortars with Nanoparticles were higher than others from silica fumes' mortars of 7th day and 28th days. It's obvious that nanoparticles are more effective enhancement in strength than silica fume. Furthermore, they discovered that nano-particles are not only a filler to enhance the microstructure, but also, it's an activator to sustain a pozzolanic reaction when they examined the rate of heat evolution and residual quantity of $Ca(OH)_2$ by SEM.

Dynamic hydration can be described in four phases (Kim et al., 2010; Neville, 2005):

- Phase 1: is a solid phase that includes C-S-H, ettringite, CH gel pores (0.5-2.5 nm) and other hydration products. In this phase, it's assumed that C-S-H is the major strength provider and the hydrated particles with external curing became hydrated resulting in RVE strength.

- Phase 2: unhydrated solid phase. In this phase the mechanical properties of cement paste can be determine by stress-strain relationship.
- Phase 3: this phase includes the nanoparticles that are nonreacted.
- Phase 4: the porosity phase, continuous of pozzolanic reaction will decrease the porosity due to due to pozzolanic conversion of C-H to C-S-H if suitable hydration conditions exists'. The four phases can be seen in Figure 2.10.

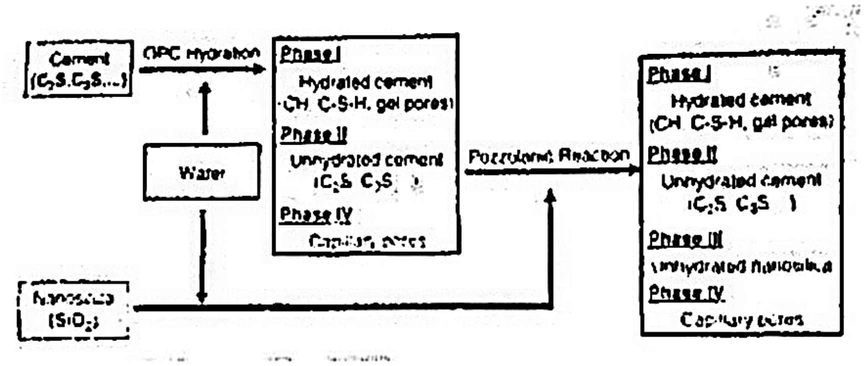


**Figure 2.10** Schematic representations of OPC hydration and pozzolanic reaction to develop the volume fractions of the four phases for a cement paste RVE (Kim et al., 2010)

Said et al. (2012) studied the effects of colloidal nanoparticles on concrete containing and other concrete addition class F fly ash with ordinary cement on compressive strength, splitting tensile strength, RCPT, thermal and microstructure analysis. They found that the mixtures containing nanoparticles showed a higher strength in all ages as well as splitting tensile strength. In general, the concrete performance with and without fly ash was visibility improved with addition a variable dosages of nanoparticles. Furthermore, RCPT results were significantly decreased with additives of nanoparticles and improved the chloride resistance of concrete.

Sanchez and Sobolev (2010) discovered that nanoparticles involved in two main approaches, the first approach is the reduction in the size of the largest structure into nano scale without changing their original properties and without atomic level control or disintegrated greater structures in to composite smaller parts. The second one is called molecular nanotechnology which engineered materials atoms or molecular components through the assembly process of self-assembly shown in Figure 2.11.

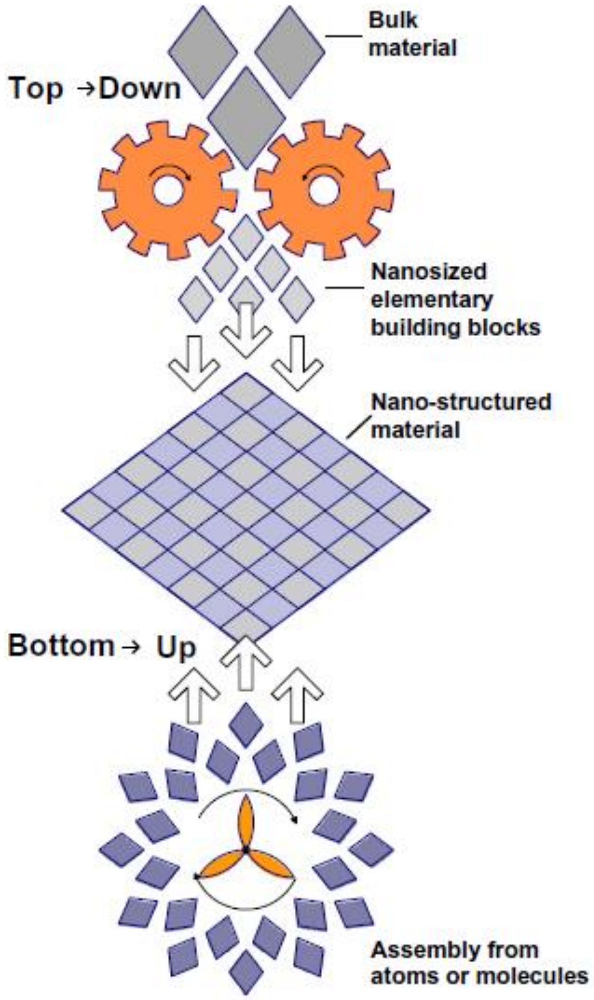


**Figure 2.11** Illustration of the ‘‘top-down’’ and ‘‘bottom-up’’ approaches in nanotechnology (Sobolev and Gutiérrez, 2005).

Furthermore, they also showed that nanoparticles have a very high characteristic surface area to volume ration when it's compared to the other particles that participates the concrete composites as seen in Figure 2.12. Nano-silica particle size and nano-silica particle surface area are two interacting factors must be considered in nano modeling hydration.

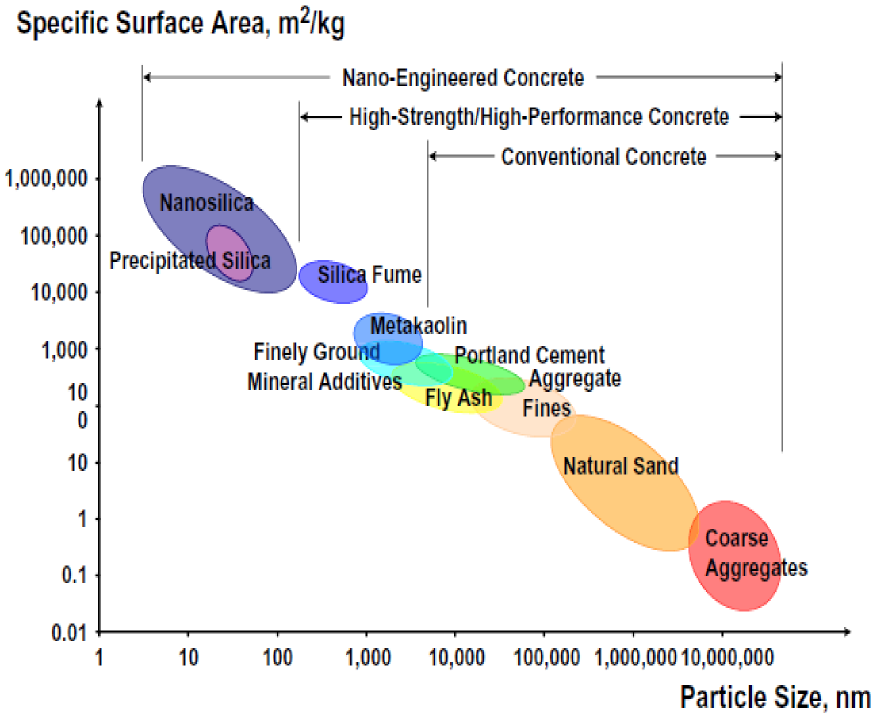


**Figure 2.12** Specific surface area and particle size related to concrete materials (Sobolev and Gutiérrez, 2005).

Du et al. (2015) studied the influence of nanoparticles on transport and mechanical properties of LWA. The strength as well as resistance of water and chloride ion penetration was enhanced. Moisture sorptivity, water penetration, chloride ions and diffusion coefficient were decreased by 23% and 10%, 23% and 49%, 5% and 0%, 22% and 12% compared to the references of two LWC mixes respectively with 1% nS. Furthermore, compressive strength increased 7.7% and 13.3% with 1% and 2% nS addition, respectively. Also, they discovered that 1% addition of nS resulted a bit of increase in the porosity because of entrapped air voids during the mixing. In general, they investigated compact and denser of microstructure, nano-filler effect and pozzolanic reactivity was enhanced the transport and mechanical properties of LWA.

Güneyisi et al. (2015) prepared experimental study on physico-mechanical properties of SCC with treated and untreated LWAFA by cold bonded process with three levels of water, nS and three binder contents. They studied water sorptivity, water permeability, gas permeability, drying shrinkage as well as compressive strength. They reported that using 5% nS and treated aggregate reduce gas permeability up to 70% for 90th days and 23% decrease for drying shrinkage. Also, compressive strength increased when reduce w/b ratio from 0.5, 0.37, 0.25 to 59.97, 77.28 and 87.81 MPa, respectively. For sorptivity test, the sorptivity coefficient percentage incremented at 28 and 90 days were 54 to 90%, 31 to 54% and 3% to 29% for 0.25, 0.37 and 0.5 w/b ratios, respectively.

Among all nanomaterial's, nanoparticles is the most widely materials that are used in cement and concrete to improve their performance because of its pozzolanic reaction and pore-filling. It’s necessary to develop durable, high strength, sustainable and cementitious composites environmentally friend due to the infrastructure development. The application of nanoparticles in concrete less or more satisfy of all the above previously said parameters, Figure 2.13 showed the role of nano-silica in cementitious system (Singh et al., 2013).

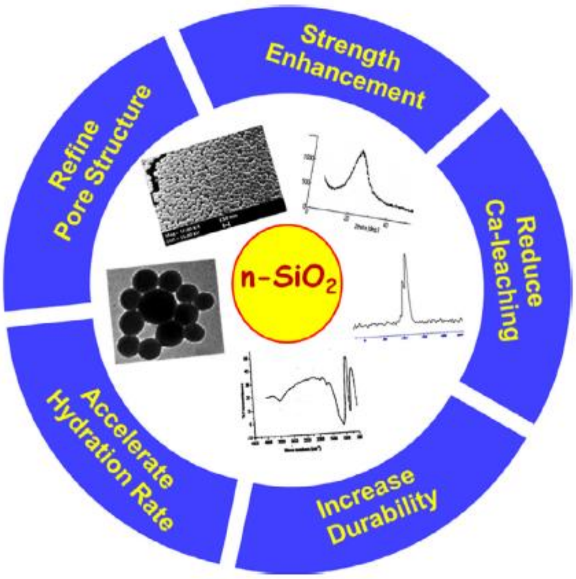


**Figure 2.13** Role of nS in cementitious system (Singh et al., 2013)

## 2.5. Transport properties of concrete

### 2.5.1. Gas Permeability

Bakhshi et al. (2006) studied the relationship between strength and gas permeability of concrete. For this purpose they used cylindrical specimens of 150 mm diameter and 300 mm height for strength and gas permeability measurements, respectively. Compressive strength measured after 28 days while gas permeability measured after two years and half with a total binder ratio of 400 kg/m$^3$ and wide range of w/b ratio (0.35-0.65) to obtain low and normal permeable concrete. They investigated the compressive strength for 28 days various between 34 to 80 Mpa for 0.65 and 0.35 of w/b ratio, respectively. Moreover, gas permeability coefficient falls within the range between 6.5× 10$^{-16}$ and 4× 10$^{-17}$ m$^2$ for 0.65 and 0.35 of w/b ratios, respectively. Figure 2.14 shows the relationship between compressive strength and the coefficient of gas permeability. Also, the results show on increase in gas permeability of concrete with increasing w/b ratio. When proposing a logarithmical equation, it’s obvious a strong correlation coefficient between compressive strength and gas permeability and its value is 0.93 as shown in Figure 2.15. If strength and permeability specimens are subjected to the same curing and tested at the same age, there is a unique correlation between compressive strength and permeability.

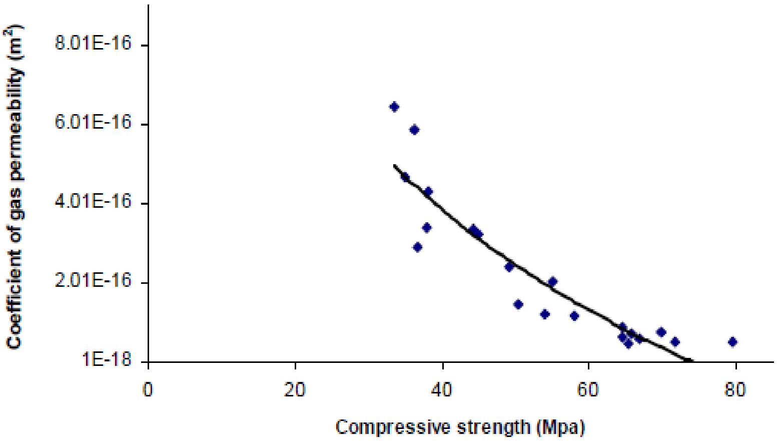


**Figure 2.14** The relationship between compressive strength and the coefficient of gas permeability (Bakhshi et al., 2006)

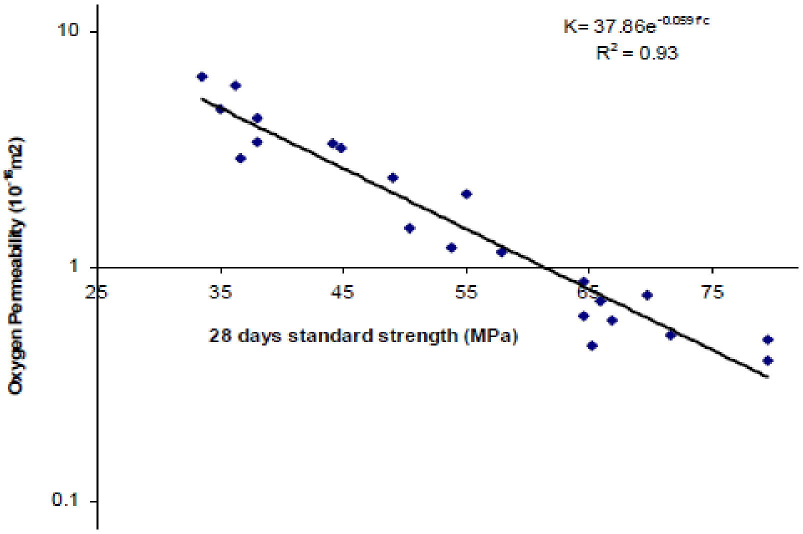


**Figure 2.15** Relation between permeability of concrete and standard strength for concretes made of different mix proportions (Bakhshi et al., 2006)

Care and Derkx, (2015) studied the influence of the microstructure of cementitious material on gas permeability values, two aggregate volumes content and cement paste of four w/c ratios used for this research. The materials microstructure can be represented by mercury intrusion porosimetry as well as gas permeability test has been done with precondition apparatus of low pressure at controlled relative humidity. They investigated gas permeability be contingent on upon the mixture (aggregate volume content, w/c and aggregate size). Aggregate size and aggregate volume content modifies the transports properties in cement mortar matrix and for this reason there is no correlation found for mortars, nevertheless, the gas permeability is correlated to the relative mass loss or the total porosity for the cement mortars.

Hui-sheng et al. (2009) discussed the gas permeability of high performance concrete (HPC) with mineral admixtures like FA and GGBFS and relationship among them. Figure 2.16 shows the correlation trends and correlation coefficient between compressive strength and nitrogen gas permeability. It can be seen that the relationship have greatly affected by w/b ratios and type of mineral admixtures. Figure 2.16a shows HPC with FA correlation coefficient values $R^2$ are 0.88 at w/b of 0.3 and 0.7 at w/b of 0.25. Figure 2.16b shows HPC with GGBFS, $R^2$ values are 0.73 at w/b of 0.3 and 0.6 at w/b of 0.35. The FA and GGBFS correlation trends are apparently for HPC. Compressive strength of HPC with GGBFS is linearly trend to the gas permeability while it shows exponentially correlated for HPC with FA.

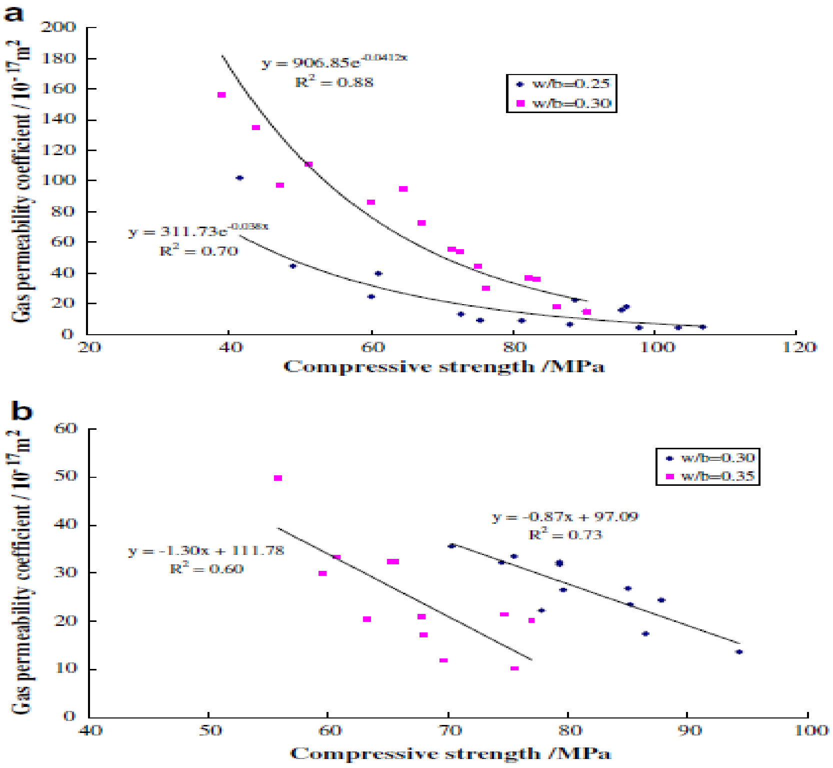


**Figure 2.16** Relationship between compressive strength and gas permeability of HPC with FA/GGBFS (a: HPC with FA; b: HPC with GGBFS) (Hui-sheng et al., 2009)

## 2.5.2. Sorptivity

Güneyisi and Mermerdaş (2007) investigated the sorptivity variation with curing regime, concrete age and w/b ratio with plain and Mk –modified concrete. From Figure 2.17, it's obvious that the sorptivity gradient tends reduced with an increase in the replacement level of MK and with increase with curing time, the sorptivity values reduces. Sorptivity values reduced in both 28 and 90 days when increasing the MK content for water cured concrete and 0.55 w/b ratio. They concluded the sorptivity values of concrete specimens including MK were ranged from 2% to 36% and from 8% to 60% lower than plain concrete at 28 and 90 days respectively, depending on the w/b ratio, curing regime and MK amount used in mixtures.

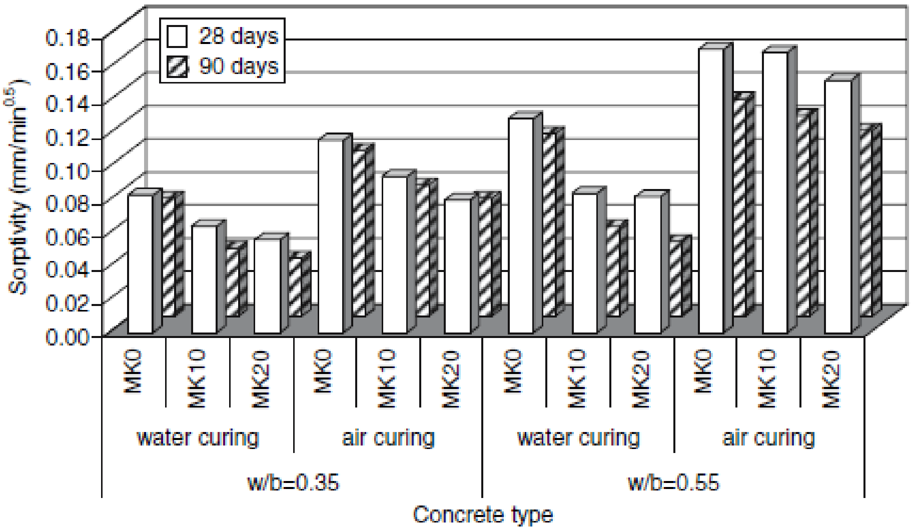


**Figure 2.17** Variation in sorptivity of plain and MK-modified concretes to different curing regimes (Güneyisi and Mermerdaş, 2007)

Yerramala and Babu (2011) investigated the transport properties of high-volume fly ash of roller compacted concrete. They employed six concrete mixes consists of cement and fly ash. They found that two mixes (RCC1 and RCC2) of high fly ash and low cement content was higher sorptivity than other mixes. Also, the sorptivity of low fly ash and high cement content (RCC5 and RCC6) were closely to that of moderate fly ash and cement content (RCC3 and RCC4) as shown in Figure 2.18. Figure 2.19 gives rapprochement between permeability and sorptivity of concrete mixes. It’s obvious from Figure 2.19 there is a good correlation that can be noticed between permeability and sorptivity values depending on the ash percentage, amount of cement, w/(c+f) and total cementitious materials. These parameters represented by the porosity and pore system functions.

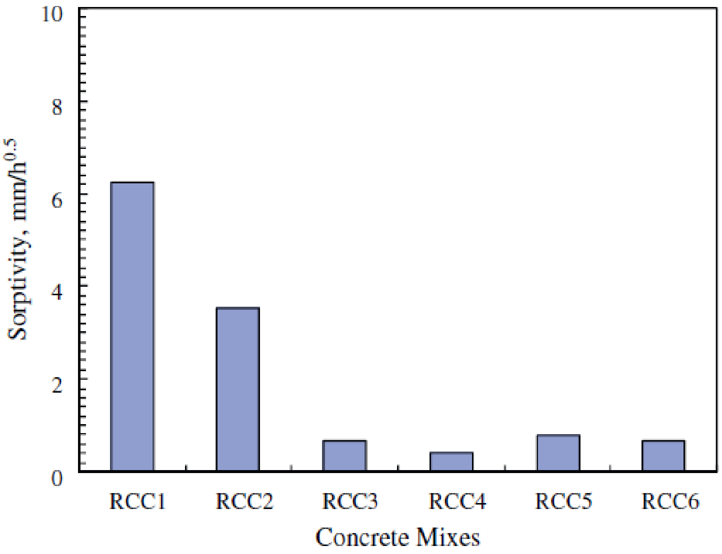


**Figure 2.18** Sorption characteristics of the concretes (Yerramala and Babu, 2011)

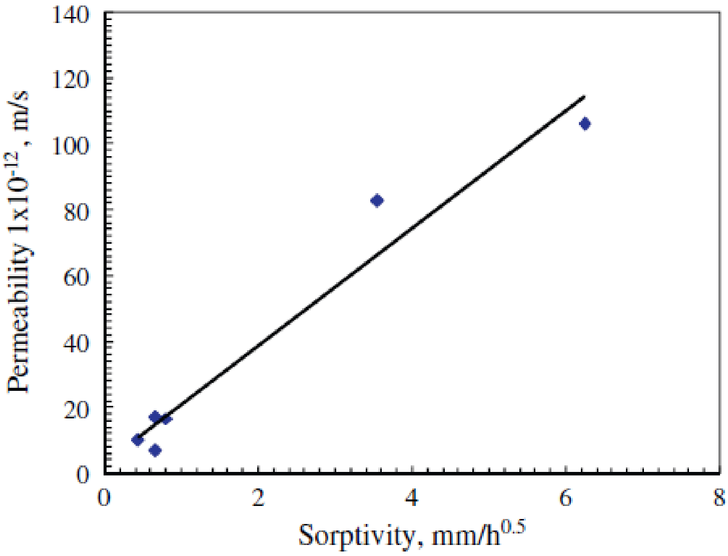


**Figure 2.19** Relationship between permeability and sorptivity (Yerramala and Babu, 2011)

# CHAPTER 3

# EXPERIMENTAL STUDY

## 3.1. Materials

### 3.1.1. Cement

A CEM 42.5 R Portland cement was utilized for both lightweight aggregate production and concrete mixes with specific gravity, loss of ignition, and Blaine fineness were 3.15, 2.99% and 394, respectively. The values are with the TS EN 197.1 (Turkish standard TS EN 197.1, 2002). Table 3.1 shows the physical properties and chemical composition of cement.

**Table 3.1** Chemical composition and physical properties of cementitious materials used

| Item | Portland cement | Fly Ash | Nano-Silica |
|---|---|---|---|
| CaO (%) | 62.12 | 2.24 | - |
| $SiO_2$ (%) | 19.69 | 57.2 | 99.8 |
| $Al_2O_3$ (%) | 5.16 | 24.4 | - |
| $Fe_2O_3$ (%) | 2.88 | 7.1 | - |
| MgO (%) | 1.17 | 2.4 | - |
| $SO_3$ (%) | 2.63 | 0.29 | - |
| $K_2O$ (%) | 0.88 | 3.37 | - |
| $Na_2O$ (%) | 0.17 | 0.38 | - |
| Loss on ignition (%) | 2.99 | 1.52 | ≤ 1.0 |
| Specific gravity | 3.15 | 2.04 | 2.2 |
| Blaine Fineness ($m^2/kg$) | 394 | 379 | - |
| Surface-volume ratio ($m^2/g$) | - | - | 150 ± 15 |
| Average primary particle size (nm) | - | - | 14 |

### 3.1.2. Fly Ash (FA)

Class F FA was used in both lightweight aggregate production and concrete mixes with specific gravity, loss of ignition and Blaine fineness 2.04, 1.52% and 379 respectively, with accordance to ASTM C 618 (ASTM, 08, 2000). In Table 3.1 the chemical compostion and physical properties of this material used.

### 3.1.3. Nano-Silica ( Nano-$SiO_2$)

NS material used as supplementary cementitious material. Its chemical composition and physical properties are shown in Table 3.1.

**Figure 3.1** Cementitious materials used

### 3.1.4. Superplasticizer

In this study, Glenium 51 superplasticizer is used which has a specific gravity 1.07. It’s a new generation admixture based on the modified polycarboxylic ether. Furthermore, it's used in concrete industry when the performance and highest durability are required. Manufacturers state values shown in Table 3.2.

**Table 3.2** Properties of the superplasticizer

| Properties | High range water reducer admixture (HRWRA) |
|---|---|
| Commercial name | Glenium 51 |
| Color tone | Dark brown |
| State | Liquid |
| Specific gravity | 1.07 |
| Chemical description | Polycarboxylic-ether |
| Alkali % | ≤ 4 |
| Chloride % | ≤ 0.10 |
| Chlorine % | ≤ 0.10 |
| Recommended dosage | 1-2% (% binder content) |

### 3.1.5. Aggregate

#### 3.1.5.1. Lightweight Aggregates (LWAs)

Cold bonded agglomeration process of PC and FA was utilized in production of lightweight aggregate. Pelletizer machine consists of three parts as shown in Figure 3.2. The main parts of pelletizer machine are pelletization disc, switch board and water reservoir. A speed controller is able to control the speed of disc revolution. The angle between the normal and disc plane is arranged between 30° -92° by a hydraulic system. A water reservoir is supplying the mixture water content by regulated pressurized water injection. Scrapping blades are found to prevent sticking and adhesion of any mix to the pelletization disc surface and working an energy barrier to ensure and get more compacted pellets. Furthermore, the scrapping blades divided the path of spherical coarse material in to inner path which contains a coarse size materials and outer path contains fine size materials (Baykal and Döven, 2000, Gesoğlu, 2004).

In order to get a different size and efficient production of LWA, it must be set the rotation speed of the disc, angle between normal and disc plane as well as mix moisture content. In this study, the pelletizer diameter has 80 cm and its depth 35 cm, the optimum rotation speed and slope angle for pelletizer are 42 rpm and 45°, respectively.

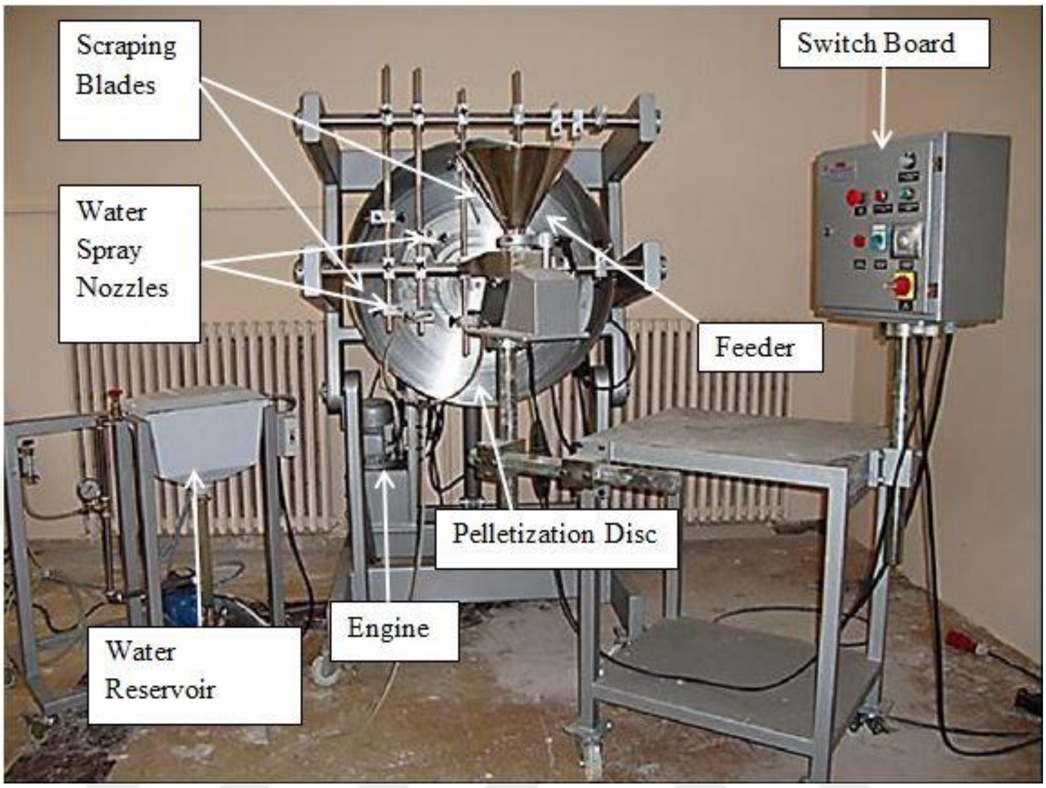


**Figure 3.2** The general view of pelletizer machine

Weight proportions dry mixes of FA and PC by 90 % and 10% respectively, was pelletized in rotating pan. A pelletization total time was completed at about 20 min. During the first 10 min of the process, water was sprayed and acted as a coagulant on the dry powder fly ash-cement. Approximately, the amount of sprayed water added to the mix by weight was 22% of total binder. The residual time used for fresh pellets growing up and stiffening. The last step of pelletization process was agglomerated fresh pellets and put it in plastic bags then closed it, stored and kept in curing room 70% and 20 C° of relative humidity and temperature, respectively ( ke et al., 2009). At the end of curing time, the hardened aggregate were sieved between (4-16) mm and used as a lightweight coarse aggregate in HSC as shown in Figure 3.3.

The water absorption and specific gravity of artificial aggregate can be determined with respect to ASTM C127 (2007). It’s found that water absorption capacity for 30 min and 24 hours were 18.29% and 21.12%, respectively. Specific gravity of LWA was found 1.64 g/cm$^3$. Moreover, crushing strength of LWAs can be determined with accordance to BS 812, part 110, (1990). It’s measured by a dial gage and transformed to the load. Its mean that different size of pellets aggregate between 4-14 mm placed between two parallel plates then loaded diametrically until failure took place by capacity load ring of 28 kN as shown in Figures 3.4 and 3.5. The crushing strength can be calculated by following Equation:

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

Where x, is the distance between loading points Pmax is the fracture load (Yashima et al., 1987; Li et al., 2000; Mangialardi, 2001; cheeseman et al., 2005).

(a) (b)

(c) (d)

**Figure 3.3** Views of a) pellets agglomerate after approximately 20 minutes b) Self-curing process c) Sieving process d) Fly ash lightweight aggregate

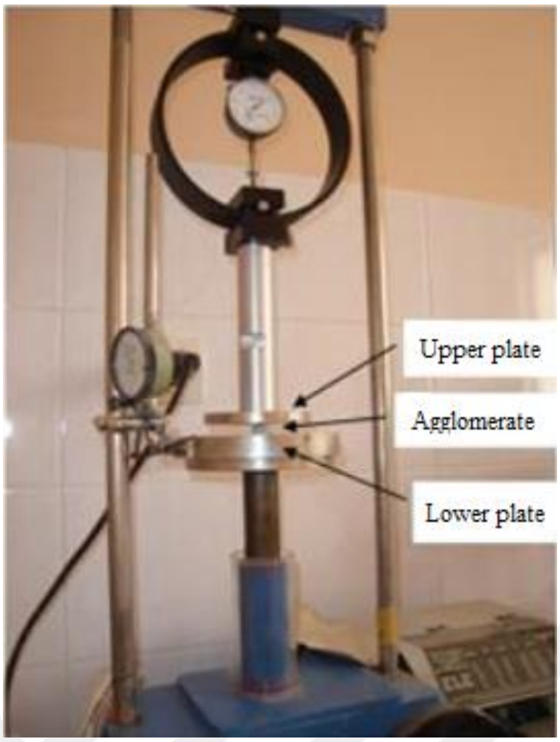


**Figure 3.4** Crushing strength test apparatus

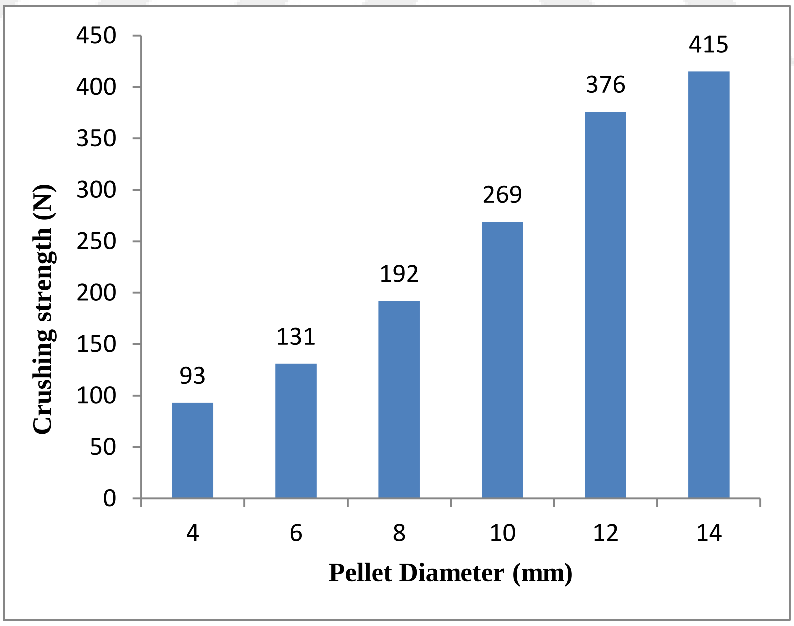


**Figure 3.5** Light weight aggregate crushing strength

#### 3.1.5.2. Normal Weight Aggregate

Natural fine, coarse fine and LWAFA were used together in order to produce the high strength lightweight concrete. Through this study, coarse aggregate were partially replaced by LWAFA to manufacture the specimens. Coarse aggregate of both river gravel and LWAFA were having a normal maximum size of 16 mm. The fine aggregate sand river has a maximum size of 4 mm. The particle size distributions of aggregate are shown in Figure 3.6.

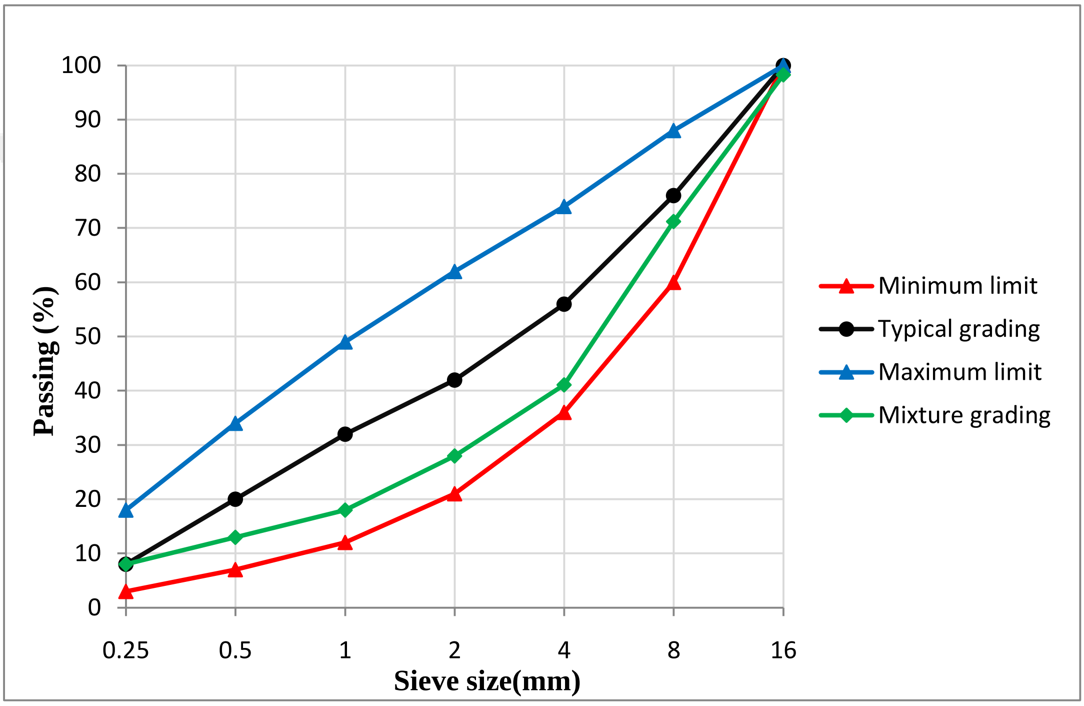


**Figure 3.6** Gradation curve of aggregate

## 3.2. Concrete Mixture Details and Casting

To find the effect of lightweight aggregate FA and nS on gas permeability, durability, and mechanical properties of HSC, 10 concrete mixes were designed with a total binder ratio of 420 kg/m$^3$ and a constant w/b ratio and fly ash of 0.35% and 20%, respectively. There are five different levels of LWA namely (0, 10, 20, 30 and 40%) of total coarse aggregate with and without nano-silica to examine the concrete properties. Mix proportions for 1 m$^3$ concrete are given in Table 3.3. Additionally, the rate of SP was used to provide the needed workability for the designed slump.

All the concrete mixtures were mixed in power-driven revolving pan mixer of 30 liter capacity. A special procedure was followed for batching, mixing and casting of concrete contains lightweight aggregate because of its higher water absorption and to avoid the quick slump loss of the mix. Initially, LWA mixed with cement then coarse and fine aggregate were added to the mixer and let the mix homogeneous after 30 second approximately mixing, then add one third of mixing water to the mix for one minute. Finally, adding of remained mixing water with SP for the 3 minute. The total period of mixing process was 5 minute. Concrete mixtures were designed for a slump test 15±2 cm for easy mixing molding and high strength concrete requires which is found by using superplasticizer. Two identical batches were carried out with same procedure and materials because of not enough mixer capacity for the needed value of the mixture. Each casting specimens were vibrated for a couple of second. The fresh poured concrete specimens wrapped with plastic sheet and kept in casting room for 24 h at 20±2 C°. Afterwards, the specimens demounted and transferred to water tank for curing up to 28 and 90 days.

Specimens casted for each mixture as shown in the following:

- Twelve 150 mm* 150mm * 150 mm cubes for compressive strength test for 3, 7, 28 and 90 days.
- Six 100 * 200 mm cylinders for splitting tensile strength test for 28 and 90 days
- Four 100 * 200 mm cylinders for sorptivity test for 28 and 90 days.
- Two 150 * 300 mm for gas permeability test for 28 and 90 days

**Table 3.3** Mix proportions for 1 m$^3$ concrete (kg/m$^3$)

| Mix ID | w/b | Binder | Cement | Water | FA | NS (%) | NS | SP (%) | SP | Fine agg | Coarse Agg | LWA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mix 1 | 0.35 | 420 | 336.0 | 147.0 | 84 | 0.0 | 0.0 | 1.5 | 6.3 | 942.5 | 932.0 | 0.0 |
| Mix 2 | 0.35 | 420 | 336.0 | 147.0 | 84 | 0.0 | 0.0 | 1.5 | 6.3 | 942.5 | 838.8 | 57.2 |
| Mix 3 | 0.35 | 420 | 336.0 | 147.0 | 84 | 0.0 | 0.0 | 1.5 | 6.3 | 942.5 | 745.6 | 114.5 |
| Mix 4 | 0.35 | 420 | 336.0 | 147.0 | 84 | 0.0 | 0.0 | 1.5 | 6.3 | 942.5 | 652.4 | 171.7 |
| Mix 5 | 0.35 | 420 | 336.0 | 147.0 | 84 | 0.0 | 0.0 | 1.5 | 6.3 | 942.5 | 559.2 | 229.0 |
| Mix 6 | 0.35 | 420 | 323.4 | 147.0 | 84 | 3.0 | 12.6 | 2.2 | 9.2 | 936.4 | 926.0 | 0.0 |
| Mix 7 | 0.35 | 420 | 323.4 | 147.0 | 84 | 3.0 | 12.6 | 2.2 | 9.2 | 936.4 | 833.4 | 56.9 |
| Mix 8 | 0.35 | 420 | 323.4 | 147.0 | 84 | 3.0 | 12.6 | 2.2 | 9.2 | 936.4 | 740.8 | 113.8 |
| Mix 9 | 0.35 | 420 | 323.4 | 147.0 | 84 | 3.0 | 12.6 | 2.2 | 9.2 | 936.4 | 648.2 | 170.6 |
| Mix 10 | 0.35 | 420 | 323.4 | 147.0 | 84 | 3.0 | 12.6 | 2.2 | 9.2 | 936.4 | 555.6 | 227.5 |

*SP: Superplasticizer, LWA: Lightweight aggregate, NS: Nano-Silica

**Figure 3.7** Slump test for LWACs mixtures

**Figure 3.8** Specimens in water curing

## 3.3. Tests for Concrete Mixtures

### 3.3.1. Compressive Strength Test

The compressive strength test was conducted on three cubical samples of 150*150*150 mm for each mix at 3, 7, 28 and 90 days by 3000 kN capacity testing machine as shown in Figure 3.9 according to ASTM C39 (2012). In this method, compressive axial load is applied to concrete cubes under a rate of loading of 4.5 kN/S until the specimen fails after the period of curing time. It's calculated from the maximum load (failure load) divided by cross sectional area that resist the load. The average results of the three samples of the mix at each testing age has been considered.

**Figure 3.9** Compressive strength test machine

### 3.3.2. Splitting tensile strength

Splitting tensile strength has been done on three specimens having Φ150*300 mm with respect to ASTM C 496 (ASTM C496, 2011). The concrete cylinder put in testing machine between its platens with horizontal axis. When the load increased, the failure happen in direct tension in the form of splitting occurs. The acceptance of splitting test bases on stress distribution is reasonable uniformly along the vertical diameter of specimen. During the test, the platens shouldn't be allowed to rotate in perpendicular plane to the axis of the cylinder. Splitting tensile strength can be found for cylinder specimen by using the following Equation:

$$f_{\mathrm{st}} = \frac{2p}{\pi h\, \Phi} \qquad (3.2)$$

Where:$p$, Φ, h are the maximum load, diameter, and length of the cylinder sample, respectively.

### 3.3.3. Water Sorptivity

This test method is also called capillary absorption. Its measures the absorption rate of water by hydraulic cement concrete by measuring the increasing in mass of specimen that result from absorption of water as a function of time with according to ASTM C1585. In this method, three specimens with dimension Φ 100*75 mm cut from Φ 100*200 mm cylinders. At the end of curing time of 28 and 90 days, specimens in first step must be dried in an oven about 100±5C° until they reach a constant mass then allowed to be cool by put them in sealed container at ambient temperature. Only one specimen surface is exposed to water. Afterwards, the specimens' sides were coated with paraffin and recorded its mass to the nearest 0.01 gram. And the test was carried out by placing the specimens on glass rods in a tray containing water and their bottom surface were 5 mm deep in water. The bottom surface allowed free movement of water according to capillary. The specimens were removed from the tray and weighed at a different time to evaluate the mass gain. The test setup was shown in Figure 3.10.

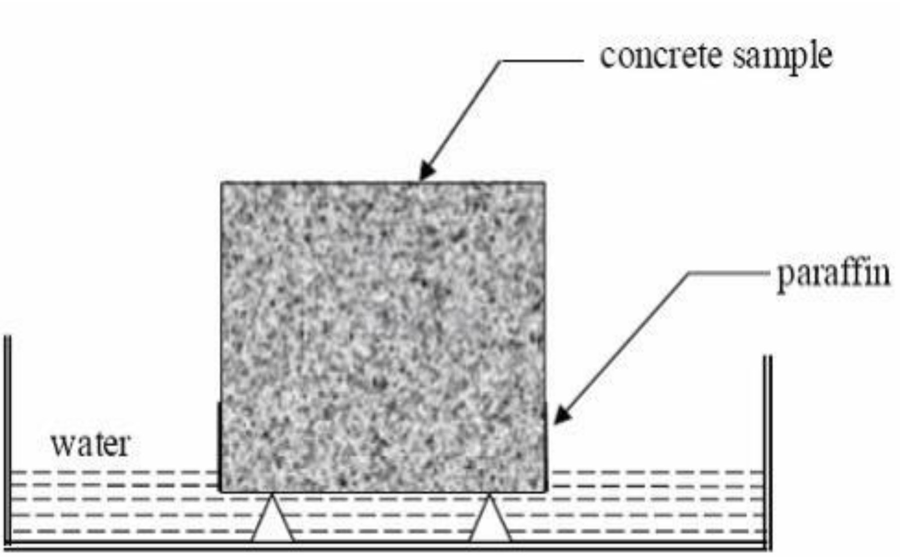


**Figure 3.10** Water sorptivity test set up

### 3.3.4. Gas Permeability

Gas permeability can be investigated for different concrete mixtures by using the CEMBUREAU method A RILEM TC 116 (1999). The gas permeability of concrete mixtures samples was conducted on a concrete disk of 50 mm height and 150 mm diameter cut from mid portion of Φ 150*300 mm cylinder at the end of curing period of 28 and 90 days. The test set up contains photographic view, schematic layout of the apparatus and details of testing cell are shown in Figures 3.11, 3.12 and 3.13, respectively. Two specimens for each concrete mixture were tested at each age and the test results reported the average of them. For gas permeability test, when the curing time was ended, the specimens must be dried at 100 ±5C° in an oven and ensure that each specimen weight change was less than 1%. Then, the specimen was kept in sealed box until the test began. The permeating medium used was Oxygen gas. The specimen applied to differential pressure varying from 150 to 350 KPa can be controlled and sealed by tightly fitting rubber pressuring under high pressure against the curved surface.

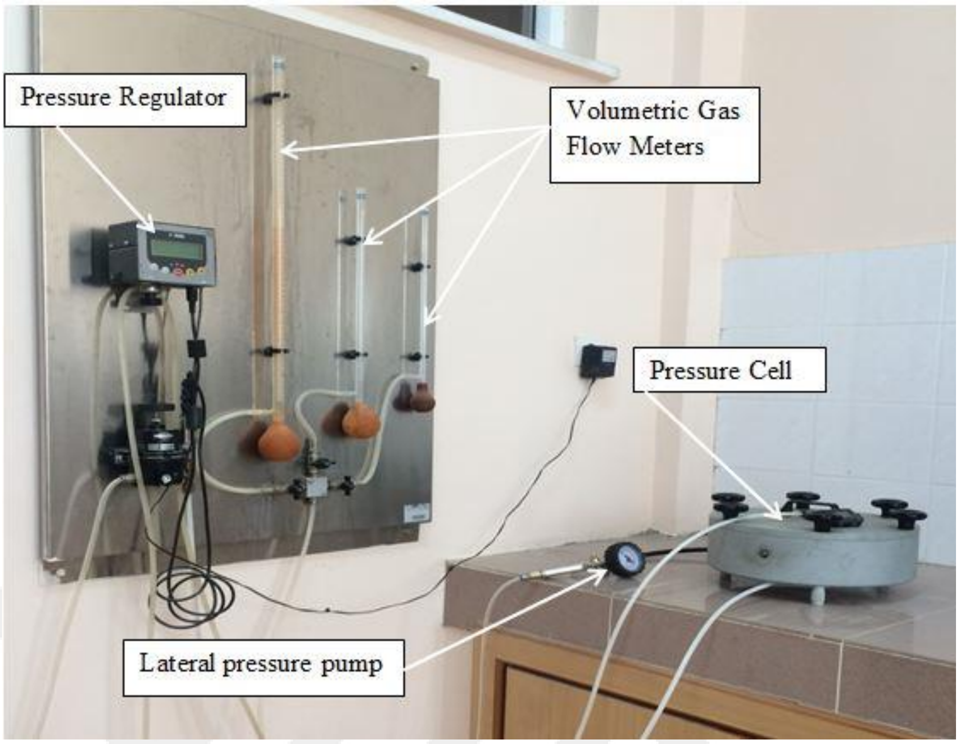


**Figure 3.11** Photographic view of the gas permeability test set up

Hagen-poiseuille relationship is the underlying principle for laminar flow of a compressible gas or fluid through a porous body with small capillaries under steady state condition. To determine the specific permeability coefficient the Hagen-poiseuille relationship can be written:

$$K=\frac{2\,P_2\,QL\eta}{A\,(P_1^2-P_2^2)} \tag{3.3}$$

Where:

K: coefficient of gas permeability

$P_1$: inlet gas pressure (N/m$^2$)

$P_2$: outlet gas pressure (N/m$^2$)

A: cross-section area of the sample ($m^2$)

L: height of sample (m)

Ƞ: oxygen viscosity ($2.02*10^{-5}$ Nsn/$m^2$)

Q: rate flow of air bubble ($m^3$/sn)

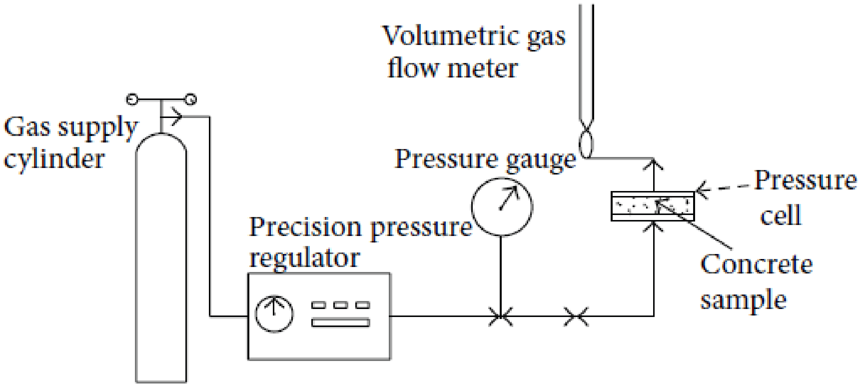


**Figure 3.12** Schematic presentation of gas permeability test set up

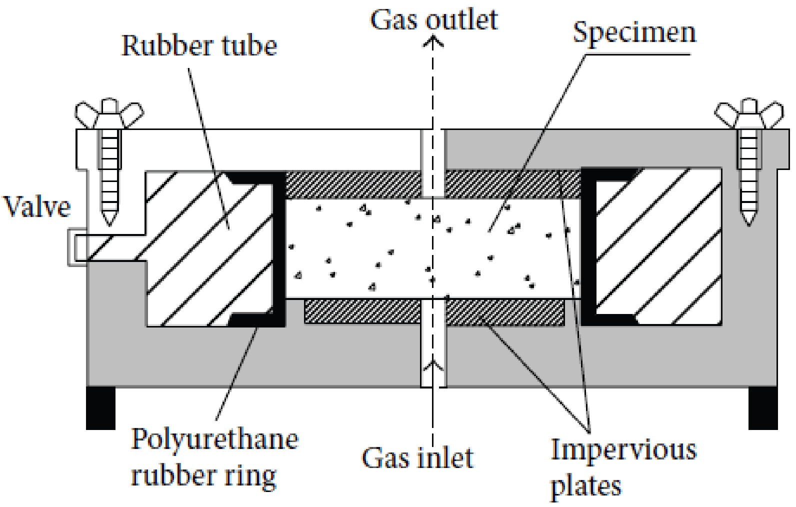


**Figure 3.13** Schematic presentation of the pressure cell and test specimen

# CHAPTER 4

# TEST RESULTS AND DISCUSSION

## 4.1. Compressive strength

The 3,7,28 and 90 days compressive strength for the mixes produced with and without nano-silica and LWA are shown in Table 4.1 and graphically displayed in Figures between 4.3 - 4.6. It’s obvious that the compressive strength values decreased when increased the replacement level of LWA and it’s generally increased with the age of curing. The 28 day compressive strength of mix 1 was 64.08 MPa whereas mix 5 of 54.08 MPA of only aggregate replacement without nS indicating 15.6% strength loss. And 28 day compressive strength of mix 6 was 72.36 MPa whereas the mix 10 of 55.87 MPa of replacement LWA and contain nS indicating 22.8% strength loss compared to the control mixes.

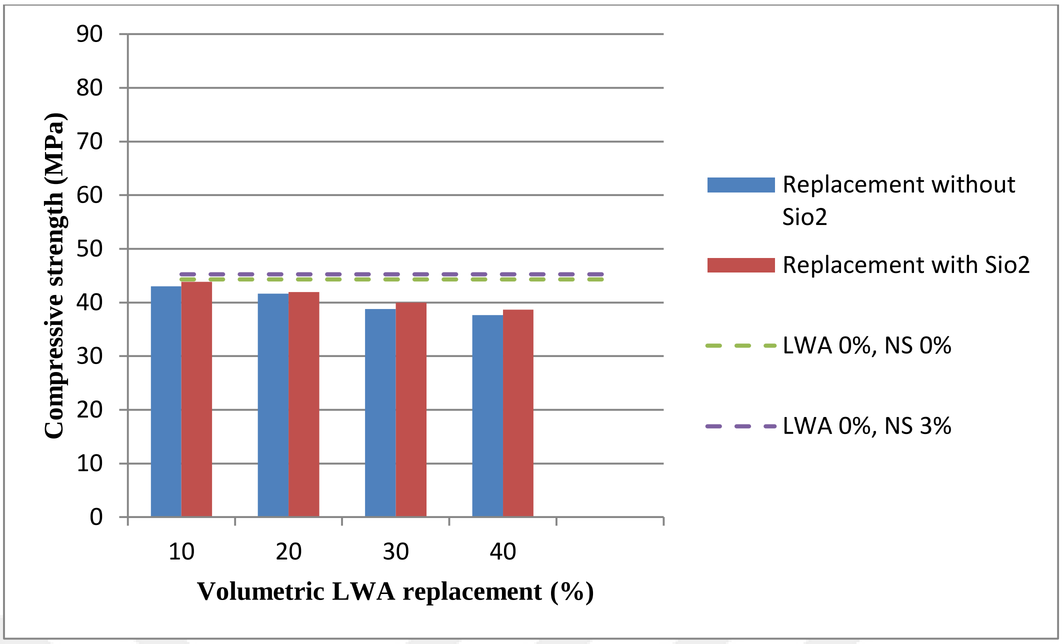
For instance, the 28 days decrease percentage of compressive strength with respect to control mix for mixes without nano particles various from 2.94% to 16% while the group two contains nano particles with same replacement of group 1, the decrease percentage various from 3.90% to 23%. In 90 days of compressive strength of concrete mixes, a similar trend has been seen and the decrease percentage for group 1 various from 9.93% to 22.80% while the group two that contained nano-particles with same replacement of group 1 various from 8.75% to 19% . The gradual decrease in compressive strength appears when replaced the LWA with NWA because of the physical properties of LWA and LWA have a specific gravity less than NWA. Additionally, the LWA have a higher water absorption ratio compared to the NWA. Also, there are unfilled micro voids in mixes increased with increasing LWA, and they acts as a weak zones that happen a lower compressive strength. In other words, NWA has a larger surface area compared to the LWA that leads to lower bonding strength in ITZ around aggregate particles (Khaleel et al., 2011).

When we compared the two groups with the same replacement level of LWA, it can be noticed the effect of nano-particles. The 28 and 90 days results showed that the overall mixes contain 3% nS by weight of cementitious material replacement had a higher compressive strength when compared with that didn’t have with the same level of replacement of LWA. An average increase in compressive strength mixes of nano particles approximately 6.90% when it’s compared to that didn’t have nano particles. The improvement in 28 and 90 days compressive strength of the second group because of reactive of nano particles and consuming the free calcium hydroxide $Ca(OH)_2$ and formation a larger calcium-silicate-hydrate crystals which ultimately led to an improvement of pore structure by filling the capillary pores and paste thickening (Bahadori and Hosseini, 2012). Moreover, the increases in compressive strength in all concrete containing fly ash when incorporation of nano-silica back to an accelerated pozzolanic activity of fly ash earlier than expected and results in additional production of C-S-H compounds (Shih et al., 2006; Mukharjee and Barai, 2014). There is another reason to improve compressive strength when incorporated nano-silica that its particles are smaller in size than cement and fly ash and be able to reduce the size pores in the cement paste. Replacing a portion of cementitious by nano particles has created a more accurate particle size distribution of concrete leads to enhance the concrete pore structure and filled most of the various size voids.

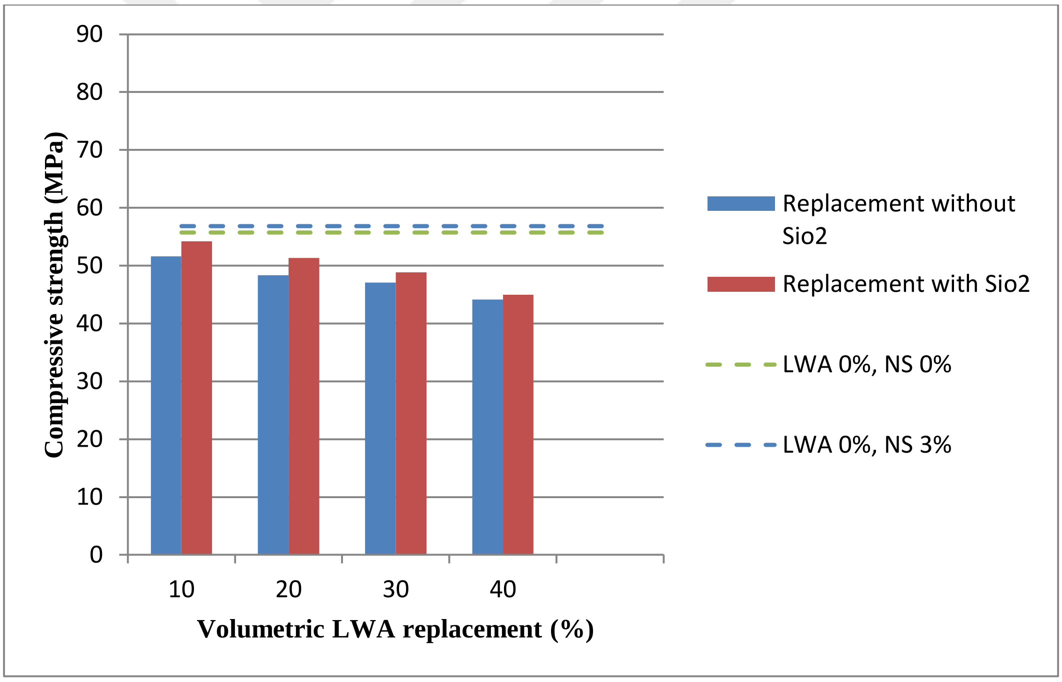
Figure 4.7 and 4.8 shows the shape of failure in compressive strength specimens. It’s obvious in 28 days the perimeter of the specimen only is failed while the core of the specimen is still constant, either in 90 days the perimeter and the core are failed in compressive strength by lateral shearing stresses therefore, they are different from each other because of more hydration process took place through a water curing condition at very long period and curing plays a great role on strength development and durability of concrete. Also, the effect of chemical admixtures such as fly ash, superplasticizer and nano-particles is significantly obvious at very long time. It is observed that the effect of nS on compressive strength values of concrete gives better results than the LWC. In general, the specimens produced a loud noise at instant of failure.

**Table 4.1** Compressive strength of concrete mixes

| Mix Type | Code | Compressive Strength (MPa) | | | |
|---|---|---|---|---|---|
| | | 3 days | 7 days | 28 days | 90 days |
| Group 1 (LWA replacement without Nano-Silica) | MIX 1<br>LWA 0%, NS 0% | 44.313 | 55.729 | 64.088 | 75.253 |
| | MIX 2<br>LWA 10%, NS 0% | 43.016 | 51.620 | 62.207 | 72.314 |
| | MX 3<br>LWA 20%, NS 0% | 41.667 | 48.367 | 57.215 | 68.496 |
| | MIX 4<br>LWA 30%, NS 0% | 38.798 | 47.087 | 56.730 | 64.998 |
| | MIX 5<br>LWA 40%, NS 0% | 37.650 | 44.146 | 54.083 | 62.789 |
| Group 2 (LWA replacement with 3%Nano-Silica ) | MIX 6<br>LWA 0%, NS 3% | 45.282 | 56.813 | 72.366 | 81.209 |
| | MIX 7<br>LWA 10%, NS 3% | 43.859 | 54.216 | 65.173 | 74.108 |
| | MIX 8<br>LWA 20%, NS 3% | 41.970 | 51.302 | 61.166 | 71.014 |
| | MIX 9<br>LWA 30%, NS 3% | 40.001 | 48.853 | 58.893 | 68.924 |
| | MIX 10<br>LWA 40%, NS 3% | 38.678 | 44.995 | 55.876 | 65.901 |

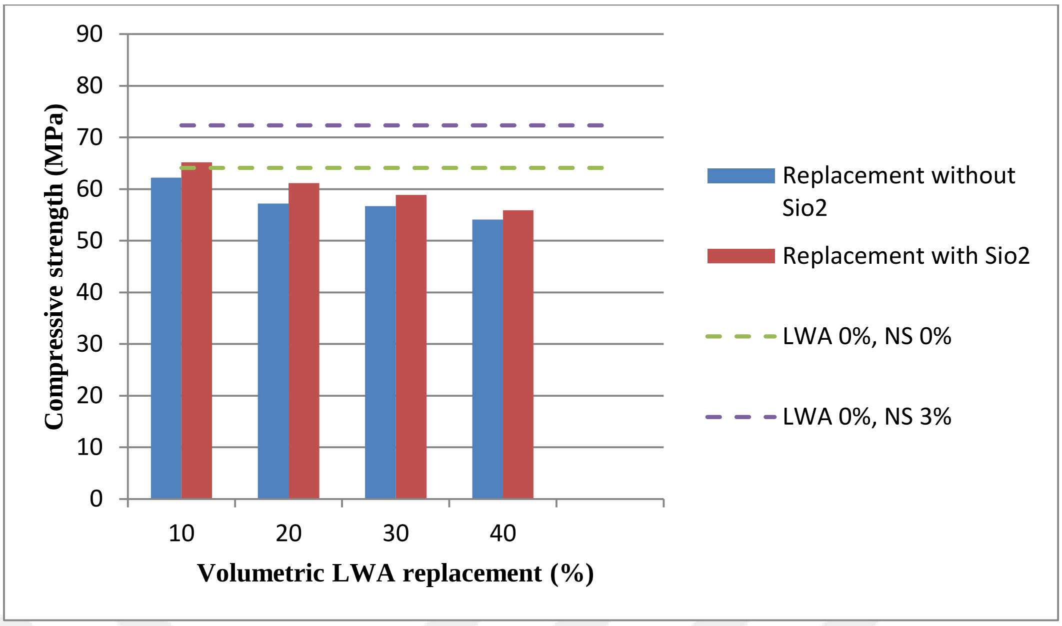


a)

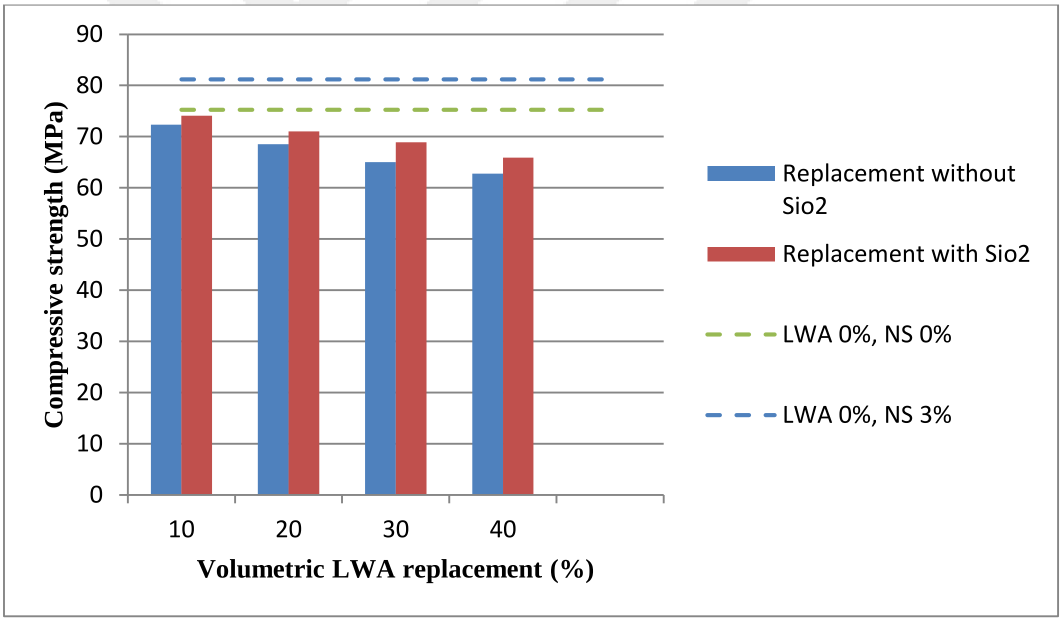


b)

**Figure 4.1** Compressive strengths of concrete mixes at a) 3 days b) 7 days



a)



b)

**Figure 4.2** Compressive strengths of concrete mixes at a) 28 days b) 90 days

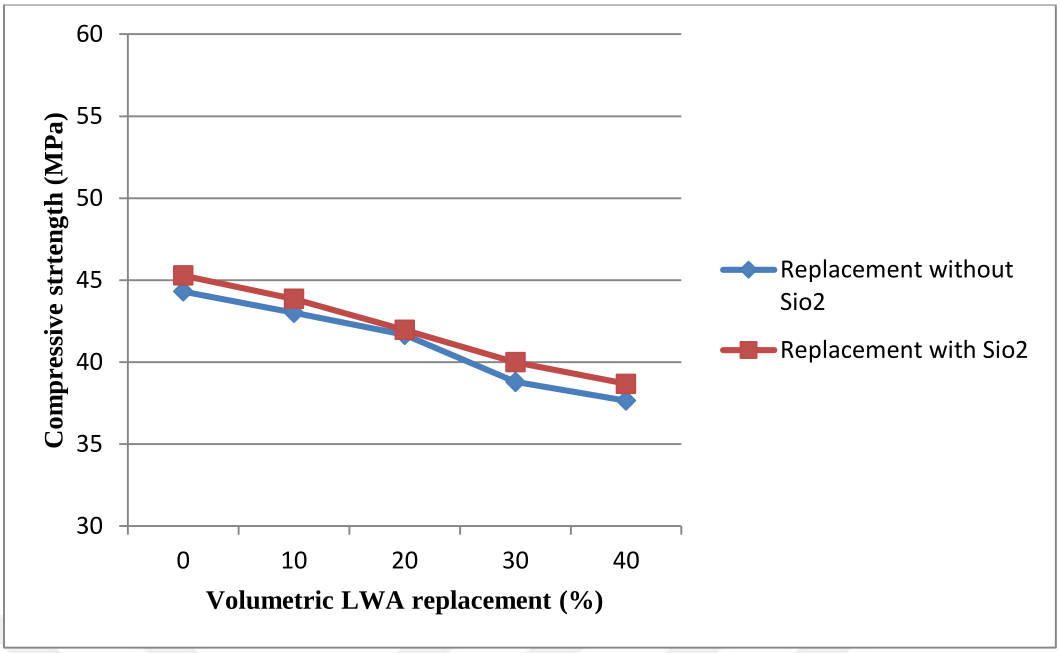


**Figure 4.3** 3-days compressive strength of concrete mixes with respect to LWA volumetric replacement level

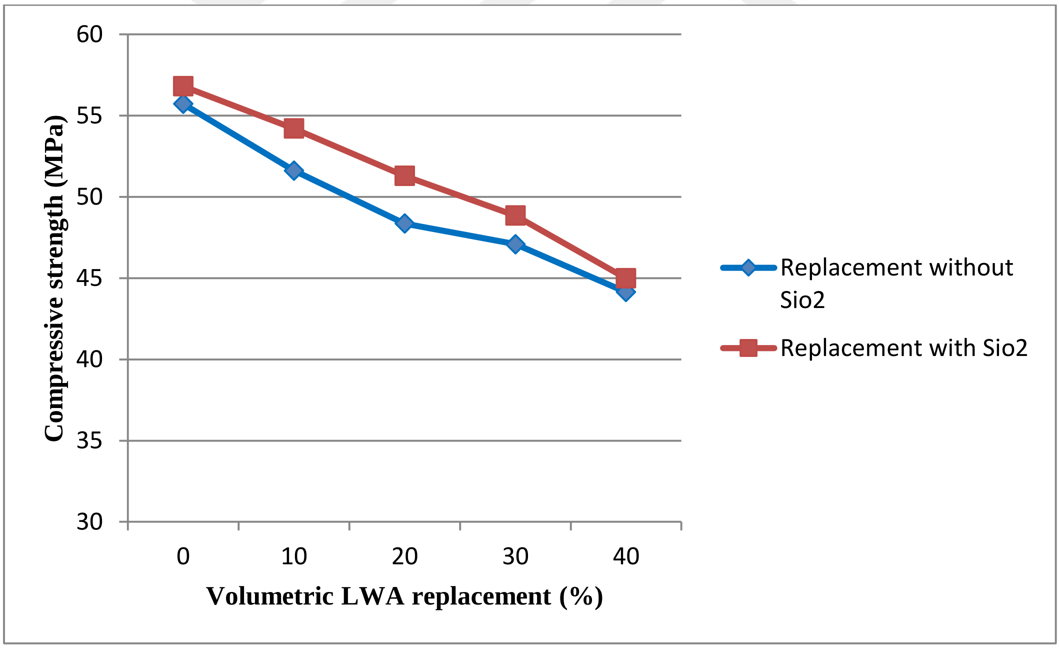


**Figure 4.4** 7-days compressive strength of concrete mixes with respect to LWA volumetric replacement level

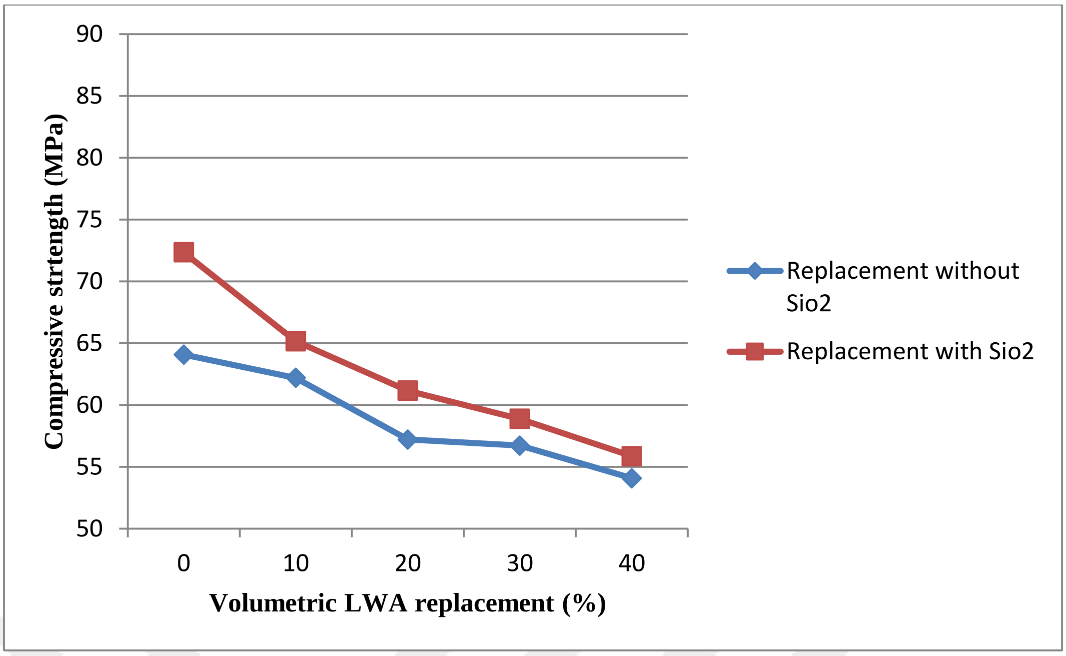


**Figure 4.5** 28-days compressive strength of concrete mixes with respect to LWA volumetric replacement level

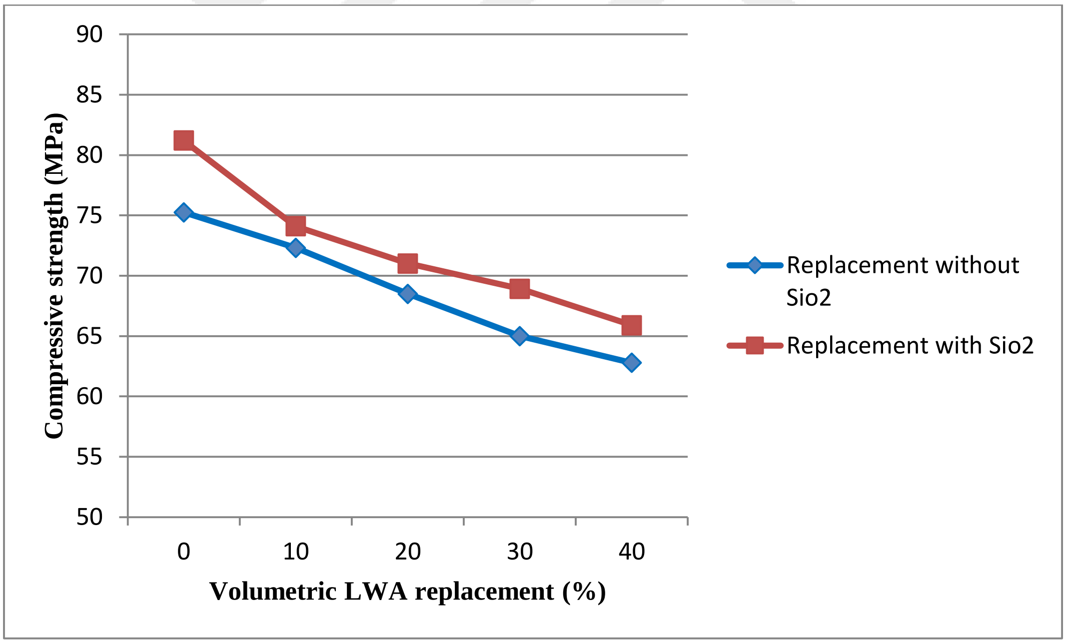


**Figure 4.6** 90-days compressive strength of concrete mixes with respect to LWA volumetric replacement level

**Figure 4.7** Compressive strength type failures at 28 days

**Figure 4.8** Compressive strength type failures at 90 days

## 4.2. Splitting Tensile Strength

The splitting tensile strength at 28 and 90 days for the two group's mixes produced with and without LWA and nano-silica are given in Table 4.2 and graphically presented in Figure 4.9. It was observed that splitting tensile strength of all mixes increased with age regard the replacement level of LWA. In general, the splitting tensile strength decreases with increasing the LWA level in the mixes. For instance, the splitting strength for 28 days for control mix of group one was 4.471 MPa while this value was found 3.925, 3.745, 3.531, and 3.454 MPa and for second group, it's found 4.951MPa while this value was found 4.648, 4.447, 4.393, and 4.017 MPa, respectively.

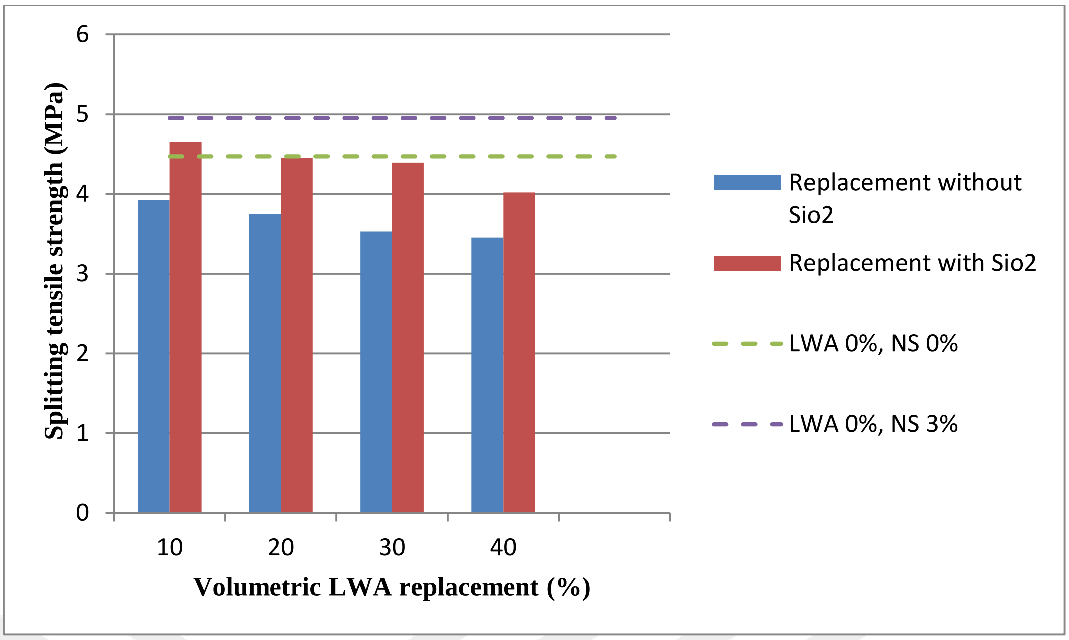
Similarly in 90 days, the tensile strength attitude same 28 days and its reduced with the increased level of LWA. Indeed, the group one mixes had lower strength value by 25.65 %, while the group two was 20.64 % respectively, with comparisons to their control mixes. Similar trends have been showed in tensile strength with substitution level of LWA in both 28 and 90 days. The splitting strength decrease when increases the artificial aggregate. A significant reduction in tensile strength is due to the formation of great moisture gradient in drying attribute to increase the overall water content as a high water absorbent artificial aggregate used in concrete production (Clarke, 1993). The influence of LWAFA on splitting strength of concrete mixes is the same of compressive strength when considering the total variation. Reducing the tensile strength of concrete mixes was due to the fracture path propagating though out grains of LWA leading to shorter fracture path. The initiation and propagation of tensile cracks happen by the weakness of LWAFA due to the unfilled micro-voids offering a lower ultimate tensile strength of concretes.

Concrete is not usually designed to resist tension. But it's necessary to know the tensile behavior to estimate the load under which cracking to be developed. In general, the splitting tensile strength is depended on strength and age of concrete, aggregate type, curing type, w/b ratio, and degree of compaction. The observations showed the fracture surface of samples displayed that crack propagation through aggregate was affected by the strength of concrete. It's found that more concrete grains strength had more probable that cracks spread through the aggregate. Figures 4.10 and 4.11 can verify the results. In high strength concrete, the crack propagates the specimen straightly and the cracks will not show and tendency to travel around the aggregate because the matrix and aggregate stiffness were close to each other. Also, high density of ITZ played a great role in providing basis for this type of failure.

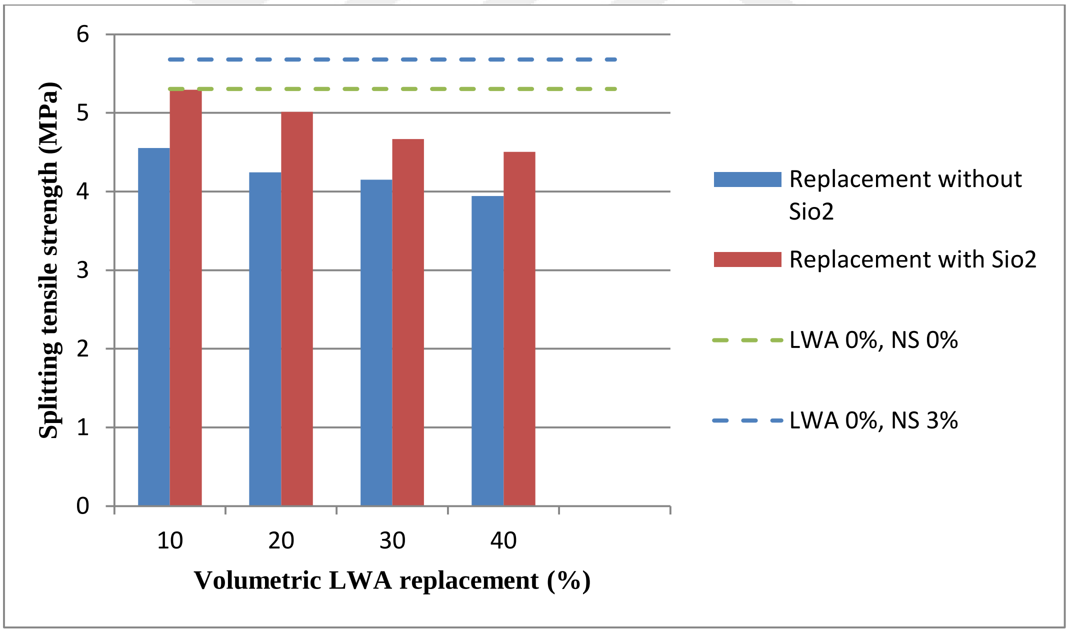
In addition, splitting tensile strength was increased by adding nano-silica to the concrete and it’s evident when comparing between first and second group mixes in 28 and 90 days with neglecting the replacement level of LWA and its attribute similar to the compressive strength by the same reasons that were mentioned in compressive strength. The average increase in splitting tensile strength is approximately 10.74% for control mixes of two groups for 90 days.

**Table 4.2** Splitting tensile strength of concrete mixes

| Mix Type | Code | Splitting Tensile Strength (MPa) | |
|---|---|---|---|
| | | 28 days | 90 days |
| Group 1 (LWA replacement without Nano-Silica) | MIX 1<br>LWA 0%, NS 0% | 4.471 | 5.303 |
| | MIX 2<br>LWA 10%, NS 0% | 3.925 | 4.553 |
| | MX 3<br>LWA 20%, NS 0% | 3.745 | 4.245 |
| | MIX 4<br>LWA 30%, NS 0% | 3.531 | 4.151 |
| | MIX 5<br>LWA 40%, NS 0% | 3.454 | 3.943 |
| Group 2 (LWA replacement with 3%Nano-Silica ) | MIX 6<br>LWA 0%, NS 3% | 4.951 | 5.678 |
| | MIX 7<br>LWA 10%, NS 3% | 4.648 | 5.296 |
| | MIX 8<br>LWA 20%, NS 3% | 4.447 | 5.012 |
| | MIX 9<br>LWA 30%, NS 3% | 4.393 | 4.668 |
| | MIX 10<br>LWA 40%, NS 3% | 4.017 | 4.506 |



a)



b)

**Figure 4.9** Splitting tensile strengths of concrete mixes at a) 28 days b) 90 days

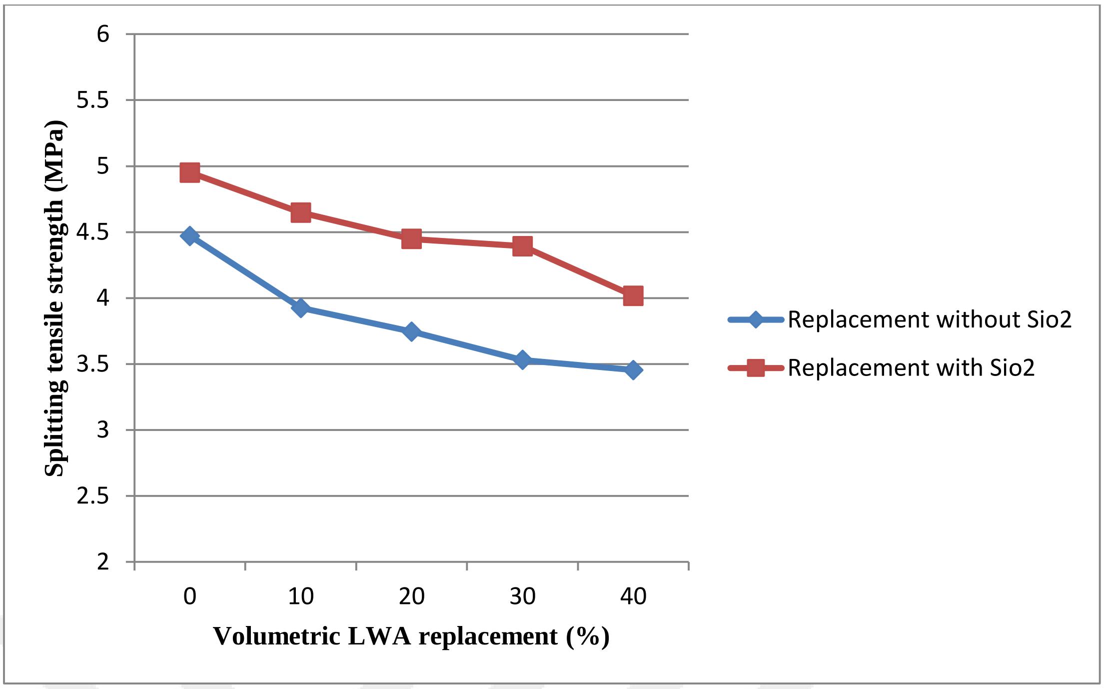


**Figure 4.10** 28-days splitting tensile strength of concrete mixes with respect to LWA volumetric replacement level

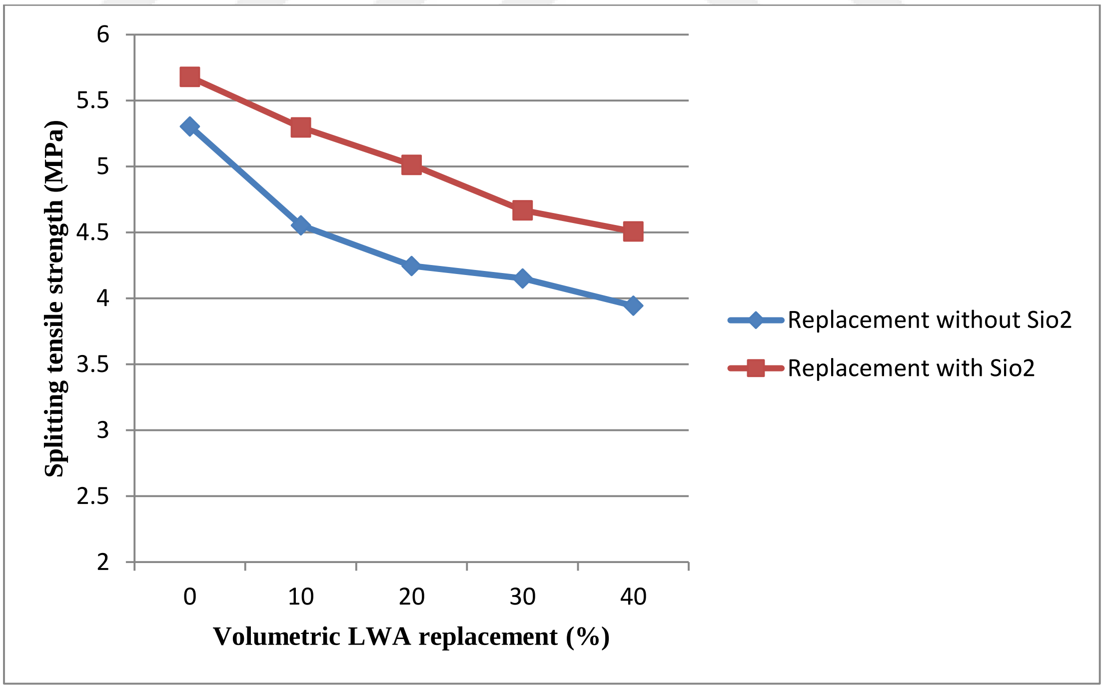


**Figure 4.11** 90-days splitting tensile strength of concrete mixes with respect to LWA volumetric replacement level

## 4.3. Water Sorptivity

The test is based on the increase in mass of concrete specimens by capillary action when only one surface of sample exposed to water with a function of time. Capillary is the transportation of liquid or gases due to surface tension. Many factors influenced this phenomenon depending on concrete mix design like, ratios of concrete mixtures, supplementary cementitious material, and the presence of chemical admixtures, physical properties of cementitious components of aggregate as well as viscosity, density and surface tension of liquid, pore structure and surface energy of concrete (ASTM C 1585). Equation 4.1 is used to calculate the sorptivity value;

$$I=S'\sqrt{t} \tag{4.1}$$

Where $S'$ is sorptivity (mm/min½) and I is cumulative infiltration (mm) at time t (min).

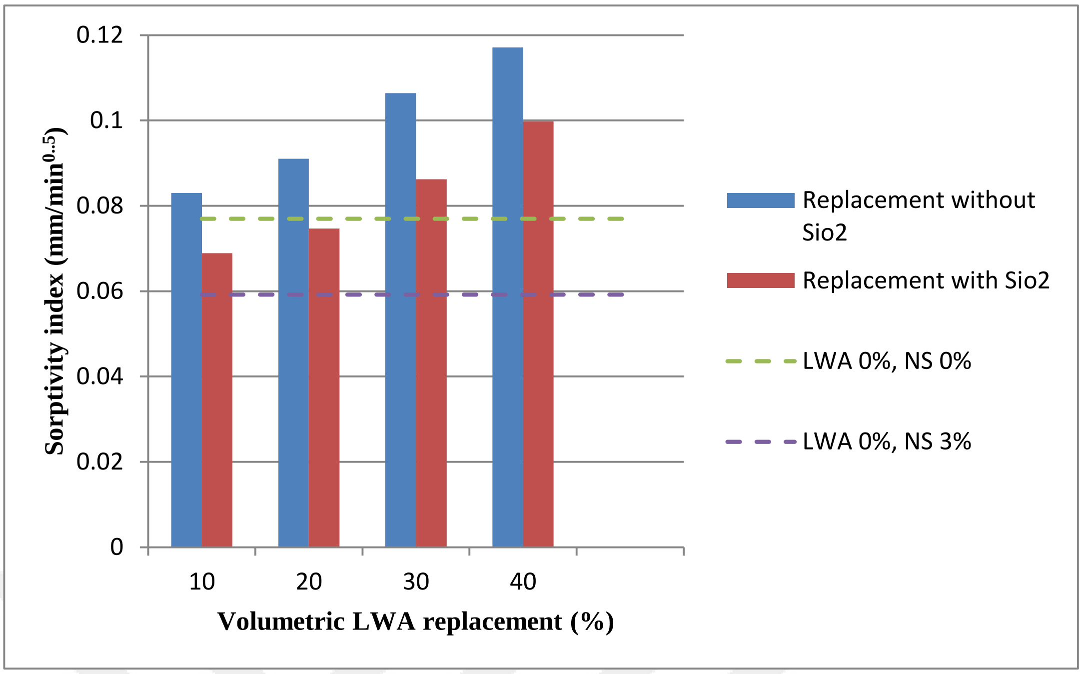
The sorptivity coefficient of 0.077 mm/min $^{0.5}$ and 0.045 mm/min $^{0.5}$ of control mix of group 1 that not contained nano-particles days were increased to 0.1171 mm/min $^{0.5}$ and 0.0783 mm/min $^{0.5}$ at 28 and 90 days respectively, when replaced 40% of natural aggregate with fly ash lightweight aggregate. While the group 2 that contain nano-particles under the same condition, it's evident increase from 0.0592 and 0.037 mm/min $^{0.5}$ to 0.0998 mm/min $^{0.5}$ and 0.0711 mm/min $^{0.5}$ when replacement 40% of natural aggregate by lightweight aggregate fly ash at 28 and 90 days respectively, as showed in Table 4.3. The increasing in sorptivity coefficients of HSC contains LWA means increasing in pore size and total porosity (Liu et al., 2011).

In general, finer pore structure in concrete have greater capillary suction pressures and the sample mass increasing is a mark of absorption water by concrete specimens. The sorptivity coefficient values in 28 and 90 days according to nS and replacement level of LWAs are demonstrated in Table 4.3 and Figures 4.12, 4.13 and 4.14. From Figures, it's obvious that water sorptivity increase with increasing the replacement level of LWA in both ages. The most evident difference between group 1 and group 2 is the effect of nS. Nano-silica is famous to reduce the size of capillary pores and increase the probability of converting the continuous pores in to discontinuous pores. Its explained by the presence of small pores in concrete can be products a large capillary force which control the ingress of fluids. The voids that were originally filled with mixing water and then stayed called capillary pores. The capillary pores are larger than C-S-H gel pores and controlling of transport process. Moreover, the pozzolanic reaction of nS and fly ash contributes in further reduction in water sorptivity of cement paste and makes the capillary porosity disconnected (Ghafari et al., 2014).

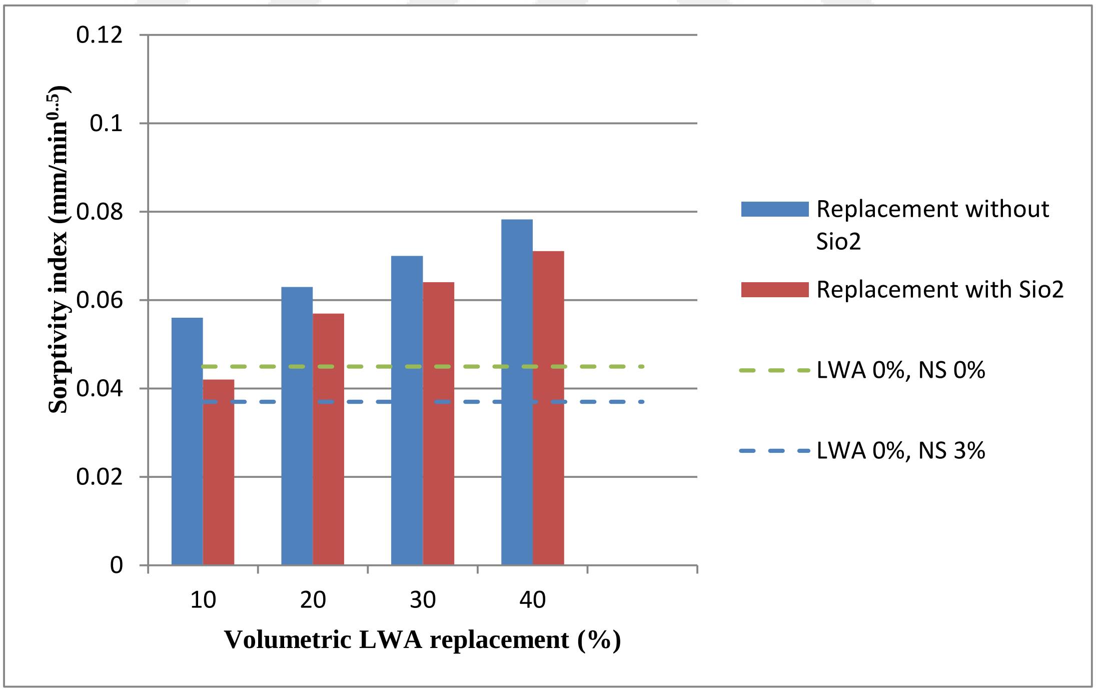
It's obvious from Figure 4.9 that sorptivity index of 90 days are closer each other when compared to 28 day. Because of the dominantly of chemical process that emerged by internal curing effect of LWAFA that increased with larger area. Also, more curing time will be allowed more hydration process take place.

**Table 4.3** Sorptivity values at 28 and 90 days of concrete mixes

| Mix Type | Code | Water Sorptivity (mm/min$^{0.5}$) | |
|---|---|---|---|
| | | 28 days | 90 days |
| Group 1 (LWA replacement without Nano-Silica) | MIX 1<br>LWA 0%, NS 0% | 0.0770 | 0.0450 |
| | MIX 2<br>LWA 10%, NS 0% | 0.0830 | 0.0560 |
| | MX 3<br>LWA 20%, NS 0% | 0.0910 | 0.0630 |
| | MIX 4<br>LWA 30%, NS 0% | 0.1064 | 0.0700 |
| | MIX 5<br>LWA 40%, NS 0% | 0.1171 | 0.0783 |
| Group 2 (LWA replacement with 3%Nano-Silica ) | MIX 6<br>LWA 0%, NS 3% | 0.0592 | 0.0370 |
| | MIX 7<br>LWA 10%, NS 3% | 0.0689 | 0.0420 |
| | MIX 8<br>LWA 20%, NS 3% | 0.0747 | 0.0570 |
| | MIX 9<br>LWA 30%, NS 3% | 0.0862 | 0.0641 |
| | MIX 10<br>LWA 40%, NS 3% | 0.0998 | 0.0711 |



a)



b)

**Figure 4.12** Sorptivity indexes of concrete mixes at a) 28 days b) 90 days

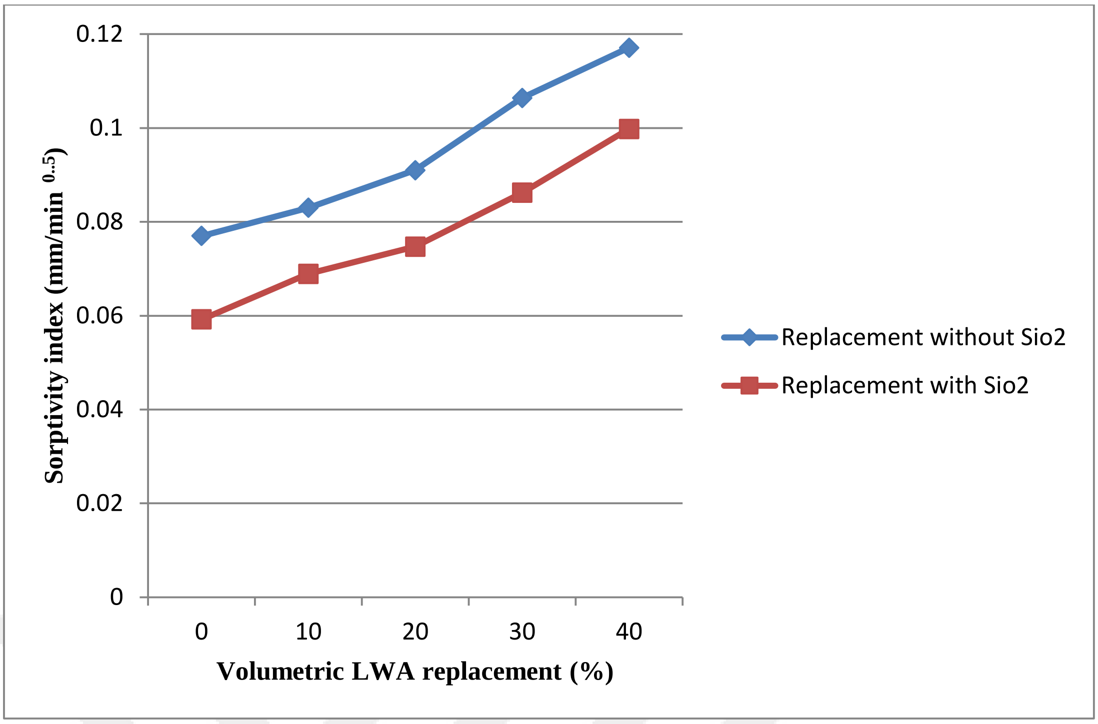


**Figure 4.13** 28-days sorptivity index of concrete mixes with respect to LWA volumetric replacement level

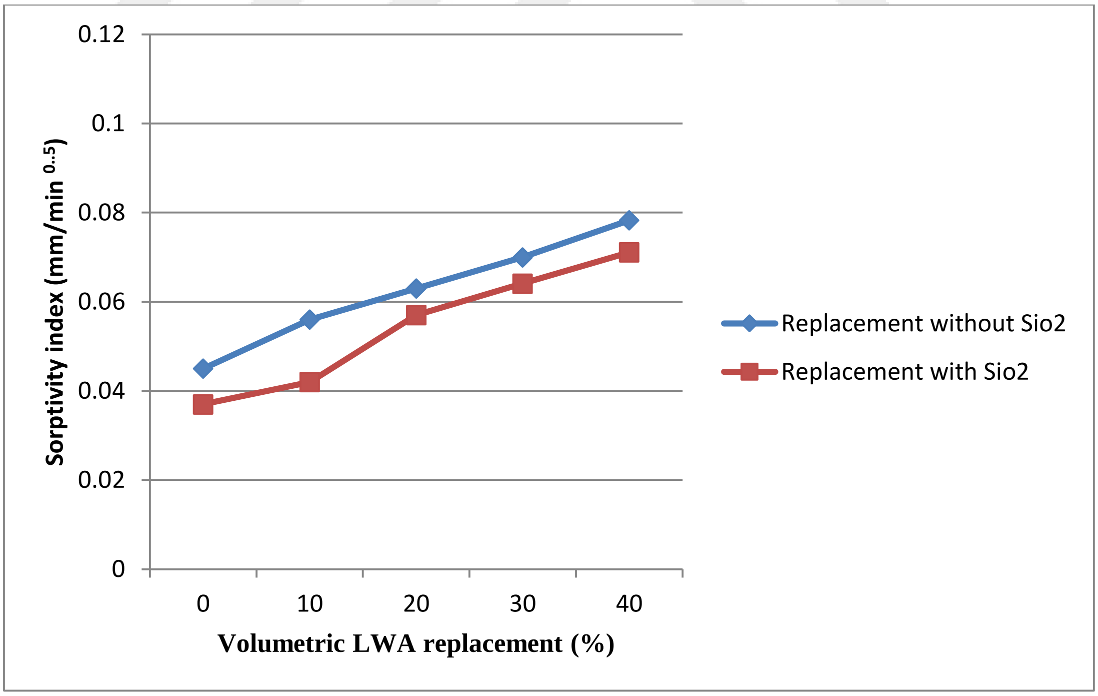


**Figure 4.14** 90-days sorptivity index of concrete mixes with respect to LWA volumetric replacement level

## 4.4. Gas permeability

This test can be considered one of the most important methods to investigate the porous material and characterize pore structure of concrete. The average coffecient of gas permeability is recommended by RILEM (1999) by using the inlet pressure of 150, 200, 250, 300,350 Kpa. Therefore, the gas permeability coefficient of specimens at 28 and 90 days are presented in Table 4.4 and graphically in Figures 4.15, 4.16 and 4.17. Moreover, taking in to account the apparent gas permeability coefficient for the control mixes of the two groups were 2.862x$10^{-16}$ $m^2$ and 1.97x$10^{-16}$ $m^2$ for 28 days and 1.343x$10^{-16}$ $m^2$ and 0.731x$10^{-16}$ $m^2$ for 90 days, respectively as shown in Figure 4.15. It's obvious from the Figure that gas permeability coefficients clearly increase when substation of natural aggregate with LWAFA depending on the replacement level of LWA in both ages. The upper limit of gas permeability coefficients has been found at 28 and 90 days were 4.896x$10^{-16}$ $m^2$ and 4.141x $10^{-16}$ $m^2$. Because of the transport properties of concrete are firmly depending on its pore structure, the raising of gas permeability in concrete can be attributed to increase the pore structure in concrete scheduled to LWA addition. Nevertheless, LWA seemed to be more prone to cause increase in gas permeability coefficient. For instance, the variation of apparent gas permeability coefficients for group 1 mixes were changed between 3.577x$10^{-16}$ $m^2$ -4.896x$10^{-16}$$m^2$ and group 2 changes between 2.47x10-16 $m^2$ -4.289x$10^{-16}$ $m^2$ at 28 days, respectively. However, as seen in figures the values of 90 days of the group 1 change between 1.988x$10^{-16}$ $m^2$ while group 2 changes between 1.344 to 3.101x$10^{-16}$ $m^2$, respectively. This was due to the concrete with low porosity is not fully accessible to gases and the higher porosity gases can penetrate concrete more easily. Moreover, the porous structure of LWAFA has contributed to the permeability of the matrix which leads to high permeability (Van den Heede et al., 2010)

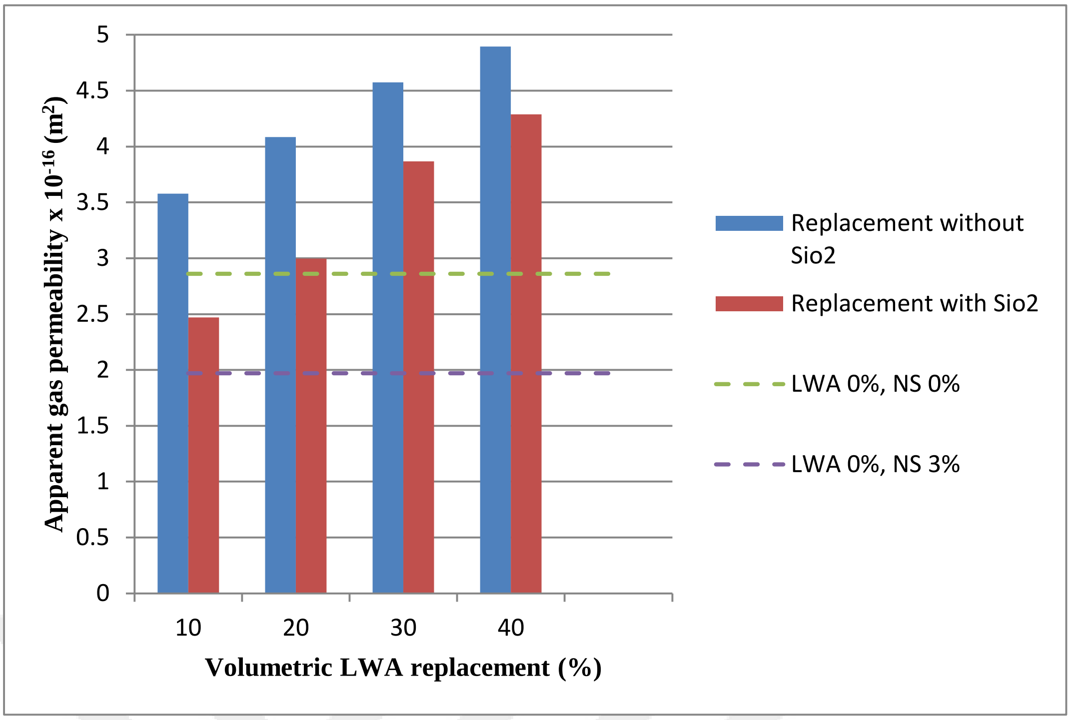
Mixture proportion of concrete, age, existence of chemical additives like silica fume or nano-silica, aggregate types and properties and type of pore structure are mainly factors that the gas depends on (Care & Derkx, 2011).

The results indicates that the use of nS in concrete mixes with LWA are increasing the efficiency of LWA concrete mixes because of the refinement of the pore structure of concrete and it was the key issue to improve the characteristics of concrete.

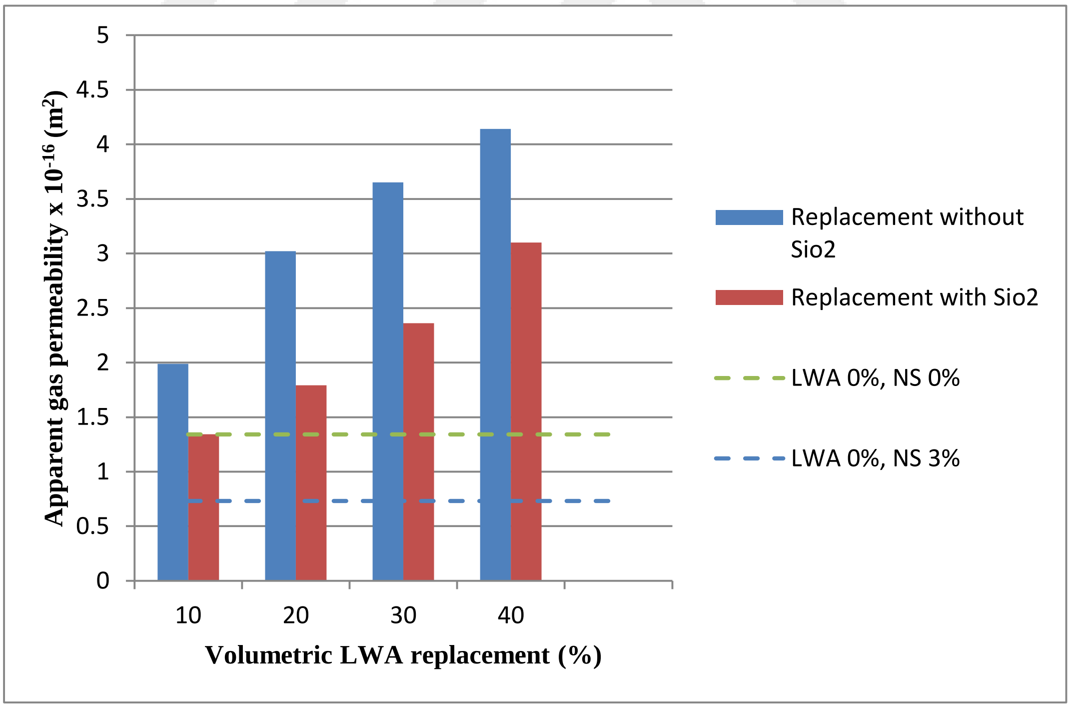
Actually, the term of durability are directly related with concrete porous structure, since the capillary pores are in charge of fluids migration in the concrete matrix. Continuous capillary pores will be decrease because of the pozzolanic reaction owning to reduction in $Ca(OH)_2$ content in the hydrated matrix. Therefore, when the value of capillary pore decreases that mean significantly enhance the resistance to the aggressive environment. Hydration process reaction between water and cement produced calcium silicate hydrate as a hexagonal crystal and they were arranged in ITZ between aggregate and binding paste matrix. As we know, nano-particles have enormous specific surface area that gives their particles the activity to react with calcium hydroxide crystals very quickly and produced C-S-H gel filled the voids to enhance the density of ITZ and the binding paste matrix (Moradi, 2014).

**Table 4.4** Apparent gas permeability coefficient of concrete mixes

| Mix Type | Code | Apparent gas permeability coefficient (x $10^{-16}$ $m^2$) | |
|---|---|---|---|
| | | 28 days | 90 days |
| Group 1 (LWA replacement without Nano-Silica) | MIX 1<br>LWA 0%, NS 0% | 2.862 | 1.343 |
| | MIX 2<br>LWA 10%, NS 0% | 3.577 | 1.988 |
| | MX 3<br>LWA 20%, NS 0% | 4.084 | 3.021 |
| | MIX 4<br>LWA 30%, NS 0% | 4.574 | 3.651 |
| | MIX 5<br>LWA 40%, NS 0% | 4.896 | 4.141 |
| Group 2 (LWA replacement with 3%Nano-Silica ) | MIX 6<br>LWA 0%, NS 3% | 1.790 | 0.731 |
| | MIX 7<br>LWA 10%, NS 3% | 2.470 | 1.344 |
| | MIX 8<br>LWA 20%, NS 3% | 2.998 | 1.793 |
| | MIX 9<br>LWA 30%, NS 3% | 3.868 | 2.361 |
| | MIX 10<br>LWA 40%, NS 3% | 4.289 | 3.101 |



a)



b)

**Figure 4.15** Variation of apparent gas permeability coefficients of concrete mixes at a) 28 days b) 90 days

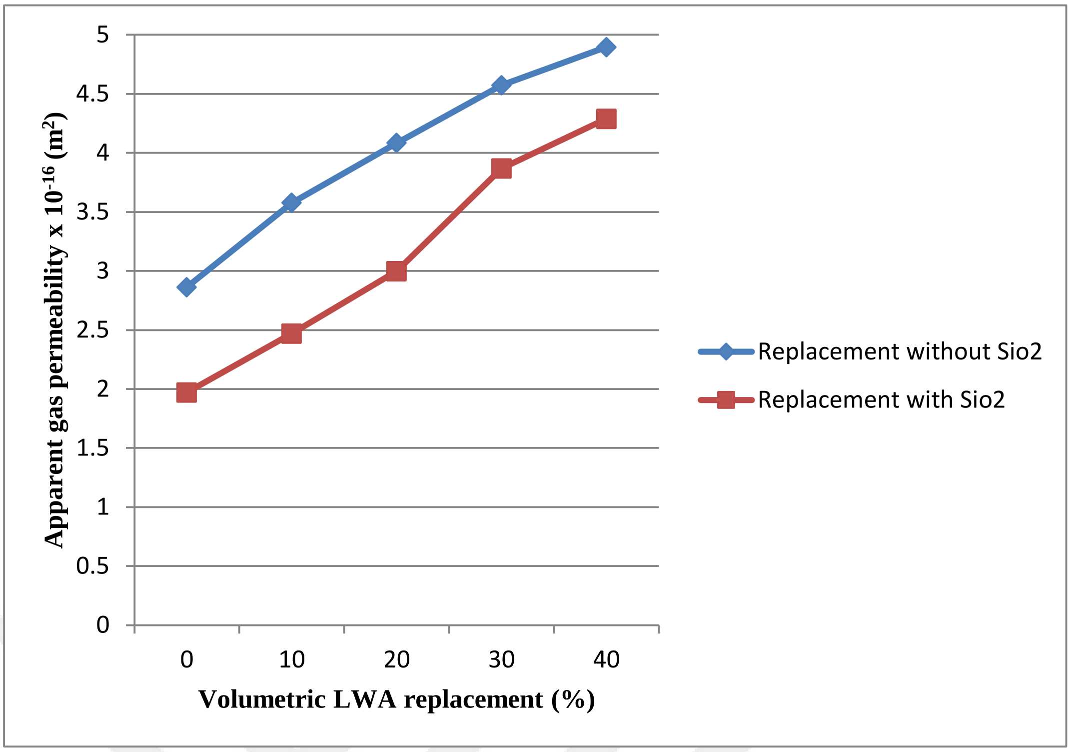


**Figure 4.16** 28-days variation of apparent gas permeability coefficients of concrete mixes with respect to LWA volumetric replacement level

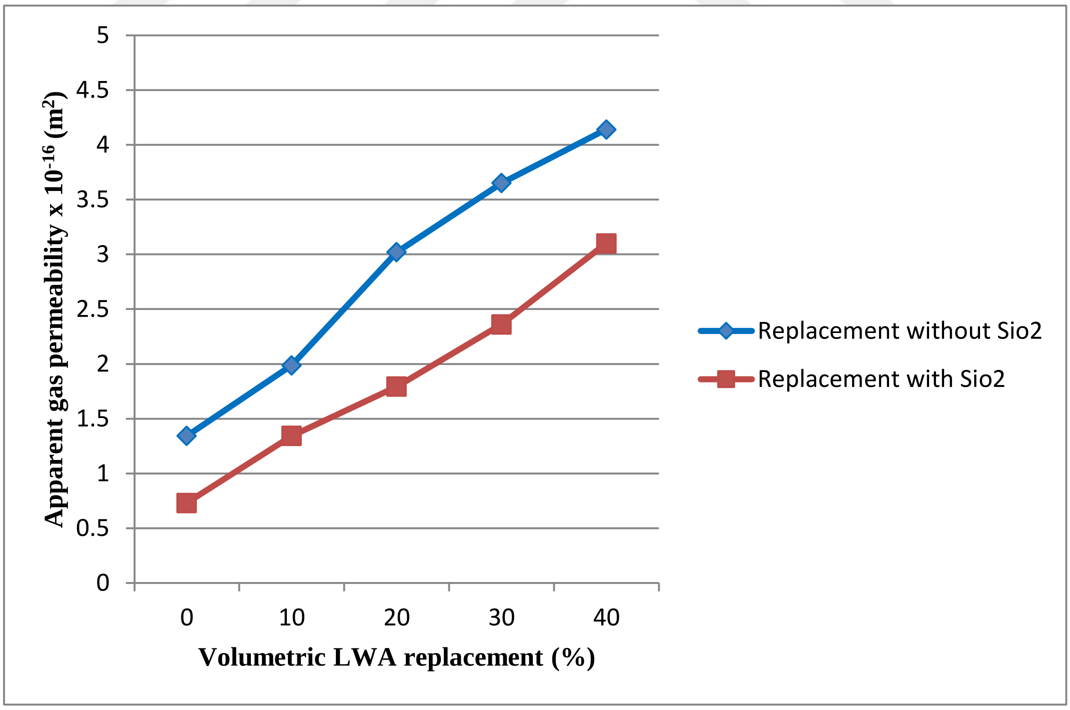


**Figure 4.17** 90-days variation of apparent gas permeability coefficients of concrete mixes with respect to LWA volumetric replacement level

# CHAPTER 5

# CONCLUSIONS

The main findings and conclusions of this experimental study are presented below.

- All the HSLCs mixtures were designed to give a slump of 15±2 cm. which was attained by changing the dosage of superplasticizer used for trial batches. The amount of HRWRA was increased with incorporation of 3% nS in order to stay in the limit of the aimed slump, because nS has a higher surface area and smaller particle size.

- There is a considerable decrease in compressive strength values depending on the replacement level of LWA. The compressive strength of 28 days for control mixes of the two groups were 64.088 MPa and 72.366 Mpa while when the replacement level was 40% it was 54.083 MPa and 55.876 MPa for the two groups , respectively. It's obvious that nS affects the compressive strength and enhances it by increasing strength percentage 18.6% and 29.51% due it smaller and finer particle size than cement particles; hence, they acted as a filler injection to fill the spaces between cement grains. This higher fine increased the rate of silica hydrated and thus accelerated strength development. For this reason explained the higher strength for the same replacement level of LWA.

- As a result of strength limitations of LWA, HSC including LWA had a lower splitting strength than the control mixes. The splitting tensile strength values changes between 4.951 MPa and 3.454 Mpa were achieved in this study for 28 days, and the tensile strength exhibited showed an identical pattern with the compressive strength.

- HSCs incorporating LWA revealed a systematic increase in sorptivity index values with increasing the replace amount of LWA at both ages. The sorptivity coefficients were measured ranging between 0.0592 mm/mm$^{0.5}$ to 0.1171 mm/mm$^{0.5}$ at 28 days. The sorptivity coefficient of concrete mixes that contain nS is better than other mixes didn't include the same replacement of LWA.

- The results indicated that the gas permeability increased with increase the replacement level of LWA. The limits of gas permeability of the group one was 4.895x10$^{-16}$ m$^2$ to 2.862x10$^{-16}$ m$^2$ respectively, at 28 days because the LWFA has a poor transport properties especially in terms of permeability. But the effect of nano-particles was obvious at the same replacement level of LWA. For group two, the limits of gas permeability was 4.289x10$^{-16}$ m$^2$ and 1.790x10$^{-16}$ m$^2$ for reason that nano-particles served in two levels in concrete. The first was chemical effect that the pozzolanic reaction of free $Ca(OH)_2$ formed more C-S-H get in the final stages and divide the larger pores to smaller pores. The second contribution due to the physical effect that nano-particles are smaller than the cement particles and they able to fill the micro-voids and improve the density of ITZ that leading to enhance in permeability properties and durability for aggressive environments.
- The investigation might be consider as a friendly research since it will truly treat a part of environment issues by utilizing disposal material like fly ash powder through a simple procedure which consumes a minimum energy as well as saving resources, decrease hazardous of waste effect, get better performance of construction industries in structural engineering and improving the rational use of lands.

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