UNIVERSITY OF GAZİANTEP
GRADUATE SCHOOL OF
NATURAL & APPLIED SCIENCES

USE OF COLD-BONDED BLAST FURNACE SLAG AGGREGATE IN THE PRODUCTION OF SELF COMPACTING CONCRETES

M. Sc. THESIS
IN
CIVIL ENGINEERING

BY
SWARA FUAD MAHMOOD
JULY 2012

Use of cold-bonded blast furnace slag aggregate in the production of self compacting concretes

M.Sc. Thesis
in
Civil Engineering
University of Gaziantep

Supervisor
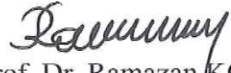**Assoc. Prof. Dr. Mehmet Gesoğlu**

by
Swara Fuad Mahmood
July 2012

T.C.
UNIVERSITY OF GAZİANTEP
GRADUATE SCHOOL OF
NATURAL & APPLIED SCIENCES
CIVIL ENGINEERING DEPARTMENT

Name of the thesis: Use of cold-bonded blast furnace slag aggregate in the production of self compacting concretes

Name of the student: Swara Fuad MAHMOOD
Exam date: 3-July-2012

Approval of the Graduate School of Natural and Applied Sciences

Prof. Dr. Ramazan KOÇ
Director

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

Prof. Dr. Mustafa GÜNAL
Head of Department

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

Assoc. Prof. Dr. Mehmet GESOĞLU
Supervisor

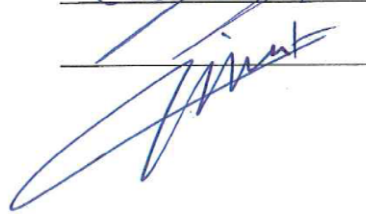Examining Committee Members   Signature

Assoc.Prof.Dr. Mehmet GESOĞLU

Assoc.Prof.Dr. ErhanGÜNEYİSİ

Asst.Prof.Dr. Nihat ATMACA

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Swara Fuad MAHMOOD

ABSTRACT

Use of Cold-Bonded Blast Furnace Slag Aggregate in the Production of Self-Compacting Concretes

Swara Fuad Mahmood

M.Sc. in Civil Engineering

Supervisor: Associated. Prof. Dr. MEHMET GESOĞLU

July 2012, 85 pages

This study addresses an experimental program carried out to investigate the properties of self-compacting concretes (SCCs) in which natural coarse aggregates had been substituted by artificial slag aggregates (ASA). For this, a powder mixture of 90% ground granulated blast furnace slag and 10% portland cement by weight were pelletized in a tilted pan through cold-bonded agglomeration process. The hardened ASA were tested for specific gravity, water absorption, and crushing strength. Thereafter, they were partially used in producing SCCs in which ASA replaced the natural coarse aggregates in the volume fractions of 0%, 20%,40%,60%,80%, and 100%. Therefore, a total of six mixes with a water/binder ratio of 0.32 were designed and cast using both natural and/or ASA coarse aggregates.Fresh properties of SCCs were observed through slump flow time, flow diameter, V-funnel flow time, and L-Box filling height ratio.Hardened properties of SCCs were measured at 28 and 56 days for compressive strength, splitting tensile strength, chloride ion permeability, gas permeability, andsorptivity. Test results indicated that utilizing of ASA enhance the fresh properties of SCCs, also reduce the amount of superplasticizerto achieve a constant slump flow diameter. Moreover, SCCs incorporating ASA displayed better performance than the control mixture in terms of compressive strength, chloride ion penetration, gas permeability, and sorptivity,only the splitting tensile strength had slightly decreasing tendency.

Keywords: Artificial aggregate,cold bonding process,ground granulated blast furnace slag, self compacting concrete, transport properties.

ÖZ

Soğuk Bağlama Yöntemiyle Üretilmiş Yüksek Fırın Curufu Agregalarının Kendiliğinden Yerleşen Beton Üretiminde Kullanılması

Swara Fuad Mahmood
İnşaat Mühendisliği Yüksek Lisans
Danışman: Doç. Dr. MEHMET GESOĞLU
Temmuz 2012, 85 sayfa

Bu çalışmada, yapay curuf agregaların (YCA) kısmi olarak doğal iri agregaların yerine kullanılmasıyla üretilen kendiliğinden yerleşen betonların (KYB) özellikleri incelenmiştir. Bunun için, ağırlıkça %90 granüle yüksek fırın curufu ve %10 çimento içeren toz karışım eğik tamburlu peletleme cihazında işlenerek soğuk bağlama yöntemiyle yapay agregalar üretilmiştir. Daha sonra üretilen YCA'lar sertleştikten sonra su emme, özgül ağırlık ve kırılma dayanımı testlerine tabi tutulmuşlardır. Bu agregalar 0%, 20%, 40%, 60%, 80%, ve 100% oranlarında doğal iri agrega ile yer değiştirilerek KYB üretiminde kullanılmışlardır. Dolayısıyla, doğal ve yapay agregalar kullanılarak 0.32 su/bağlayıcı (s/b) oranına sahip toplam altı adet KYB karışımı tasarlanmıştır. KYB'lerin taze özellikleri yayılma çapı, yayılma süresi, V-hunisi akış süresi ve L-kutusu yükseklik oranı bakımından incelenmiştir. KYB'lerin sertleşmiş özellikleri ise 28 ve 56 günlük kür süreleri sonunda basınç dayanımı, yarma dayanımı, klorür iyonu geçirimliliği, gaz geçirimliliği ve kılcal su emme deneyleri ile belirlenmiştir. Deney sonuçlarına göre YCA, KYB'lerin taze özelliklerini iyileştirmesinin yanı sıra sabit yayılma çapı elde etmek için kullanılan kimyasal katkı ihtiyacını da azaltmıştır. YCA içeren KYB'lerin basınç dayanımı, klorür iyon geçirimliliği, gaz geçirimliliği ve kılcal su geçirimliliği gibi özellikler bakımından kontrol betonuna göre daha iyi performans gösterdiği görülmüştür.Ancak, yarmada çekme dayanımı özelliğinde hafif azalan eğilim gözlenmiştir.

Anahtar Kelimeler: Yapay agrega, soğuk bağlama işlemi, öğütülmüş granüle yüksek fırın cürufu, kendiliğinden yerleşen beton, geçirimlilik özelliği.

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

ACKNOWLEDGEMENTS

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS/ ABREVIATIONS

SCC   Self-compacting concrete

GGBFS   Ground granulated blast-furnace slag

FA   Fly ash

W/C   Water/cement ratio

W/B   Water/binder ratio

ASA   Artificial slag aggregate

PC   Ordinary portland cement

VMA   Viscosity modifying admixtures

RCPT   Rapid chloride permeability test

HPC   High performance concrete

SCHPC   Self-compacting high performance concrete

K_a Gas permeability

HRWRA   High rang water reducer admixture

EFNARC   European Federation for Specialist Construction Chemicals and Concrete

AC   Acrylic copolymers

PCE   Poly-carboxylate-ethers

SMF   Sulfonated melamine formaldehyde

SNF	Sulfonated naphthalene formaldehyde
ITZ	Interfacial transition zone
ACI	American concrete institute
ASTM	American standard for testing materials
AASHTO	American Association of State Highway and Transportation Officials

CHAPTER 1
INTRODUCTION

1.1 General

Self compacting concrete (SCC) is considerably a new technology in concrete that was developed in the last two decades. The technology was first realized in 1986 by Japanese investigators to improve concrete durability by increasing concrete workability and thus by enlarging the quality of construction [1]. SCC is an advanced type of highly flowable, non-segregating concrete appropriate for placing in over reinforced structures without vibration. Employ of SCCs can also lend a hand to minimize hearing-related damages on the worksite that are induced by vibration of concrete. One more benefit of SCCs is that the time necessary to place large sections is noticeably reduced. Such concrete should have quite low yield value to make sure high-flow ability, a medium viscosity to withstand segregation and bleeding, and must keep its uniformity through transportation, placing and curing to certify sufficient structural performance and long-term durability [2-4]. For SCCs, in order to achieve high mobility its commonly necessary to use superplasticizer. Adding a large volume of portland cement (PC) or viscosity modifying admixture (VMA) in order to eliminate segregation [5,6]. Usages of high volume of PC and chemical admixtures increased the cost of SCCs remarkably[7-10]. However, using mineral admixtures such as blast furnace slag, fly ash and/or limestone filler, etc, could decreasematerial cost of SCC and also enhanced concrete's fresh and hardened properties [11,12].

The perception has been developed for this research study after following all the general purpose of testing new sustainable production processes, as these involved by the SCCs, in the construction field, in order not only to save natural raw materials and reducing energy consumption, but also to recycle industrial by-products. Blast furnaces represent the main steel-making processes used in the iron metallurgy, approximately 600000 tones of grand granulated blast furnace slag (GGBFS) is generated annually in turkey by steelmaking processes [13]. Although, theutilizedGGBFS in the construction industry and other various purposes is small amount.

Since aggregates affect the mechanical and durability performance of SCCs asoccupying 60%of SCC volume, aggregates have an essential effect on SCCcharacteristic properties [14]. The creation of artificial aggregates is a suitable step to greatly increase this by-product use. Especially, through the manufacturing of aggregate by the process, namely, cold bonding and sintering.

By producing artificial aggregate, the natural and/or scarce materials of aggregates can be conserved and damaging activities of natural aggregate mining can be prevented by using artificial aggregates in the place of natural aggregates [15]. For this purpose, There area considerable numberof studies have been reported in the literature focusing on the artificial lightweight aggregates made with fly ash [16-19].

However, using of GGBFS has not found adequate attention in manufacturing artificial aggregates. Mayfield and Louati carried out an investigation on the use of pelletized blast furnace slag as a lightweight aggregate in structural concrete [20].Cold bonding or pelletization is one of the used ways to produce artificial aggregates. This process required minimum energy consumption for making pellets

having spherical shape of powder material. Generally these aggregates are produced by pelletizing a mineral powder through a rotating finned drum with controlled amount of water [21-24]. Gesoğlu et al produced artificial slag aggregates through cold bonding process by using water as a coagulant [25]. The overall studies conducted by various researches showed that the aggregate produced artificiallycould change the properties of concrete [26]. It is found in the study of Wu et al. that fresh SCCwith lightweight aggregate have good filling ability, fluidity, deformability,minimum resistance to segregation and uniform aggregate distribution [27]. The study of Wang showed that the SCCs made with artificial aggregate with a lesser water/binder ratio had poorer chloride diffusion, less weight loss and smaller number of cracks [28]. However, there is a lack of information in the literature on the properties of self compacting concretes incorporating cold-bonded slag aggregates. Therefore the characteristic properties of concrete must be investigated for each type of aggregate.

1.2 Research Objectives

The study presented here investigates the properties of self-compacting concrete made with cold bonded blast furnace slag aggregates. For this purpose, artificial blast furnace aggregate was produced by means of cold bonding process at room temperature.Thereafter artificialaggregatereplaces the natural coarse aggregates within the self-compacting concrete at a different replacement level to monitor the shape and mineralogical effects of rounded artificial aggregate on the fresh, mechanical and durability properties of self-compacting concretes. Experimentally, six SCCs mixtures were prepared with water-binder ratio of 0.32 and a total binder

3

content of 550 kg/m^3. Testing parameters relevant to cold bonded aggregate are mainly the coarse aggregate volume fraction. The selected volume fractions of artificial aggregates are 20, 40, 60, 80 and 100 percent of the total coarse aggregate volume. Fresh properties of SCCs were observed through slump flow time and flow diameter, V-funnel flow time, and L-box height ratio. Hardened properties were evaluated in terms of compressive strength and splitting tensile strength, Moreover; the SCCs were tested for chloride ion permeability, sorptivity index and gas permeability.

1.3 Thesis Organization

This thesis consists of five chapters. Chapter 2 presents a literature review and general background information about SCC, workability requirements and material behavior werealso explained. A brief definition and theory of the pelletization process were presented. Moreover, includes summary information about the concrete aggregate-cement paste interface bond characteristicsthrough previous studies. Carrying out a brief introduction about the structure, formation, properties of mineral admixtures, namely fly ash and ground granulated blast furnace slag (GGBFS) and their effects on the fresh, mechanical, and durability properties of SCCs were also discussed.

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

Chapter 4 provides the test results of the experiments conducted in this task. Furthermore, how the self-compacting concrete made with a cold bonded blast furnace slag aggregate affect the fresh, mechanical and durability properties of SCCs are explained in this chapter.

In chapter5, conclusions of the thesis and recommendations for future studies are given.

CHAPTER 2
LITERATURE REVIEW AND BACKGROUND

2.1 Introduction

This part presents a literature review and general background information about SCC, workability requirements and material behavior are also explained. A brief definition and theory of the pelletization process is also presented. Also include summary information about the concrete aggregate-cement paste interface bond characteristics through previous studies.Carrying out a brief introduction about the structure, formation, properties of mineral admixtures, namely fly ash and ground granulated blast furnace slag (GGBFS) and their effects on the fresh, mechanical, and durability properties of SCCs are also discussed.

.

2.2 Self Compacting Concrete (SCC)

2.2.1 Definition

SCC is the concrete which widens through the overcrowded reinforcement, reaches every narrow and deep section of the formwork and consolidated under its own weight. It provides advanced passing ability, filling ability and exhibits good segregation resistance [29]. Okamura considered SCC as a new type of high-performance concrete (HPC) due to its uniformity as well as resistance to segregation that make it flow from side to side and fill the reinforcement gaps and corners of moulds without any internal or external mechanical vibration [30], if

the criteria of performance such as high strength and durability for HPC are incorporated with SCC in the company of low water-binder (W/B) ratio, it can be called as self-compacting high-performance concrete(SCHPC). A SCHPC is that unusual concrete, which would give the optimized performance with respect to flow characteristics,strength, transport properties and durability consistent with the requirements of service life under a given set of materials, loads and exposure conditions. in additionto the primary materials used for ordinary concrete the composition of SCCs mixes includes considerable volume of powdered inorganic substances and this provides outlooks for employment of mineral admixtures, which are presently waste end products with no feasible applications and expensive to dispose [31]. SCC unlike the ordinary concrete includes proportions of component materials considerably different , it contains a greater fine aggregate content , a large amount of binder, lower amount of coarse aggregate and less water content than ordinary concrete [5,32]. The successful development of SCC offers benefits, economic and wide engineering varieties.

2.2.2 Workability requirements of fresh SCCs

SCC in fresh state should meetthe following means of properties ,which is recommended by EFNARC technical committee to be described as follows[33]:

Filling ability:Filling of entire formwork and encapsulation of reinforcement and other inserts with maintaining homogeneity in both vertical & horizontal directions are essential.

Passing ability:SCC is passing through restricted area such as narrow parts of the formwork even closely spaced reinforcement, etc without blocking caused by interlocking of aggregate particles.

Resistance to segregation:SCC is supplying uniformity during mixing, transportation and casting. Also it provides resistance to segregation during placement due to its dynamic stability. Moreover, resistance to segregation, bleeding and settlement of surface after casting as a reason to static stability.

In addition to the above mentioned three important fresh properties, the following criteria must be satisfied by SCC [34]:

Precision &Accuracy :More essential to obtain target workability for SCC as the casting is totally hanging on the material properties as no tools usually will be on hand for manual material transport and compaction.

Pumping Ability :SCC is mostly simpler to pump. Relying on the special rheological properties of the fresh concrete the pumping pressure versus the feeding rate has to be optimized.

Finishing Ability: SCCgenerally have fewer bleeding tendencies. In a number of cases the finishing will be made on a coarser and stickier surface. Appropriate materials on the finishing tools are thus to be recommended.

When the produced concretes achieved expected workability requirements, the following most important advantages can be obtained [30]:

- quicker construction
- Decrease in site manpower
- Improved surface finishes
- Simpler placing
- Better durability
- Giving more freedom to the designer

- Thinner concrete sections

- Quieter site work, without vibration

- Improving site Safety

2.3 Materials for SCCs

As mentioned above, mixture proportions for SCC vary from those of ordinary concrete in that the former has more powder content and fewer coarse aggregate. Moreover, SCC incorporate high range water reducer (HRWRA, superplasticisers) in larger amounts and frequently a viscosity modifying agent (VMA) in small doses. The questions that dominate the selection of materials for SCC are: (i) limits on the amount of marginally unsuitable aggregates; that is, those deviating from ideal shapes and sizes, (ii) choosing of chemical admixture taking account the type, interaction and compatibility with cement, (iii) Usage of mineral admixture, to enhance the deformability and stability of concrete.

2.3.1 Aggregates

The mass of a concrete mixture is occupied by aggregates giving dimensional stability to concrete. Among the various properties of aggregate, the important ones for SCC are the shape and gradation. Many researchers have been able to produce self-compacting concrete with locally available aggregate. It is observed from these studies that self compatibility is achievable at lower cement (or fines) content when rounded aggregates are used, as compared to angular aggregates. Although there have been several studies on the effect of coarse aggregate content on the flow behavior of SCC,enough attention has not been paid to quantify roll of aggregate

shape. In the case of SCC, rounded aggregates would provide a better flow ability and less blocking potential for a given water-to-powder ratio, compared to angular and semi-rounded aggregates. Moreover, the presence of flaky and elongated particles may give rise to blocking problems in confined areas, and also increase the minimum yield. Incorporation of aggregate shape in the mixture design would enable the selection of appropriate paste content required to overcome these difficulties[35-37]. It is possible that the highly flow able nature of SCC could allow a higher proportion of flaky aggregates compared to normal concrete.

However, this aspect needs to be checked. O'Flannery and O'Mahony [38],have devised a method for shape characterization of coarse aggregate, which could assist in designing SCCs mixtures having marginally unsuitable aggregates. Incorporation of aggregate shape in mixture design, based on the method developed by O'Flannery and O'Mahony, is explained in Table 2.1.

Another insufficiency in aggregates is poor gradation. Use of fillers (either reactive or inert) has been suggested as a means of overcoming this problem [39,40]. At present, a trial and error approach is used to fix the type and amount of filler. Alternatively, to decrease the numeral of experimental trials particle packing models might be used [41, 42].

Table 2.1 Use of shape characterization of aggregate

	Conventional method	Suggested method
Aggregate shape	• Rounded versus crushed (subjective assessment) • Flakiness index • Elongation index	•Cubicity, sphericity, and roundness indices (based on Flannery and Mahony) - Cubicity (Cubicity index $I_c = 100XYZ/X^3$, where X, Y, and Z are dimensions of the aggregate) to indicate the likely degree of potential compaction; values of index between 60 and 10 are cubic, between 30 and 60 indicate flakiness (100 for perfect cube), while values below 30 suggest elongation - Sphericity index to describe the polyhedral shape of the particle, and - Roundness index to describe the degree of angularity; values between 84 and 100 are angular, and between 52 and 68 are rounded
Adjustments in mixture proportioning	• Adjustment in water content by type of aggregate – rounded or crushed • No recommendation for flaky aggregate	• Use index value for adjustment of mixture; also, quantify the degree of flakiness or elongation by a weighted value for the index

In view of increased awareness of the environmental impact of mining river sand and depleting supplies of the same, use of manufactured sand and other alternative aggregate has become essential in some parts of the world. There are studies that have shown that quarry run could be used as a filler instead of limestone for SCCs [43]. In fact, river aggregate is simply not available in many areas, studies conducted by various researches shown that the aggregate produced by pelletization can be an effective aggregate in concrete production [44].

2.3.2 Chemical Admixtures

Chemical admixtures denote those components which can be supplemented into concrete mixture directly before or during the time of mixing. In order to enhance some essential features of fresh and hardened concrete, using of chemical admixtures such as water reducers, retarders, high-range water reducers or superplasticizer (SP), and viscosity-modifying admixtures are required in turn state of large amount of

cementitious material. Theyprovide more efficient effects in increasing strength and self-compatibility of concretes with lowly handy water to binder ratio. Trial batches must be evaluated to determine the efficiency of chemical admixtures by comparing strengths. Also, within these trial batches an investigation to the compatibility between cement and water reducers as well as supplementary cementing materials must be done .Accounting on these, for any given admixture it will be possible to conclude the workability, setting time, bleeding, and amount of water reduction for dosage rates via addition times.

2.3.2.1 High Range Water Reducing Admixture (HRWRA)

HRWRA is of low molecular-weight, water-soluble polymers designed to achieve high amounts of water reduction (12-30%) in concrete mixtures in order to reach a desired slump [45].

These admixtures are used frequently to produce high-strength concrete (>50 MPa) since workable mixes with water-cement ratios well below 0.40 are possible [46]. Several studies have been conducted on the employ of different types of HRWRA with or without viscosity modifying agents in self-compacting concrete. These studies seem to indicate those that HRWRA that work on the principle of 'steric hindrance' require a lower dosage compared to those based on 'electrostatic repulsion'. Stated in other words, acrylic copolymers (AC) and poly-carboxylate-ethers (PCE) are effective at lower dosages compared to sulfonated condensates of melamine (SMF) or naphthalene (SNF) formaldehyde [47], also the economical side and availability has a significant effect on choosing type of HRWRA.

Some increases in compressive strength can be expected, when water-reducing admixtures are used in concrete mixtures, and these increases can be observed in as early as one day if excessive retardation does not occur. It is generally agreed that increases in compressive strength are up to 25% greater than would be anticipated from the decrease in water-cement ratio alone. Perhaps, uniform microstructure improvement when the cement is dispersed, reflects that fact .The permeability of concrete can be reduced by the use of HRWRA due to the creation of a more uniform pore structure and reduction of the water-cement ratio follow-on general enhancement in durability of concrete [48].

In cement paste, opposing charges on adjacent particles of cement can exert considerable electrostatic attractions, causing the particles to flocculate (Figure 2.1a). A considerable amount of water is tied up in these agglomerates and adsorbed on the solid surfaces, leaving less water available to reduce the paste viscosity and so that of the concrete. Molecules of the water-reducing admixtures interact to neutralize these surface charges and cause all surfaces to carry uniform charges of like sign. Particles now repel each other, rather than attract, and remain fully dispersed in the paste (Figure 2.1b), thus most of the water is available to reduce the viscosity of the paste and concrete [49].
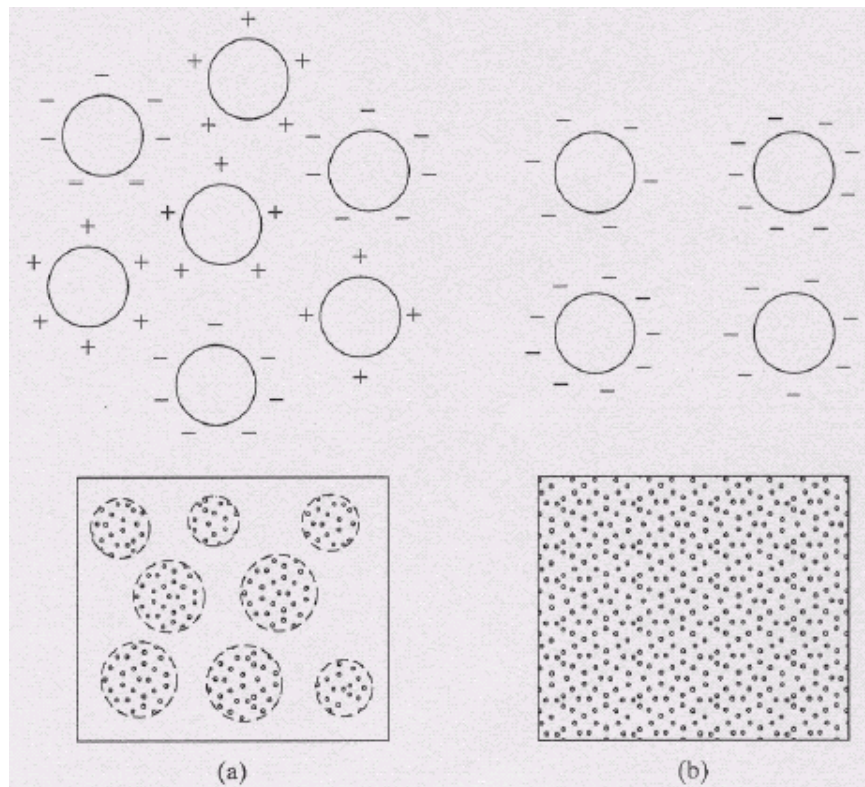
Figure 2.1Dispersing action of water-reducing admixtures: (a) flocculated paste; (b) dispersed paste [49]

2.3.3 Mineral Admixtures

These material are generally by-product from other processed or natural material. They may or may not be further processed for use in concrete. Some of these material are called pozzolans which don't have any cementitious properties by them self, but when used with portland cement react to form cementitious compounds. Other material such as slag, do show signs of cementitious properties. According to American Concrete Institute (ACI), a pozzolan is defined as "siliceous or siliceous and aluminous materials which in themselves possesses little or no cementitious value but will, in finely divided form and the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties". The chemical reaction between the siliceous and/or siliceous-alumina components in the pozzolans, calcium hydroxide and water named

14

as pozzolanic reaction as defined by ACI 231.Relying on materials' properties and the desired effect on concrete, mineral admixtures are supplemented to concrete as part of the total cementitious system. They may be used besides to or as a partial replacement of portland cement in concrete [49].

The specific concrete characteristic such as workability, strength or compatibility can be enhanced by using mineral admixtures. The establishing of the optimum quantity should be tested in order to determine (1) If the material is truly improving the characteristic, and (2) the correct dosage ratio, as an more or less amounts can be damaging or not obtain the required effect, on account of; they act differently with different cements [50].

2.3.3.1 Fly Ash

Fly ash is a by-product of the burning of coal in thermal power plants for electricity production. It is also known as pulverized fuel ash. It is removed by the dust collection system as a fine particulate residue from the combustion gases before discharging into atmosphere. Fly ash contains meta-stable alumino-silicates that react with calcium ions, in the presence of moisture to form silica hydrates. Coal used in thermal power plants is pulverized before use. The fine coal particles are transported in an air stream to the boiler where they are burned, and the heat produced is used to generate steam in the steam-generating unit. Through the combustion process, the volatile material is vaporized, and carbon is burned-out. As the particles enter the burning zone, temperatures increase rapidly and typically reach values around $1000 - 1500°$ C. Mineral components present in the coal gangue, the inorganic part of the coal, such as clays and feldspars melt and form

fused droplets that on rapid cooling solidifies as spherical glassy particles that include the coal ash. Some mineral components also remain in the crystalline phase. The coarser ash collects in the bottom of the furnace, and is known as bottom ash. The finer ash is carried in the flue gases are collected by precipitators. It is this ash that is termed fly ash [51].

Fly ash is considered as a most familiar artificial pozzolan worldwide. The use of fly ash in concrete technology dates back to late 1930s. It is estimated that about 450 million tons of fly ash is produced worldwide annually, however just 6 % used as a pozzolan in blended cements or in concrete mixtures from total available fly ash [52]. In Turkey there are twelve active coal-burning power plants. The country produce about 15 million tons fly ash annually [53,54].

Fly ash can be utilized as a blending component in blended cement or can be added separately during the concrete production. According to ASTM C 618, fly ash are divided into two categories: Class C andClass F. The Class C fly ash typically contains analytical CaO 15 % to 35 % whereas Class F fly ash generally contains less than 10 % CaO [55]. On the other hand, the manufacture of Class F fly ash is from bituminous and anthracite coals combustion, is a low lime fly ash and mainly classified as a pozzolan. The Class C fly ash, however, is manufactured from combustion of either sub-bituminous or lignite coal. Due to the high calcium content Class C ashes possess substantial cementious properties besides pozzolanic properties [56]. Fly ash particles, as shown in Figure 2.2, have mostly spherical, glassy particle shapes with different sizes varying from a few μm to 100μm [57].
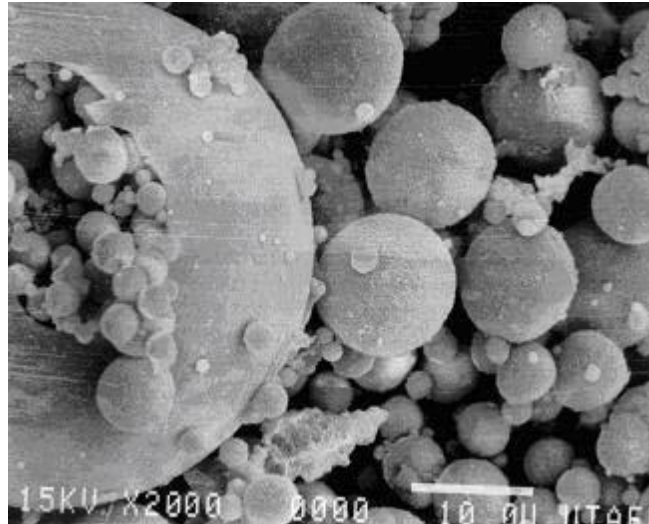
Figure 2.2 Fly ash particles [57]

2.3.3.2 Ground Granulated Blast-Furnace Slag(GGBFS)

GGBFS is a by-product of iron production. The iron ore is a mixture of oxides of iron, silica and alumina, and the chemical reactions within the blast-furnace reduce iron ore to iron. The iron ore is fed into the furnace with coke and limestone. The slag is formed at a temperature of $1300 - 1600^oC$ as a liquid layer floating on the top of liquid iron, then it is collected and cooled [58]. The method of cooling affects the properties of the slag, when cooled rapidly, the slag has a non crystalline, glassy structure. If water is used for cooling, sand sized particles of slag is obtained. An alternative treatment, pelletization, can also be used for granulation. The granular slag is then dried and finally ground to cement fineness or finer. During the iron production process about 300 kg of slag is produced for each ton of pig iron [59].

In production plants with older technology, however, the amount of slag obtained is usually higher. The use of blast furnace slag as a cementitious material dates back to the second half of 19th century. About 100 million tons of slag is produced annually worldwide but only a very small fraction is utilized. Today slag is widely used in

Europe as a component in blended cements but the degree of usage varies significantly between different countries. Netherlands, for example, utilizes about 90 % of its slag production [60] and slag cement has a market share of about 60 % in the country [61].

During concrete and construction applications in 2003 about 3.1 million tons of slag cement was shipped for use in US as said by the American slag cement association. Besides used as a blending component in cement, slag can also be added to concrete during production. Although many pozzolanic by-products are being used as blending materials, blast furnace slag is the nearest to portland cement in chemical composition. The chemical composition of the slag depends on the materials used for iron production and the procedure for cooling. The CaO content of slags are mostly between 40% and 50%, and the SiO_2 is between 30% and 40%. There were three grades; 80, 100 and 120 classification of the blast furnace slag, this classification is based upon the strength to the mortar containing 50 % slag by mass. Particle size of the blast furnace slag depends on its grinding process [62]. Blast furnace slag particles have mostly rough, sharp edged shapes as shown in Figure 2.3.
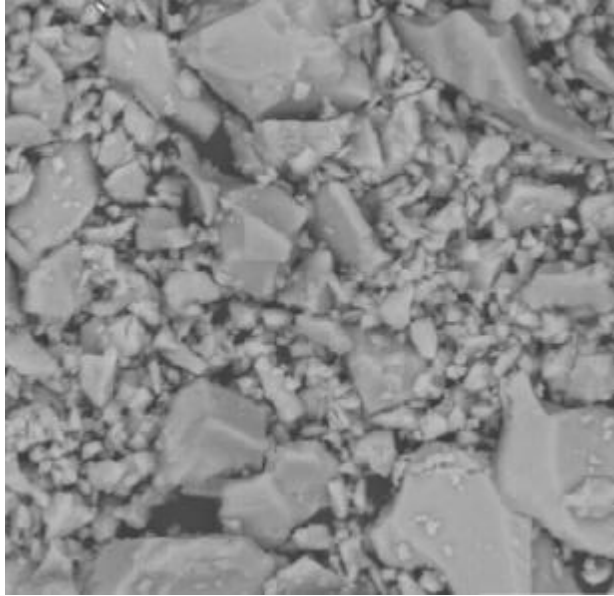
Figure 2.3 Ground granulated blast furnace slag particles [62]

2.4 Pelletizing Process

2.4.1 Definition

The idea of pelletization process was first put forward by A. G. Anderson, a Swedish researcher, in 1912, and then by C. A. Brackelsberg in Germany who devised a similar balling process. This was a revised process with the addition of binder to the fines agglomerated and the pellets strengthened at elevated temperatures during production. The desired grain size distribution of an artificial aggregate is either crushed or by means of agglomeration process. Agglomeration (also called "pelletization") can be carried out by incitement, where powder particles are introduced onto an inclined rotating disk along with a wetting agent and an suitable binder. Balling of the material happens by the creation of seeds, which finally grow into pellets of a particular maximum size, generally about 9.5 mm to 15.87 mm. diameter [63].

The pelletization process is used to manufacture coarse aggregate; some of the parameters need to be considered for the efficiency of the production of pellet such as pelletizer disc revolution speed, pelletizer discangle , pelletization duration, and moisture content [64]. Different types of pelletizer machine were used to make the pellet such as disc or pan type, drum type, cone type, and mixer type. With disc type pelletizer the pellet size distribution is easier to control than drum type pelletizer. With mixer type pelletizer, the small grains are formed initially and are subsequently increased in particle size by disc type pelletization as shown in Figure 2.4 [65]. In the cold bonded method the strength of pellet increase with increasing the binder/cement ratio as 0.2 and above (by weight) [66]. The disc angle and moisture content are from the parameter influence the pellets size enlargement [64]. The dosage of binding agent is more important for making balls and the optimum range was found to be around 20% to 25% by the total weight of binders [65].

Initially some percentage of water is added in the binder and then poured in a disc; remaining water is sprayed during the rotating period because while rotating without water in the disc the fly ash powder tends to form lumps and does not increase the distribution of particle size. The pellets are formed approximately in duration of 20 min. At the end of the process the product called as "Fresh Pellet". For transportation and stockpiling purposes the fresh pellet must have enough crushing strength. The pellets may also be sintered through a detailed time interval after production hanging on few concerns like the pelletized fine properties , the aim of using, and the pellets engineering performance increment rate [67-70].
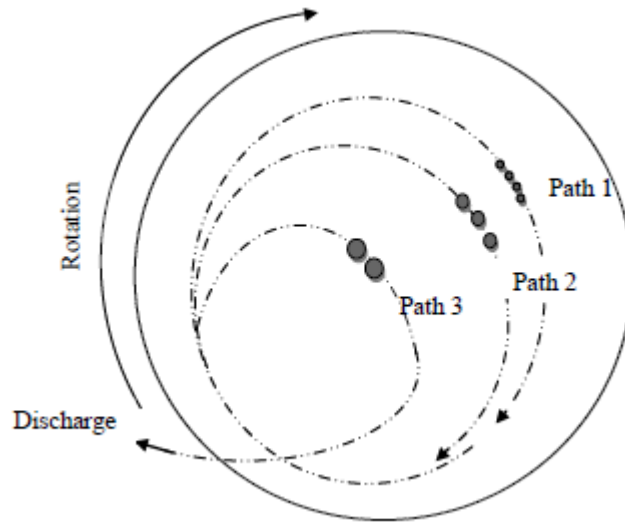
Figure 2.4 Growing path of pellets [65]

2.4.2 Pelletization Mechanisms

Pelletization is the process of forming nearly spherical pellets by tumbling moist particulate fines (with or without addition of binders and other necessary additives) in such devices as drums, discs, or cones. Mineral, ceramic, chemical, food, fertilizer, nuclear, pharmaceutical, waste processing and a host of other industries make use of pelletization to alleviate problems associated with fine particles. However, from a tonnage stand point, pelletization is most commonly used for agglomeration of iron ore concentrates. Detailed reviews of various practical and theoretical aspects of the pelletization of fine particles have been published [71-73].As shown in Figure 2.5, the driving potential for the pelletization of fine particles is the lowering of the total system surface free energy through a reduction of the effective air-water interfacial area [73].

The forces which bring about this change are of two kinds: (a) physical and (b) applied [74]. The physical forces responsible for the formation and the strength of

pellets arise from a number of sources - (i) interfacial effects giving rise to capillary and surface tension forces, (ii) van der Waal's interaction, magnetic and electrostatic interactions, (iv) interlocking effects among the particles, and (v) immovable bridging bonds. The applied forces which arise due to the tumbling motion of drums or discs serve the purpose of bringing individual liquid wetted particles into proximity with each other so that the physical forces become operative and pelletization is initiated.

$$\Delta G_{agglom} = (S_{nuclei} - S_{feed})\, \gamma_{air-water}$$
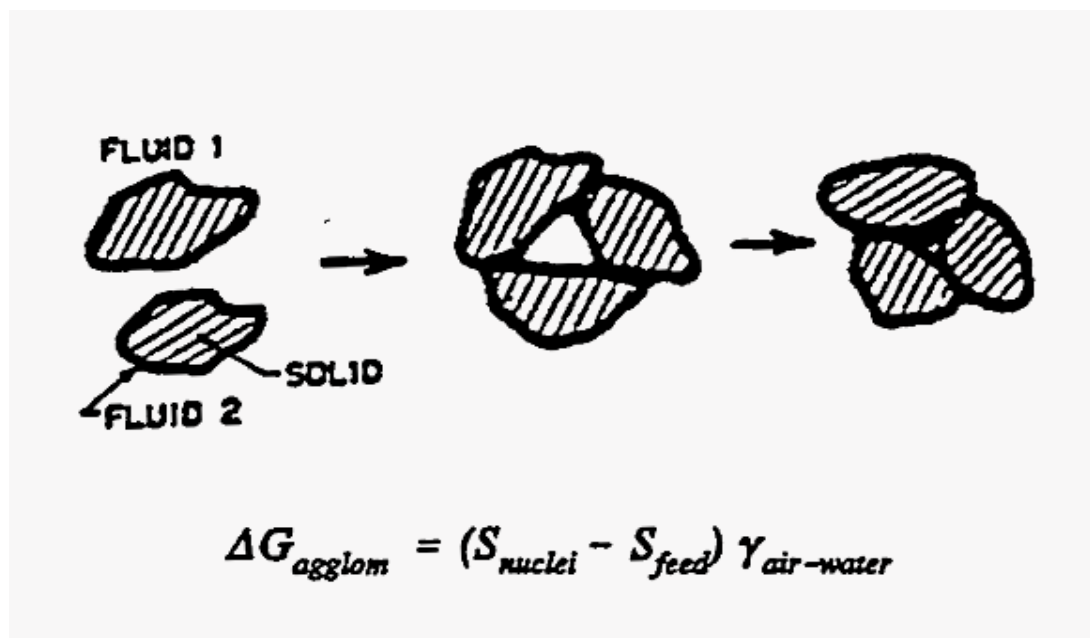
Figure 2.5. A schematic representation of the driving force for pelletization due to reduction in total air-water interfacial area [73]

Calculations by Rumpf [75] indicate that, for the case of solid particles which are completely wetted by a bridging liquid, capillary and surface tension forces are the most predominant. The magnitude of capillary forces depends upon the type of bond between the particles. These bonds, depending upon the relative proportion and distribution of the air and water phases in the pellet are referred to as (i) pendular, (ii) funicular, and (iii) capillary bonds. The changes in the state of the agglomerating system can in principle be accounted in terms of the above described forces, but it is

simpler to make use of the concept of size change mechanisms. Such a view point is advantageous because of the inadequate understanding of the occurrence of these various forces at a molecular or microscopic level. A total of seven mechanisms of agglomerate formation and size change was suggested earlier [74]. These include (i) nucleation, (ii) dissociation, (iii) coalescence, (vi) breakage, (v) layering, (vi) attrition, and (vii) abrasion transfer. Among our debate it is enough to consider three of the seven mechanisms - nucleation, coalescence, and layering (see Figure 2.6).

Nucleation refers to the formation of particles from the continuous phase due to interactions within the environment in itself. Clearly, nucleation causes appearance of new particles along with a discrete change in the size of the newly born agglomerates. As soon as the initial formation of nuclei occur, coalescence begins to set in. It causes discrete size changes and leads to decrease in the number of agglomerates but not their mass. The third mechanism of layering corresponds to continuous size change of the particles and is affected by interaction of particulates with the environment (continuous phase). Accordingly, layering brings changes in the mass of the agglomerates but not their number. Clearly, layering can occur only when both the agglomerates and new feed are present.

MOIST FEED, P_1 PELLETS (well-formed species), P_i

NUCLEATION

$jP_1 \rightarrow P_j$

COALESCENCE

$P_i + P_j \rightarrow P_{i+j}$

LAYERING

$P_i + jP_1 \rightarrow P_{i+j}$
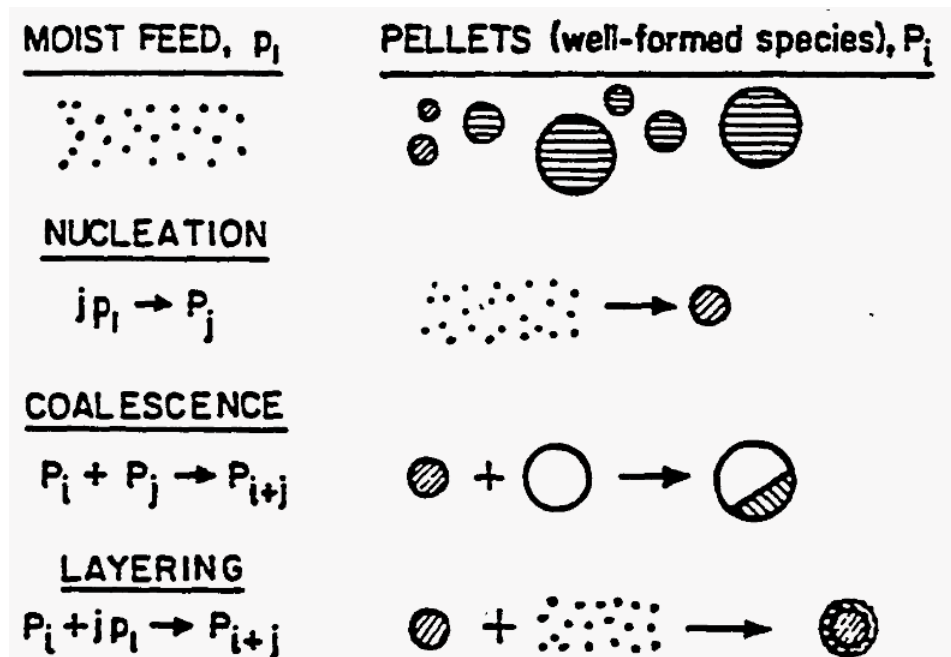
Figure 2.6. Three main mechanisms of pellet formation and growth: nucleation, coalescence, and layering [74]

These mechanisms take place simultaneously during any agglomeration process unless the design and operating conditions are otherwise chosen. Actually, the simultaneous occurrence of these mechanisms is known to result in undesirable agglomerate size distributions and cycling of the performance of an agglomerating unit. Also it is recognized that different growth mechanisms can prevail depending upon the type of feed being pelletized. According to Kapur and Fuerstenau [76] , the growth of pellets in the initial stages of batch pelletization proceeds fast by nucleation and then mainly by the coalescence mechanism. In later stages of pelletization there is evidence that a limited amount of breakage of pellets occurs. In industrial pelletizing operations where a continuous supply of moist feed is charged to the pelletizing device, the growth mechanism of layering (or snowballing) of added moist feed onto the pellets becomes important.

The optimum water content has estimated to be between 20 and 25%. Figure 2.7 presents the ball formation mechanism for less than the optimum moisture content

.In this state, the moisture particles move closer and become connected with water bridges. By increasing the degree of saturation, the voids' volume decreases thus the air drove out leaving the pore spaces for the particles and water. In this stage, capillary bonding occurs if additional moisture had feds to the structure.

In Figure 2.8, the ball formation mechanism is shown with above optimum moisture content. During this case the formation is weaker and the capillary force is diminished because of wetting excessively. The formations are random sized and may be easily destroyed by the mechanical forces created in the balling drum and disc. Because the granulometric distribution of pellets cannot be controlled during the pelletization process this methodology is disadvantageous. Damage of the capillary force is resulted in both below and above the optimum binder amount, which then factors a great variety in engineering performance and size of the produced pellets. Keeping content of moisture equal to or below than the optimum content is responsible for final product better performance [67-70].
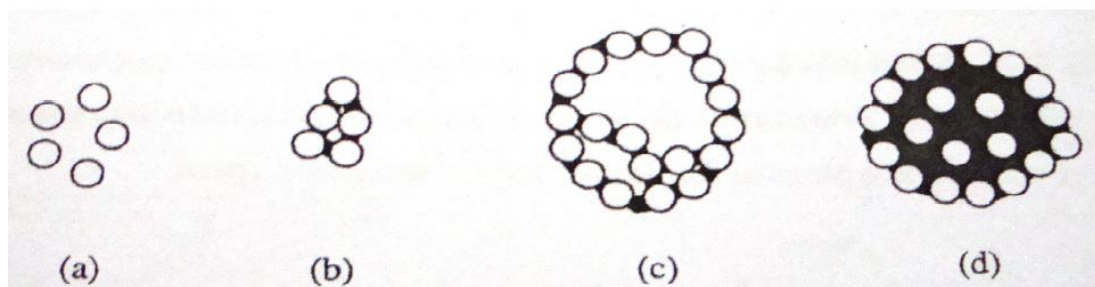
Figure 2.7 Nuclei ball formation mechanism (water content below optimum state) [68]
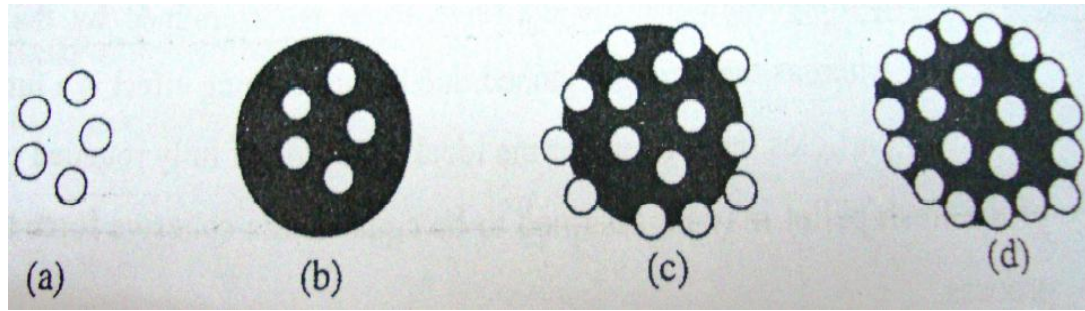
Figure 2.8 Nuclei ball formation mechanism (water content above optimum state) [68]

2.5 Bonding between Cement Paste and Aggregate

Aggregate–cement paste interface performed the physical strength and reliability of concrete mixture, and this bond variously hangs on aggregate particle surface nature and the directly near hydrated cement character, so functionally the interface quality is managed by both cement paste and aggregate properties [77].

The interfacial regionthat surroundsthe aggregate particle has been shown to bedifferent from thebulk of paste and called interfacial transition zone (ITZ). Aggregates used in concrete had varied shape, roughness of surface and degrees of porosity in addition to the chance of upholding dust and dirt [78].

Basing on the aggregate effect on high-strength concretes the study of Kosmatka et al, suggested that further interest must be given to aggregate size, shape, surface texture, mineralogy, and cleanness. Within high-strength concretes, the very important factors are aggregate self strength and its bond with cement paste. According to the test's results, it was found that compressive strengthobtained by using crushed-stone aggregates in concrete was higher than gravel aggregate concreteat same size and cementing materials content.

26

Also it has been assumed that using a rough, angular, crushed material increase the strength due to a superior aggregate-paste bond [50]. Moreover, coarse aggregates used in high-strength concrete should be clean, so that, it must be unattached of detrimental coating's impurities such as clay anddust, because of their effect on fines quantity, aggregate-paste bond and water demand of the concrete mixture [49].

Depending upon the previous studies, it was observed that picking suitable materials or adjusting the physical interfaces among the materials could get better the parameters of concrete. It was found that in a 25-50 μm thick zone surrounding the aggregate, a duplex layer of calcium hydroxide - $Ca(OH)2$ – and a porous shell, present different properties from bulk cement paste. These considerations promote the accumulation of oriented crystals of calcium hydroxide, giving increment to weak planes along which micro cracks occur. For improving the aggregate paste interface some methods were hinted thus, (1) decrease the water-cement ratio, (2) including small amounts of micro silica, and pre-coating the aggregate particles with that reactive layer of cement-micro silica slurry lead to increase bond strength, visible through a compressive strength increase, and practically eliminating the transition zone that could be observed through porosity reduction [79].

The concrete properties, such as strength, bond between aggregate-cement paste, and permeability for water and ions in the pore water are caused by week and porous composition of the interfacial transition zone (ITZ). Due to its thickness (around 50 μm) and porosity, a large fraction of the cement matrix belongs to it, the fact which affects the aggregate and the cement paste bonding. An investigation for the interfacial transition zone has discovered that an event named as "syneresis" is behind the formation of a water-rich layer around the aggregate, which weakens the

aggregate-paste bond. Syneresis takes place when a system sustains rapid flocculation, which most particles tend to be linked to two or three other particles and the result is a loose flock. The weak structure of these flocks includes a considerable quantity of entrapped water. The creation of a great number of contacts leads to a contraction of the dispersed phase, and when its volume decreases the water is rapidly ejected from the flocks [80]. Among the same study, it was discovered that in order to decrease the thickness of the interfacial transition zone fly ash and silica fume might be in concrete due to the pozzolanic reaction mechanisms.

Depending on an inspection that done on the orientation of calcium hydroxide crystals in the interfacial zone. The Firmly orientation of calcium hydroxide crystals in this zone was observed. It was also found in the same study that the axes of the crystals were vertical to the aggregate surface, and the orientation degree presently grow with time without relying on aggregate particle's sizes and types [81].With concerning the roll of the surface conditions of aggregate on the compressive strength of concrete and aggregate-cement bond a study was carried out. In this study, 15 mm diameter's ground glass ball was utilized with various roughness degrees as aggregate particles. The result indicates that increasing degree of aggregate particle's roughness reduces the formation and extends of microcracks generally in the interfacial transition zone, and thus develop the aggregate-cement bond and compressive strength of the concrete. On the other hand, it was found that, in common, the concrete strength made of watchfully elected aggregate was depended either on aggregate particles–cement paste bond strength or cement paste strength [82].

2.6 Effects of mineral admixtures on the fresh properties of concrete

2.6.1 Effects of fly ash on the fresh properties of concrete

As a reason of lighter weight, the mass of used fly ash is usually equal to or greater than the reduced mass of cement. For this ,the total amount of cement plus fly ash normally exceeds that of cement in similar concrete mixtures not containing fly ash. depending on the used proportions, this increase in paste volume produces a concrete with better plasticity and better cohesiveness. In addition, the increase in the volume of fines from fly ash can pay off for lacking aggregate fines.

Because of their spherical morphology, when using fly ash admixtures as replacement for cement, workability and long-term strengths are achieved in concretes. In such cases, they act like small balls to reduce inter particle friction. In order to reduce permeability, heat of hydration and bleeding, fly ashes are used in concrete mixtures [49]. According to ACI 232.2R-96 [83] report, using of fly ash may extend the setting time of concrete if the portland cement content is reduced.
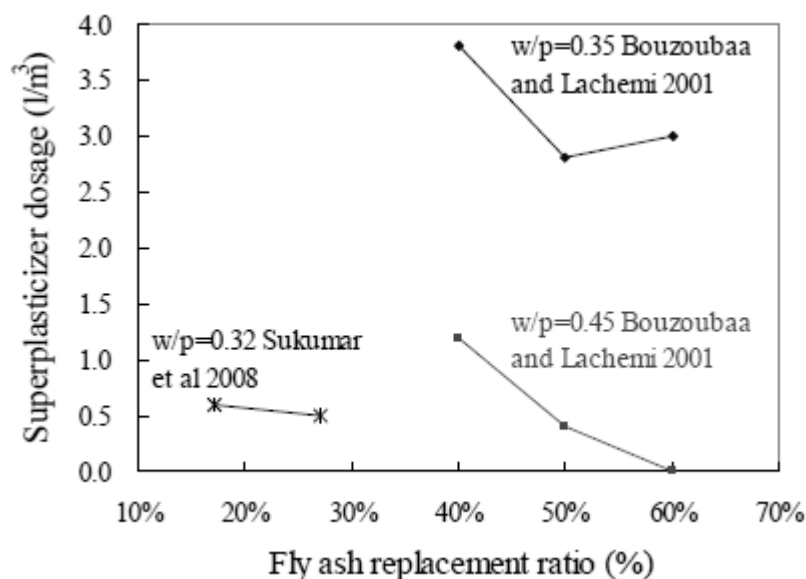
Figure 2.9 Effect of fly ash on superplasticizer dosage of SCCs [84,85]

Setting time of SCCs incorporating 40~60% Class F fly ash by weight was 3~4 hours longer than that of a control, 100% cement at the same 28-day compressive strength The relation between fly ash and superplasticizer dosage content existed in SCCs mixtures. It was found that with increasing fly ash content up to 39% superplasticizer dosage decreased as shown in Figure 2.9; while incorporation of higher than 39% volume fly ash did not change the required superplasticizer [84,85]. SCCs incorporating fly ash has long setting time because of fly ash slow reactivity and the delaying effects of superplasticizer and viscosity modifying admixture (VMA)[86]. During a study have done to propose the mix design method for high volume fly ash SCCs and to evaluate the effects of replacing cement by fly ash on the strength and durability of the SCCs, it was concluded that SCC at 50% replacement level of FA had excellent workability and filling ability at the construction site [87].

Fly ash in SCCs helps to reduce early-age cracking in SCCs which decreases with an increase in strength, low drying shrinkage, low permeability and good freeze-thaw resistance of SCCs were achieved by incorporating 30~40% fly ash (Blaine surface area of 500~600 m^2/kg); the fly ash had a similar effect to VMA on fresh concrete: improving the viscosity of fresh concrete and keeping consistence constant; 28-day compressive strength of such SCCs could reach 71 MPa [88]. It was reported that 30% fly ash replacement of cement by resulted in exceptional flowability and workability which could be referred to the super flowing properties of concrete containing fly ash [89].

2.6.2 Effects of Ground granulated blast furnace slag on the fresh properties of concretes

When comparing both concretes with and without ground granulated blast furnace slag (GGBFS), the workability and place ability of GGBFS concrete yielded enhanced characteristics. This result was owing to the formation of smooth slip planes caused by surface characteristics of the GGBFS in the paste. Furthermore, due to the smooth, dense surface of the GGBFS particles little water was absorbed by the GGBFS during initial mixing, unlike portland cement. Down to the increased powder content and enlarged cohesiveness of the paste, cementitious matrix containing GGBFS had better workability. [90].

Compared to paste of portland cements alone pastes containing GGBFS displayed varied rheological properties. Either with or without water-reducing admixtures the outcome indicated a better particle dispersion and higher flowability of the pastes and mortars containing GGBFS. [91]. When GGBFS is used in concrete mixtures as a partial replacement of the portland cement setting time increasing expected. The affected degree of setting time is reliant on the proportion of the blend used , the initial temperature of the concrete, the characteristics of the portland cement and the water-cementitious materials ratio. GGBFS supplies responsive fines with a low heat of hydration. A high ratio of GGBFS may influence stability of SCC resulting in reduced robustness with problems of consistence control at the same time as slower setting can also increase the threat of segregation [33]. As the amount of portland cement in a mixture normally determines setting characteristics of concrete, changing the GGBFS volume may be taken under consideration in cold weather, thus utilizing of GGBFS cause significant retardation, for this reason traditional accelerators, such as calcium chloride or other accelerating admixtures should be

used. The slower rate of setting is suitable in most cases at high temperatures, but attention may require to be taken to make light of plastic shrinkage cracking. [91].

2.7 Effects of mineral admixtures on the hardened properties of concretes
2.7.1 Effects of fly ash on the hardened properties of concretes

Owing to the slow pozzolanic response of fly ash, fly ash concretes generally have a lower early strength depending on fly ash properties and contents [92]. At later ages, however, with proper curing fly ash concretes can have a greater strength compared to portland cement concrete. Figure 2.10 illustrates effect of fly ash content on the strength of concrete [59]. The fineness of the fly ash is very significant for the adjustment of cement paste-aggregate interfacial zone, which is the weakest link in concrete, cause pozzolanic effect seizes on the surface of the particles, thus, expanding the surface area of fly ash has an pompous effect on pozzolanic action.
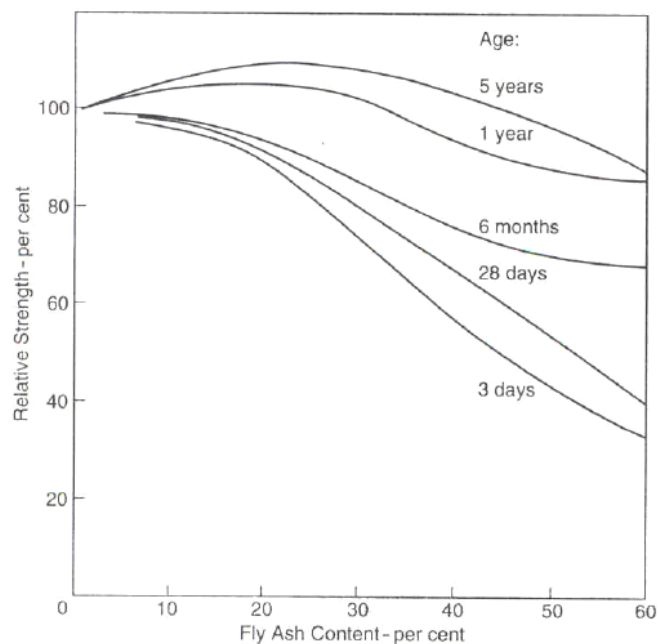
Figure 2.10 Effect of fly ash content on the strength development of concrete [59]

32

In a recent study in order to monitor effect of fly ash fineness on concrete physical properties and strength development, a coarse F type fly ash with a surface area of 222 m^2/kg was ground to four unlike finenesses such as 604; 538; 450 and 337m^2/kg. The resultant retained values on a 45 μm sieve were 3.7%, 5.2%, 10.1%, 29.9% and 50% respectively. a mill type ball was used in fly ash grinding. Results showed that fly ash fineness has substantial effect on concrete strength development especially for long curing times; with increasing fineness of fly ash, concrete compressive strength increases significantly, and more noticeable results are obtained for low cement/binder ratio. Results confirmed that fly ash concrete performance depend not only on chemical composition and mineralogical of fly ash, but also on its physical properties such as fineness and particle shape, and also on the water-binder ratio of the mixture [93].

The effect of fly ash fineness on the compressive strength is illustrated in Figure 2.11. In order to obtain higher strength with coarse fly ash, it was recommended to reduce water content or increase the binder content [94].
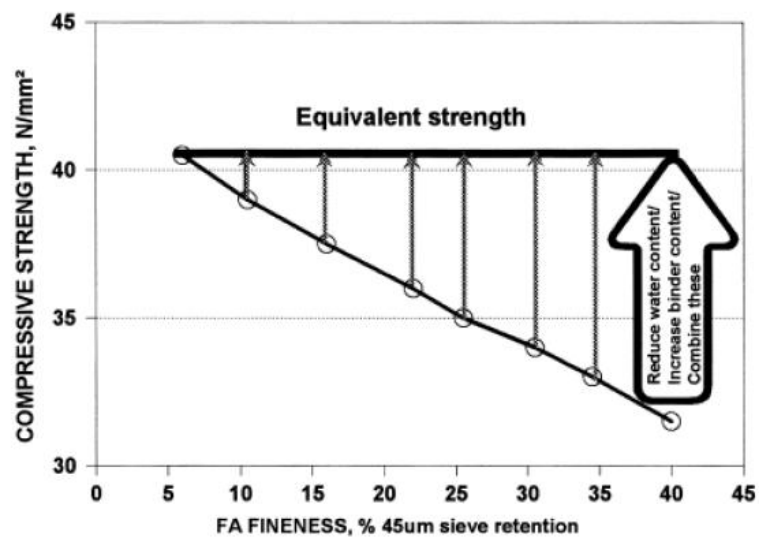
Figure 2.11 Effect of fly ash fineness on the compressive strength [94]

2.7.2 Effects of Ground granulated blast furnace slag on the hardened properties of concretes

Slag concrete's strength is generally lower at early ages but slag concrete can outperform Portland cement concrete at later ages. The curing conditions, replacement amount, and properties of slag are significant factors affects the strength development of the slag concretes. The amount of slag are inversely proportional to the early age strengths of slag concretes and the replacement amount of slag is usually higher than fly ash (i.e. 50–70%) [91]. Separate grinding of slag and clinker, and blending them according to specific needs is a more optimized process [95].

Figure 2.12 shows slag content effect on mortar's strength development [91]. As illustrated in the figure, strength of slag mixtures at later ages are significantly higher comparing to mixture containing portland cement alone. For the pozzolanic activity of the granulated blast furnace slag the particle size factor is also important, similar to the fly ash, the strength of slag concretes also increases with increasing slag fineness [96]. By using finely ground blast furnace slag, the aggregate – cement paste interface which is the weakest link in concrete can be improved and the thickness of this zone can be reduced. Better particle packing due to finer materials and the pozzolanic reaction of the slag are the reasons for this enhancement. By the densification of the aggregate–cement paste transition zone, concrete becomes more homogeneous and higher strengths can be obtained. This improvement may be more effective at lower water/binder ratios which can cause a better performance of the pozzolanic material. Figure 2.13 shows slag fineness effect on the compressive strength of mortars containing 75% slag [97].As illustrated in the figure, the mortar strength increased about 30 % when the fineness of the slag was changed from 300 m^2/kg to 450 m^2/kg.

34
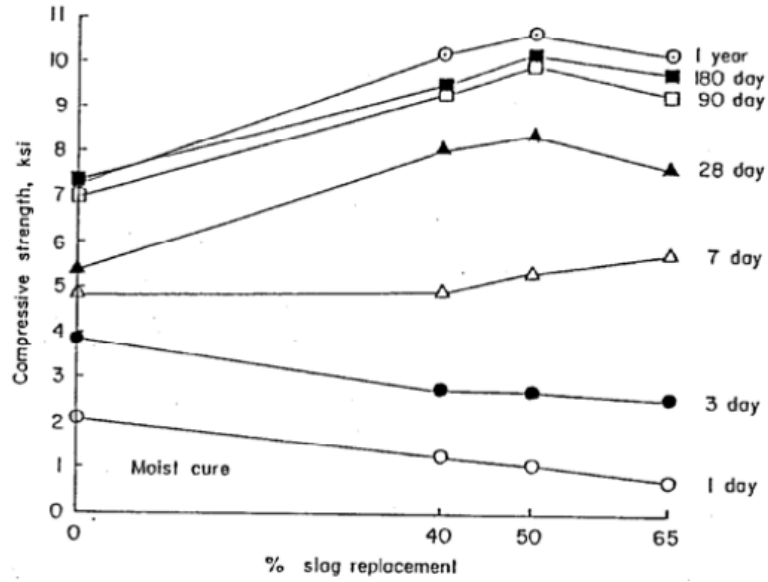
Figure 2.12 Effect of slag replacement level on the strength development of mortars [91]
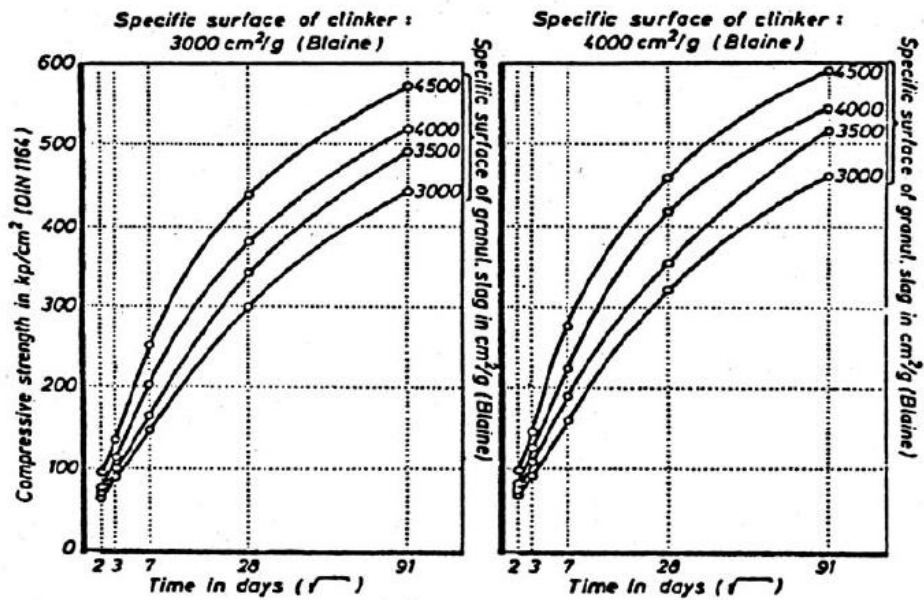
Figure 2.13 Effect of slag fineness on the strength development of mortars [97]

2.8 Effects of mineral admixtures on the durability properties of concretes

2.8.1 Effects of fly ash on the durability properties of concretes

The penetration of aggressive substances into concrete is the mean reason of concrete weakening and that depends on microcracks and interconnected pore system. Comparing to that of portland cement concrete, permeability of fly ash concretes at early ages can be significantly higher. Conversely, at later ages fly ash concretes can have much lower permeability relying on the content and characteristics of the fly ash used [98]. Incorporation of fly ash changes concrete microstructure, and much finer pore system can be obtained, which affects the durability of concrete. Clogging of pores and increase in tortuosity of pore channel are responsible for the improved permeability properties [99].

Durability tests covering water permeability, water absorption, chloride diffusion and carbonation rates were evaluated to inspect the utilitization of high volume of fly ash as a cement component in concrete. It was observed that water permeability, water absorption and chloride diffusion tests indicated improved performance with high fly ash levels, while carbonation showed similar performance to portland cement concrete although this possibly somewhat not as good as by low strength design of concrete [100].

According to ASTM C 1202 report on 10 year old concretes measurement for chloride ion penetration resistance indicate the long term performance of concretes with pozzolans .The charge passed through the concrete mixtures investigated in the study was less than 1000 coulombs at 10 years indicating very low chloride-ion penetrability. The passed charge for high-mass fly ash concrete was 0, giving a chloride-ion penetrability rating of this concrete as negligible. It is extremely rare to

achieve values as low as this in portland cement concrete; one can obtain such a low value only for polymer or polymer impregnated concrete because of the extremely low porosity of the system [101,102].

Scaling of concrete exposed to deicing salts occurs when immature or non air-entrained concrete pavements are exposed to large quantities of deicing salts in a freezing and thawing environment. Concrete pavements containing fly ash that are exposed to deicing salts should be air entrained and allowed to reach a specified strength or maturity. There is some laboratory research that indicates concrete containing 40 percent fly ash, as a partial replacement of total cementitious material, may be more resistant to scaling [83].

2.8.2 Effectsof Ground granulated blast furnace slag on the durability properties of concretes

Studies have shown that the concretes containing blast furnace slag provides significantprotection against chloride induced corrosion of embedded steel. The rate of chlorides greatly reduced due to the improved pore structure of concrete. Hanging on slag amount and characteristics, chloride diffusivity of concrete can be decreased by a factor of 150 [103]. with increasing slag content the resistance of concretes to chloride ion penetration increases [104-106]. Figure 2.14 illustrates slag replacement effect on concrete resistance versus chloride penetration [107]. Results given in the figure were obtained on concrete cubes stored in NaCl solution for one year.

The chloride content had been analyzed in a layer 20 – 40 mm under the concrete surface. As seen in the figure, the effect of slag is insignificant up to 20 % replacements, but beyond this ratio substantial decrease in the chloride content was

observed. Very similar results for the effect of slag content on the chloride diffusivity were also reported [103, 108]. As a result of improved pore structure of hydrated paste of a portland cement-GGBFS blend, and also because of low content of calcium hydroxide, the resistance to the sulphate attack is improved [109].

The electrical resistivity of concrete is an important component of reinforcing steel corrosion cells, as high resistivity of the concrete reduces corrosion currents, and thus slowing the rate of corrosion. To investigate GGBFS effects on the electrical resistivity of the self-compacting concretes a study carried out. In that study GGBFS replaced Portland cement at (20%, 40% and 60%) levels. Investigation outcome indicate that the lowest electrical resistivity was obtained at normal portland cement concrete with 12.8 kohm-cm and a gradual increment was noticed in SCC electrical resistivity with enlarging GGBFS content [110].Field studies carried out on concrete structures along the sea coast confirm the better performance of slag concretes in marine environment [103, 111].
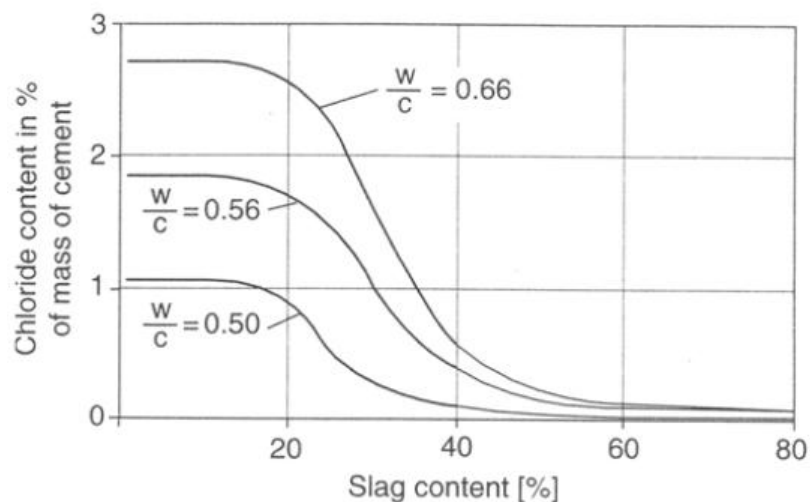
Figure 2.14Effects ofslag replacement on the chloride penetration resistanceof concrete [107]

CHAPTER 3
EXPERIMENTAL PROGRAM AND METHODOLGY

3.1 Introduction

The properties of SCCs made with artificial cold-bonded slag aggregates (ASA) was investigated through an experimental program which involves mainly two parts. Firstly, ASA was produced through the pelletization of GGBFS and cement at ambient temperature. Thereafter, the manufactured ASA was used in the production of SCCs. The slump flow, T_{50}flow time, V-funnel flow time and L-box height ratio tests were carried out to identify required properties and characteristics of fresh SCCs. The hardened concretes were tested for the compressive strength and splitting tensile strength at 28 and 56 days for the evaluation of mechanical properties. Moreover, the durability tests were conducted to investigate the resistance to chloride ion penetration, sorptivity index and gas permeability at the ages of 28 and 56 days.

3.2 Materials

3.2.1 Cement

An ordinary Portland cement was used in this study (PC CEM, I 42.5R) conforming to the TS EN 197-1 [91] (which mainly based on the European EN 197-1). It had a specific gravity of 3.15 and Blaine fineness of 326 m^2/ kg. It was utilized in the production of both artificial aggregates and concretes. Physical and chemical properties of the cement are given in Table 3.1.

Table 3.1 Physical and chemical properties of Cement, Fly Ash, and Slag.

Chemical Composition (%)	Cement	Fly Ash	Slag
CaO	62.58	4.24	34.12
SiO_2	20.25	56.20	36.41
Al_2O_3	5.31	20.17	10.39
Fe_2O_3	4.04	6.69	0.69
MgO	2.82	1.92	10.26
SO_3	2.73	0.49	-
K_2O	0.92	1.89	0.97
Na_2O	0.22	0.58	0.35
Loss of ignition	3.02	1.78	1.64
Specific gravity	3.15	2.25	2.79
Blaine fineness (m^2/kg)	326	287	418

3.2.2 Fly Ash

Fly ash (FA) used in concrete was a class F type according to ASTM C618-08 [55], and replaced the cement at 20% by weight. It was supplied from Ceyhan Sugözü thermal power plant. It had a specific gravity of 2.25 and the Blaine fineness of 287 m^2/ kg. Physical and chemical properties of the fly ash are given in Table 3.1.

3.2.2 Ground Granulated Blast Furnace Slag

The ground granulated blast furnace slag (GGBFS) used in the manufacture of ASA was obtained from Iskenderun cement production factory. It had a specific gravity of 2.79 and Blaine fineness of 418 m^2/kg. The physical and chemical composition of GGBFS is also given in Table 3.1.

3.2.3 Superplasticizer

A superplasticizer (SP) with a specific gravity of 1.07 was used to achieve the target workability. The properties of superplasticizer are given in Table 3.2.

Table 3.2 Properties of Superplasticizer

Property	Superplasticizer
Name	Daracem 200
Colour	Dark Brown
State	Liquid
Specific Gravity	1.07
Chemical Description	Sulfonated Naphthaline Formaldehyde
Freezing Point^{o}C	-4

3.2.4 Aggregates

3.2.4.1 Artificial Cold-Bonded Aggregates

ASA produced through a cold bonding process was used in manufacturing of SCCs. During the cold bonding process a dry mixture of cement/ GGBFS in particular magnitude were pelletized through moisturizing in a rotating inclined pan at an ambient temperature. The pelletizer used had a pan diameter of80 cm and adepth of 35 cm as shown in Figure.3.1. Firstly, some percentage of water was added to the mixture and then poured in a disc; remaining water was sprayed during rotating period because while rotating without water in the disc the GGBFS powder tends to form lumps and does not increase the distribution of particle size. The amount of sprayed water was about 18-20 % by weight of the dry powder mixture .The pellets formed approximately in 10 min. After formation the second step was go on with pelletizing to more stiffening of the fresh pellets that would takes approximately 10 min .

So the characteristic production period held about 20 min. Afterward, the produced fresh aggregates were kept in sealed plastic bags and stored for hardening in a curing room at a temperature of 20 ^{o}C and a relative humidity of 70% for 28 days. Thereafter, the hardened ASA was sieved into fractions of 4-16 mm sizes to be used

in SCCs production as coarse aggregate as seen in Figure 3.2. European Federation for Specialist Construction Chemicals and Concrete Systems(EFNARC) states that the maximum aggregate size used in SCC should be 20 mm [33].

The determination of aggregate properties are needed for this the specific gravity and the water absorption tests were carried out as per ASTM C127 [113],while crushing strength test was performed as per BS 812, part 110 [114].

Water Absorption after 24 hr showed 4.38% while specific gravity of produced aggregate for bulk, saturated surface dry and apparent specific gravities were 2.04, 2.14, and 2.39 respectively. Moreover, crushing strength of the produced aggregate is shown in Figure 3.3.
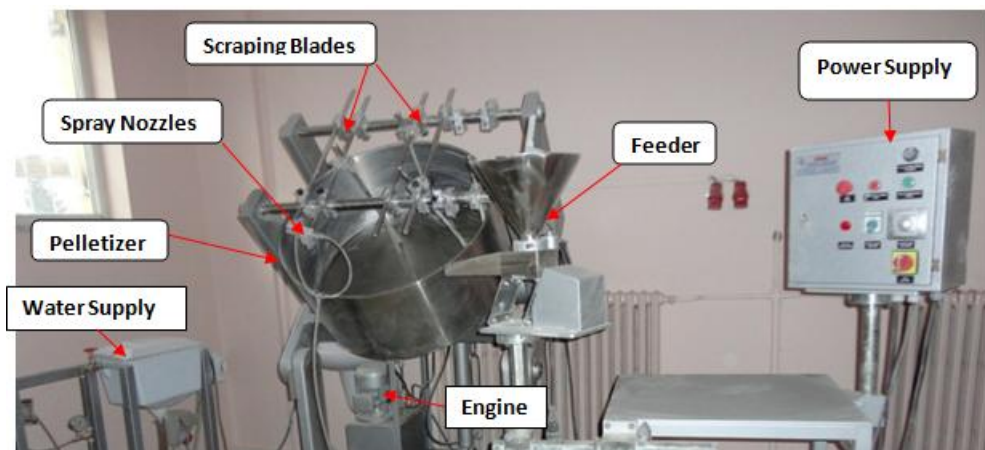
Figure 3.1 The general view of the pelletization disc

Figure 3.2 View of Cold bonded slag aggregate
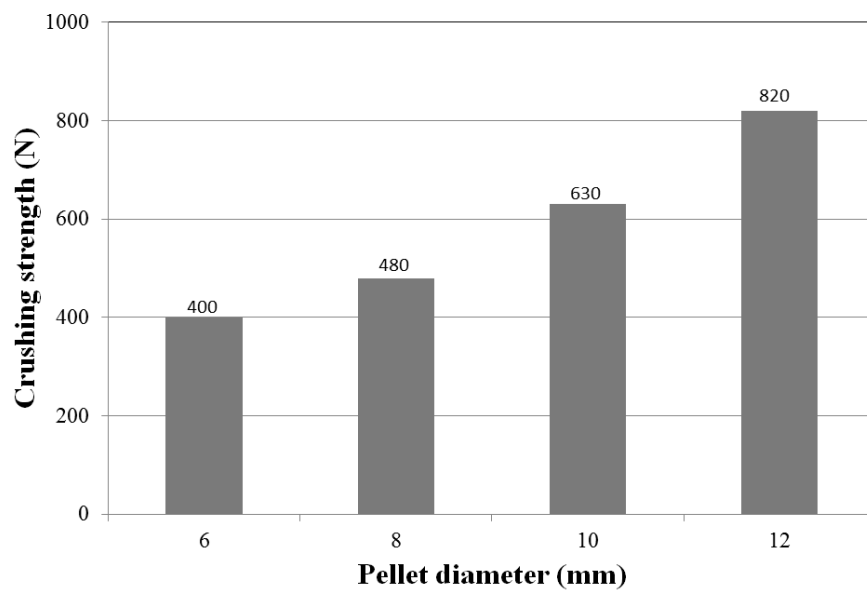
Figure 3.3 Crushing strength of the produced ASA

3.2.4.2 Natural Aggregates

The coarse aggregate used was river gravel with a nominal maximum size of 16 mm. As fine aggregate, a mixture of natural river sand and crushed limestone was used with a maximum size of 5 mm. The coarse aggregate had water absorption about 0.45%. The water absorptions of natural river sand and crushed limestone were 0.55% and 0.92% respectively The particle size gradation obtained through the sieve analysis, physical properties, and specific gravity of the fine and coarse aggregates are presented in Table 3.3.

Table 3.3 Sieve analysis and physical properties of natural aggregate

Sieve Size(mm)	Fine Aggregate (%)		Natural Coarse Aggregate (%)
	River sand	Crushed sand	
31.5	100	100	100
16	100	100	100
8	99.7	100	31.5
4	94.5	99.2	0.4
2	58.7	62.9	0
1	38.2	43.7	0
0.5	24.9	33.9	0
0.25	5.4	22.6	0
Fineness modulus	2.79	2.38	5.68
Specific gravity	2.66	2.45	2.72

3.3 Concrete Mixture Details

A total of six concrete mixtures at a constant water/binder ratio 0.32 were designed to cover a range of different mixture variations. A total binder content of 550 kg/m^3 was used by incorporating binary cementitious blends in which a proportion of portland cement was replaced with 20% fly ash constant for all the mixtures. Testing parameters relevant to cold bonded GGBFS aggregate (ASA) are mainly the

coarseaggregate volume fraction. The selected volume fractions of ASA are 20, 40, 60, 80 and 100 percent of the total coarse aggregate volume as shown in Table 3.4.

3.4 Concrete Casting, Test Specimens, and Curing

In the manufacturing of SCCs, the mixing sequence and duration are very important. All concretes were mixed in accordance with ASTM C192 [115] standard in a power driven rotating pan mixer. A procedure for batching and mixing was followed to supply the same homogeneity and uniformity in all mixtures [116]. Before mixing, the cold bonded aggregates are immersed in water for 30 minutes to ensure saturated surface dry condition of aggregate [23,25,117].

The batching sequence consisted of homogenizing cement and mineral admixtures for 30 s in a rotary planetary mixer, then adding the cold bonded aggregate into the mixer and continuing to mix for 30s. Thereafter, the fine aggregates were added and mixing was resumed for 30s then the natural coarse aggregate was added and mixing for 30s. Finally, HRWRA with water was added in two parts to avoid the segregation. The concrete was mixed for 3 min and then left for 2 min rest. Eventually, the concrete was mixed for additional 2 min to complete the mixing sequence. The workability of the SCCs were controlled through the slump flow test. The slump flow diameters of all the mixtures were designed to be in the range of 70 ± 5 cm to satisfy the EFNARC limitation [33]. Trial batches were produced for each mixture until the desired slump flow was obtained by adjusting the dosage of the HRWRA. From each concrete mixture, four 150 mm cubes, eight Ø100 x 200 mm cylinders and two Ø150 x 300 mm were also cast full without any vibration or compaction. After 24 hours of casting the samples were demoulded and cured in water until the testing ages.

Table 3.4 Concrete mixture proportions in kg/m^3

No.	Mix ID	P.C	FA	Fine Aggregate		Coarse Aggregate		Water	S.P	W/b ratio	Density
				Crush sand	Natural sand	Natural coarse	ASA				
1	M1	440	110	194	598	824	0	176	8	0.32	2350
2	M2	440	110	194	598	659	130	176	8	0.32	2315
3	M3	440	110	194	599	495	261	176	7.4	0.32	2282
4	M4	440	110	194	599	330	392	176	7	0.32	2248
5	M5	440	110	194	601	165	523	176	5.6	0.32	2215
6	M6	440	110	195	602	0	656	176	4.2	0.32	2182

3.5 Tests For Fresh Properties

The slump flow, T_{50} flow time, V-funnel flow time and L-box height ratio tests was carried out to identify the required properties and the characteristics of fresh SCCs mixtures with the recommendations given in EFNARC [33].

3.5.1 Slump Flow Test

To measure the slump flow, an ordinary slump flow cone is filled with SCC without any compaction and leveled. The cone is lifted and average diameter of the resulting concrete spread is measured as seen Figure 3.4. A slump flow value ranging from 55 cm to 85 cm for a concrete to be compacted according to EFNARC [33]. In this study, slump flow diameter of all the mixtures was kept constant at about 70 ±5 cm. In the slump flow test, the time (T_{50}) was also measured which determines the time taken for the concrete to reach the 50 cm spread circle. A lower time indicates greater flowability. EFNARC [33] suggests a T_{50} of 2 to 5 sec for a SCCs.
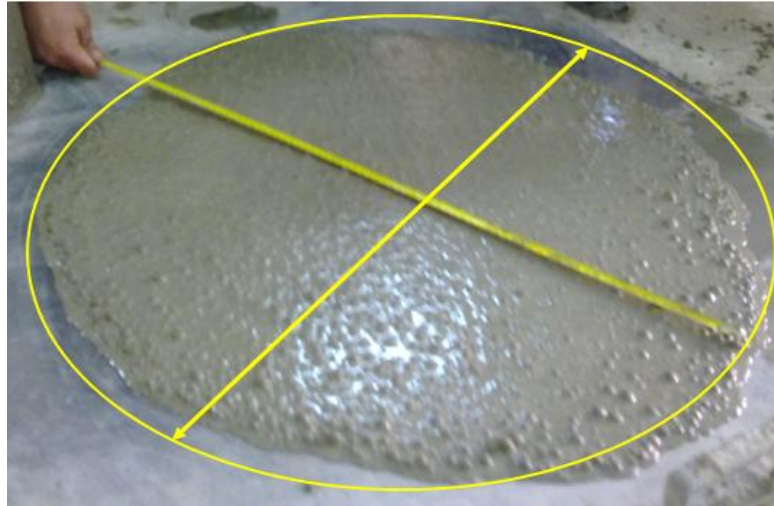
Figure 3.4 Photographic view of slump flow diameter measurement

3.5.2 V-Funnel Flow Test

In evaluating the filling ability and the viscosity of the mixtures the V-Funnel test was conducted as presented in Figure 3.5. The fill time is determined using a simple procedure in which the funnel is completely filled with fresh concrete, and the flow time is measured as the time between the opening of the orifice and the complete emptying of the funnel. Good fill able and stable concrete would consume short time to flow out. According to Khayat et al [118], a funnel test flow time (t_{V-f}) less than 6 sec is recommended for a concrete to qualify for self compacting. According to EFNARC [33], t_{V-f} ranging from 6 to 12 sec is considered adequate for SCCs.
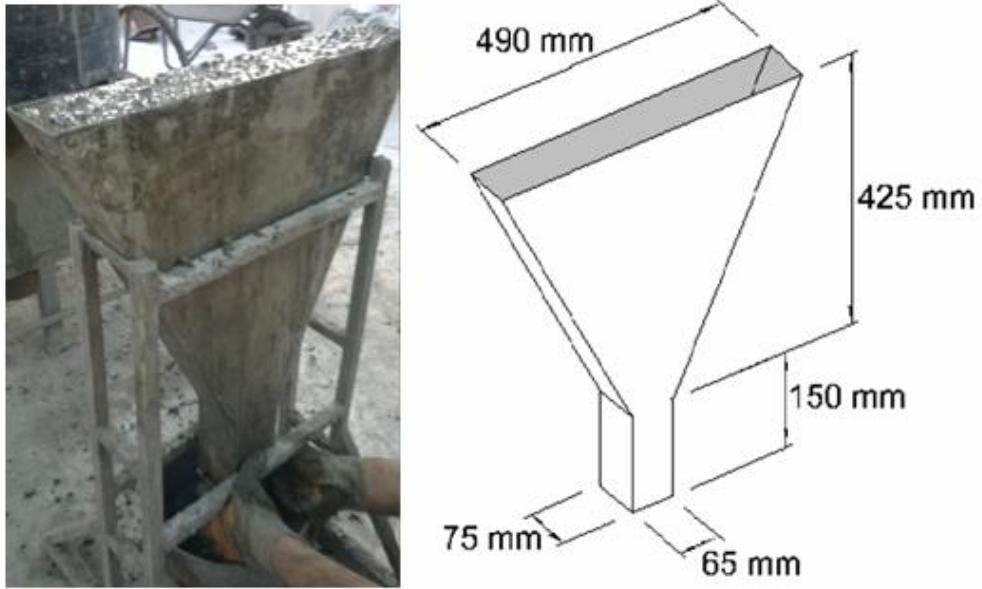
Figure 3.5 V-Funnel Test Apparatus

3.5.3 L-box test

The L-box apparatus consists of a rectangular-section box in the shape of an 'L', with a vertical and horizontal section, parted by a moveable gate, in frontal of which vertical portions of a reinforcement bar are provided Figure 3.6. The vertical section is filled with concrete, and then the gate is lifted to allow the concrete flow into the horizontal section. When the flow has stopped, the highness of the concrete at the end of the horizontal section is declared as a ratio of that residual in the vertical section. This is an signal of passing ability, or the degree to which the passage of concrete between the bars is limited. L-box test reviews filling and passing ability of SCCs, and serious lack of stability (segregation) can be discovered visually. Segregation may also be discovered by following sawing and checking sections of the concrete in the horizontal section. Typical approval values according to EFNARC [33] are in the range of 0.8 to 1.0. If the concrete flows as freely as water, at rest it will be horizontal, so H_2/H_1 reaches (1).

48
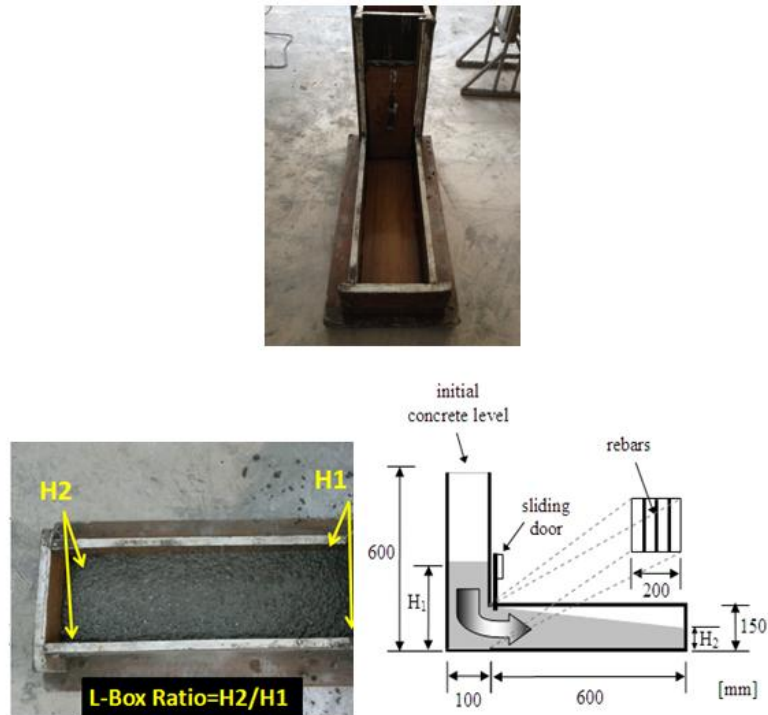
Figure 3.6 Photographic view of L-box apparatus and testing procedure

3.6 Tests for Mechanical Properties

3.6.1 Compressive and splitting tensile strength

Compression tests were conducted on the concrete samples at the end of 28 and 56 days curing periods. These tests were made on four 150 mm cubes with respect to ASTM C 39 [119]. The loading rate was constant and same for all concretes.

3.6.2 Splitting tensile strength

The splitting tensile strength determination was generally carried out in accordance with the ASTM C 496 [120]. Two 100x300 cylinders for each mixture were tested at the ages of 28, and 56 days. The tensile strength was calculated by the equation;

$$ft = \frac{2P}{\pi DL} \tag{1}$$

Where f_t is the tensile strength in MPa; P is the maximum load applied in N; and D and L the diameter and the length of the cylindrical specimen, in mm. The result is given as the average of samples in this study.

3.7 Determination of Concrete Durability Related Performance

3.7.1 Rapid chloride permeability

In order to determine the penetration resistance of the concrete to chloride ions, rapid chloride permeability test (RCPT) was performed according to AASHTO T277 [121]. RCPT is based on the electrical conductivity of the concrete. Concrete discs of 100 mm in diameter and 50 mm in height were used for the test. The curved surface of the specimen is coated with paraffin first. Before the test, a standard vacuum saturation procedure was applied to the specimens. Specimens were put between test cells, one of which containing NaCl solution and the other NaOH solution as seen in Figure 3.7. Then the concrete sample was subjected to a potential difference of 60 V and the total charge was measured by data logger registered the current passing through concrete over six hours period and expressed in terms of Coulombs as a basis for the evaluation of the concrete chloride permeability. Terminating the test after 6 hours, AASHTO T277 had a classification to chloride permeability in concrete which consist of five classes starting from 'High' to 'Negligible' on the basis of the coulomb as shown in Table 3.5. Figure.3.8 shows graphic arrangement of the test set up for RCPT.

Figure 3.7 Rapid chloride permeability test
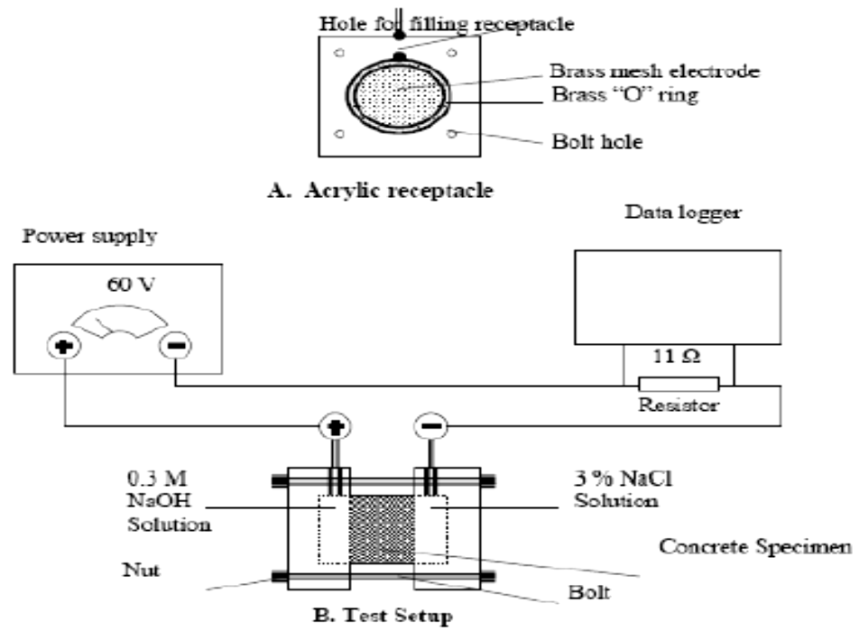
Figure 3.8 Schematic presentation of the test set up for RCPT

Table 3.5 Analysis of Test results obtained using RCPT

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

3.7.2 Gas permeability

The gas permeability of the concrete mixtures was performed by using a CEMBUREAU Method recommended by RILEM TC 116 [122] The graphic view and line diagram of the apparatus as well as the detail of the testing cell are shown in Figure 3.9-3.11. Two specimens were taken simultaneously for each concrete mixture after curing period of 28 and 56 days was ended. Both specimens should have a diameter of 150 mm and a thickness of 50 mm; concrete disc specimens cut from the mid portion of Φ150x300 mm cylinder. Cutting process must be careful to ensure the avoidance of cracking or any other damage. Oxygen gas was used as passing through medium, oxygen gas was applied to the specimens at disparity pressures changeable from 150 to 500 KPa in pressure cells, which were secured by a strongly fitting rubber pressuring under high pressure next to the curved surface. Before testing the pre-conditioning of the specimens is necessary to obtain meaningful results.

For this the specimens would be dried at 105° C in oven to guarantee maximum 1% weight change within the specimens. After oven drying process specimens were kept in a sealed envelope till test began. The average of two specimens was reported as a test result.

Underlying principle was Hagen- Poiseuille relationship [123] for laminar flow of a compressible fluid through a porous body with small capillaries under steady-state conditions. The relationship solved for the specific permeability coefficient K_A can be written as follows:

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

Where K_A is the gas permeability coefficient in m^2, P_1 is the inlet gas pressure in N/m^2, P_2 is the outlet gas pressure in N/m^2, A is the cross-sectional area of the sample m^2, L is the height of sample in m, μ is the viscosity of oxygen ($2.02 \times 10^{-5.12}$ Ns/m^2), and Q is the volume flow rate in m^3/s.
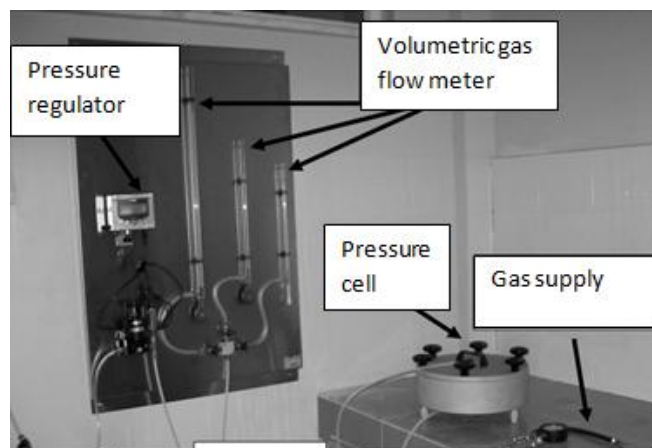
Figure 3.9 Photographic view of the gas permeability test set up and details
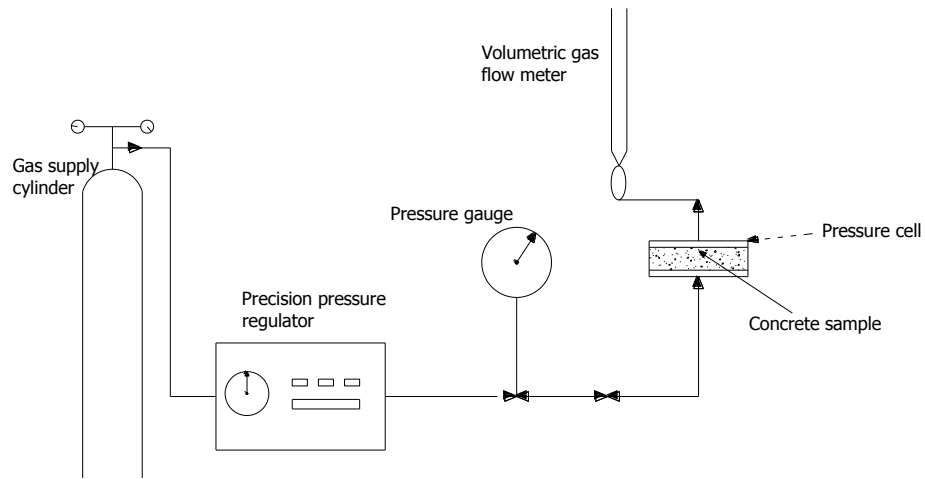
Figure 3.10 Schematic presentation of the gas permeability test set up
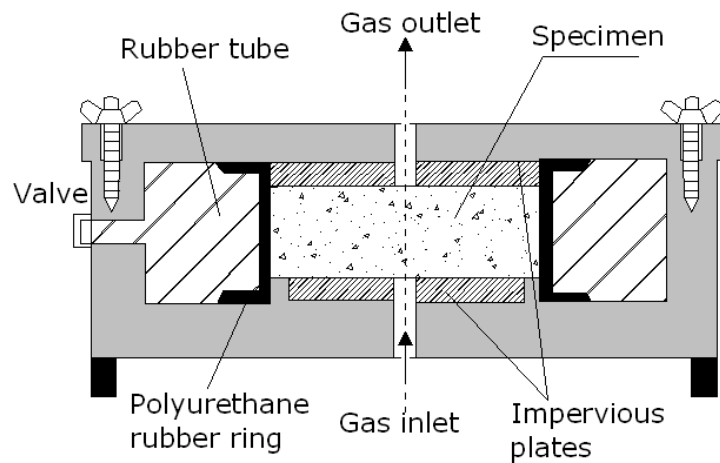
Figure 3.11 Schematic presentation of the pressure cell and test specimen

3.7.3 Sorptivity

Water absorption evaluated by the water uptake from the concrete per unit cross-sectional area with time, is referred to as the sorptivity according to ASTM C 1585 [124]. The test was conducted on the surface of concrete which is in contact with a thin water layer while the sides of the specimens were coated by paraffin, capillary suction was considered the dominant invasion mechanism .

This test was performed on two cylinders specimens of 100 mm in diameter and 50 mm in height, which are supported by rods immersed in water of 3~5 mm as shown in Figure.3.12. Prior the sorptivity test the specimens must dried in a low temperature of 50 °C to prevent micro cracking, thus leading to relatively realistic values and then allowed to cool to ambient temperature in a sealed container. The initial weight of the specimen was measured before contacting water. Specimens were removed from the tray and weighed at different time intervals up to 1 hour to evaluate the mass gain.

By dividing the mass gained by the supposed surface area of the specimen the volume of water absorbed was calculated and the density of water then plotted with respect to square root of time. Sorptivity coefficient was represented as the slope of most excellent fit line.
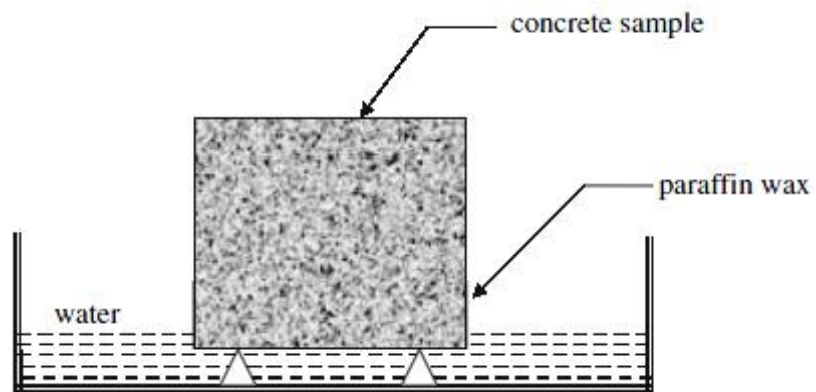
Figure 3.12 Measurement of concrete sorptivity

CHAPTER 4
TEST RESULTS AND DISCUSSIONS

4.1 Fresh Concrete Properties

4.1.1 Slump flow diameter

Among this study, the design limits for all of concrete mixtures were to give a slump flow diameter of 70±5 cm, which being achieved using HRWRA at varying amounts. Consequently, as seen in Table 4.1 slump flow diameter of the concretes ranged from 70 to 75 cm, conforming EFNARC recommendations, which state lower and upper approval limits of slump flow diameter to be in between 55 and 85 cm, respectively. The lowest slump flow diameter was measured for the control concrete with 0% ASA, namely (M1) while the mixture had the maximum slump flow diameter was for (M6) with 100% ASA. Besides the efficiency of ASA to increase the slump flow diameter it had another advantage to decrease the HRWRA demand required to obtain the expected slump flow as it is obvious in Table 4.1. In case of control mixture M1, for example, 8 kg/m^3 of HRWRA was incorporated while M6 (the mixture with 100% replacement of ASA) needed only 4.2 kg/m^3 of HRWRA for a given slump flow diameter. For that reason, theSCCs made with ASA coarse aggregates, had better flow characteristics. This can be referred to the rounded shape as well as relatively smooth surface of the ASA grains which provides ease in flow of the other aggregate particles and paste. Moreover, due to the increase in the ratio of roundness within the total coarse aggregate volume the

inclusion of ASA offers an advantage in flow improvement against the blocking effect of angular particles as a result of interlocking in the fresh state. The recent studies about SCCs also confirmed the roll of aggregate particles shape to achieve mixture self-compatibility, it was observed from these studies that self compatibility is achievable at lower cement (or fines) content when rounded aggregates were used, as compared to angular aggregates [35-37].Figure 4.1 showed that the target slump flow diameters were able to be achieved for all the mixtures so that the fresh SCCs appeared to match SF2 slump flow class as planned. Such concretes are applicable for greater part of R.C structural members [33].

4.1.2 Times of V-funnel flow and slump flow

$T_{50 cm}$ slump flow and V-funnel flow times of the produced SCCs were presented in Table 4.1 Figures4.2 and 4.3, respectively. It was observed that increasing the replacement level of ASA decreased both $T_{50 cm}$ slump flow and V-funnel times of SCCs. For example, $T_{50 cm}$ slump flow and V funnel flow times were 3.43 and 17.22 sec, respectively for the control mixture. However, as the ASA replaced the natural aggregates as in the case of mixture M6, the corresponding measurements decreased to 1.0 sec for the former and 5.31 sec for the latter. According to EFNARC [33] viscosity should be specified only in special cases such as best surface finish and in limiting the formwork pressure or improving the segregation resistance.

Depending upon conformed viscosity limit in EFNARC [33], slump flow time vs. V-funnel time of the SCCs were plotted in Figure 4.4. As seen in Figure 4.4 that, out of six SCCsmixtures, the mixtures M1 to M4 were classified as VS_2/VF_2 while the other two (M5 and M6) were in the category of VS_1/VF_1. The concretes having

viscosity class of VS_2/VF_2 may be applied at the ramps and walls/columns with SF2 class slump flow diameter. However for the higher replacement levels of ASA namely, 80% and 100%, viscosity shifted to the VS_1/VF_1 class which makes these concretes as the most suitable types for construction of wide span slabs. The tendency of the change of viscous behavior of the concretes can also visually be observed from Figure 4.4. The path shown by the arrows on Figure 4.4 indicated that the flow times, especially, for V-funnel, noticeably reduced by increasing the amount of ASA. In the study of Tobes et al.it was concluded that the shape and texture of coarse aggregate modify the flowability and strongly affect the plastic viscosity of SCC mixing energy as well [125].

4.1.3 L-box height ratio

In order to identify the passing ability of the produced SCCs, L-box height ratio was determined. The test provided H_2/H_1 ratio as a measure of the passing ability among the reinforcing bars. The variation in the three bar L-box height ratio is presented in Figure. 4.5. To declare that a self-compacting concrete has the passing ability, L-box height ratio must be equal to or greater than 0.8. It should be noted that this ratio being 1.0 for perfectly fluid behavior of the concretes. It was obviously monitored in Figure 4.5 that all of the mixtures satisfied the EFNARC limitation given for the L-box height ratio. Findings of this test pointed up that incorporation of ASA provided a systematic increase in the L-box height ratio up to 80% as listed in Table 4.1. Since the maximum height ratio had been reached at that replacement level, increasing ASA amount to 100% also yielded the same height ratio as expected. Although there have been several studies on the effect of coarse aggregate content on the flow behavior of SCC, it was concluded that in the case of SCC, rounded aggregates

would provide a better flow ability and less blocking potential for a given water-to-powder ratio, compared to angular and semi-rounded aggregates [35-37].

Table 4.1 Slump flow, L-box , V-funnel properties and HRWRA content of SCCs

Mix NO	Mix Description	Slump flow		V-Funnel flow time	L-box	HRWRA
		D	T_{50}			
		(cm)	(sec)	(sec)	(H_2/H_1)	(kg/m^3)
M1	Control 0% ASA	70	3.43	17.22	0.887	8
M2	20% ASA	74	2.28	17.15	0.946	8
M3	40% ASA	73	2.25	14.03	0.962	7.4
M4	60% ASA	73	2.12	8.4	0.993	7
M5	80% ASA	74	1.56	5.41	1	5.6
M6	100% ASA	75	1	5.31	1	4.4
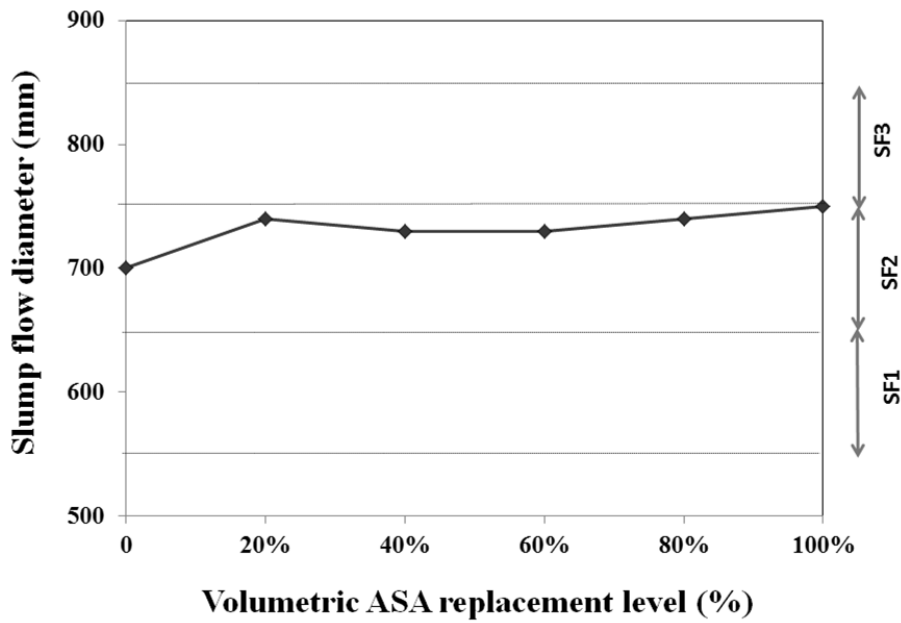
Figure. 4.1 Variation of slump flow diameter with the cold bonded ASA contents
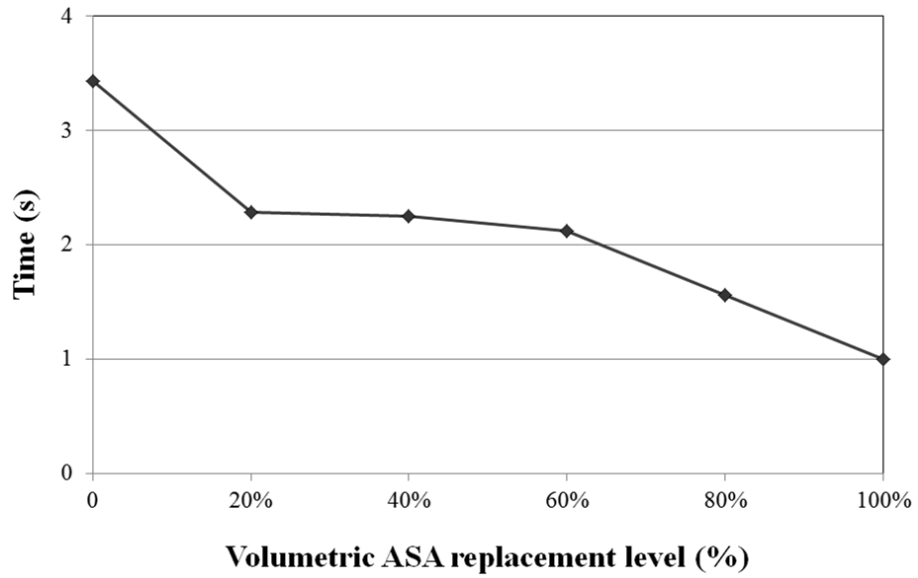
Figure.4.2 Variation of $T_{50\,cm}$ slump flow time with the cold bonded ASA contents
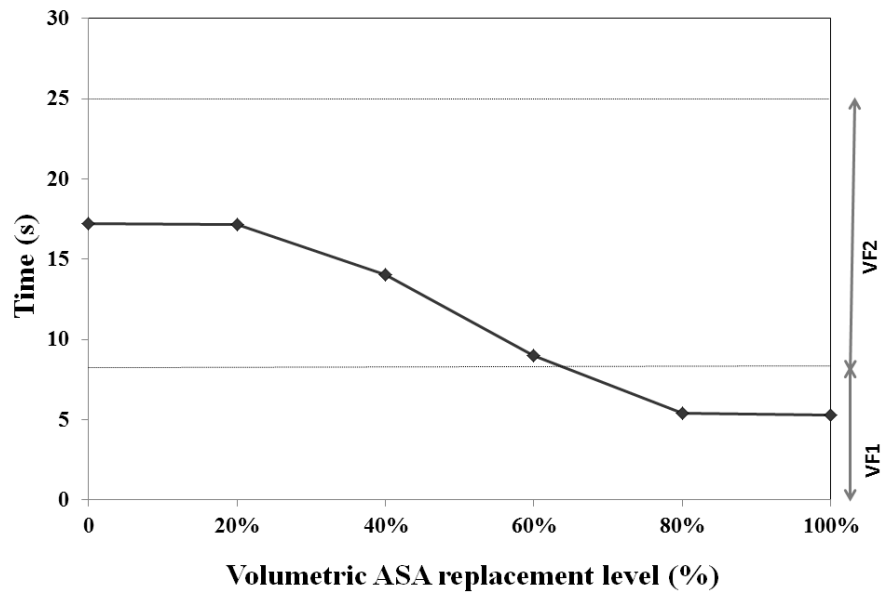
Figure 4.3 Variation of V-funnel flow time with the cold bonded ASA contents
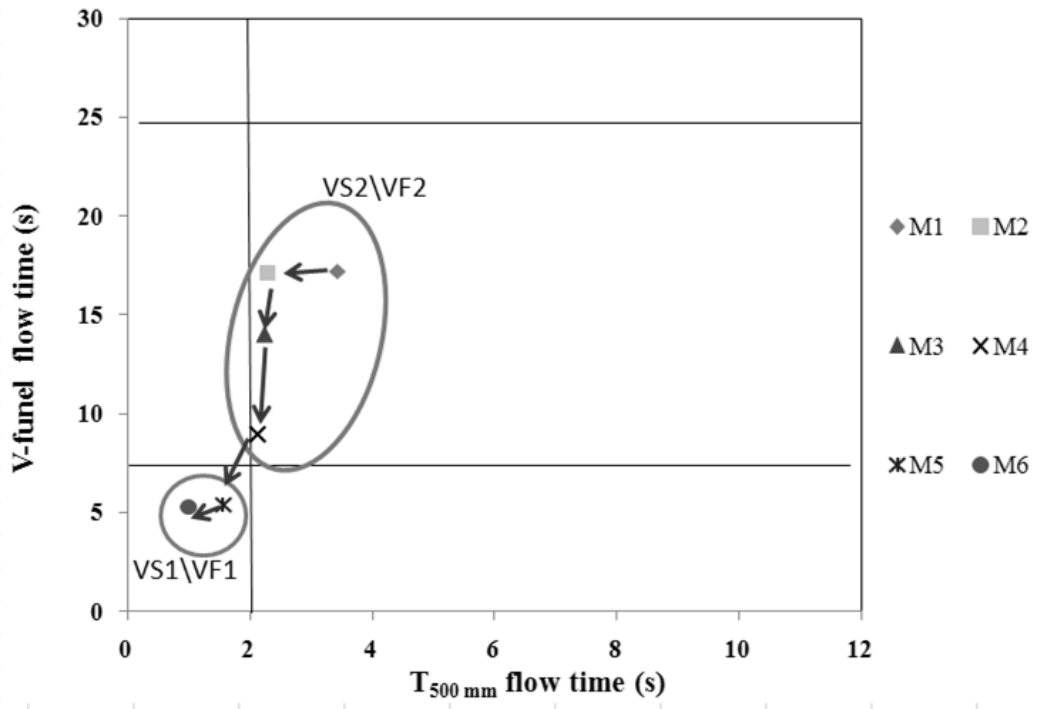
Figure 4.4 Variation of viscosity classes with $T_{50 cm}$ slump flow and V-funnel flow times
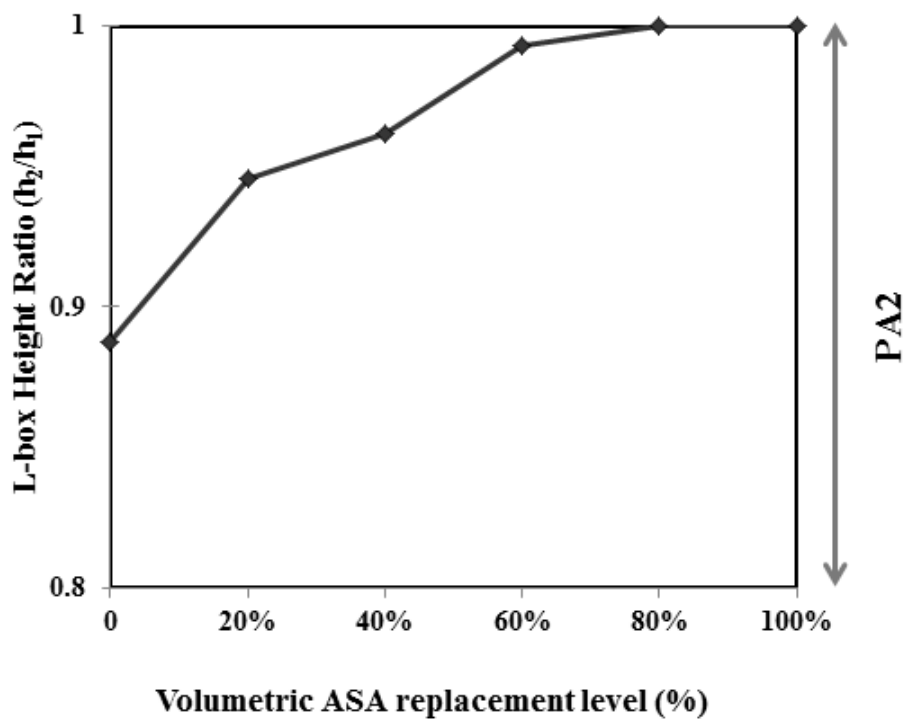
Figure 4.5 Variation of L-box height ratio with the cold bonded ASA contents

4.2 Mechanical Properties

4.2.1 Compressive strength

Variation in compressive strength of the concretes incorporating varying amounts of ASA (0%, 20%, 40%, 60%, 80% and 100%) was presented in Figure 4.6. The summary of the test results relevant to the compressive strength of the concretes are given in Tables 4.2. It was observed that the concretes with cold-bonded ASA had higher compressive strength than the control concrete, irrespective of the testing age. When compared to control concrete tested at 28 days, the compressive strength of concretes increased by 5.6%, 9.5%, 14.4%, 6.7% and 5.4% as ASA had replaced the natural coarse aggregates at 20, 40, 60, 80, and 100 % respectively. For the same replacement levels, using ASA enhanced the 56-day compressive strength by as high as 10% compared to the reference concrete. The highest strength was obtained at 60% replacement level of ASA indicating this level being optimum content of ASA as long as the compressive strength is taken into account. This improvement in the compressive strength of concretes is linked to pozzolanic reaction occurring between dissolved minerals from cold-bonded slag algorithm and calcium from portlandite. The action appeared to be more pronounced with higher mineral content and longer curing period. Hydroxyl ions break down the silica in the algorithm, which in turn react with the calcium in the portlandite to form CSH paste. This reaction increases the bond strength between the aggregate and cement paste. Since artificial cold-bonded aggregate are of porous structure, a pozzolanic reaction expected on the surrounding phase of this aggregate cause slag to be a real binder [26]. During the hydration of Portland cement, the Ca(OH)2 enters in reaction with slag components forming the CSH which playing the role of filling empty spaces in binding medium thus reinforcing the concrete structure [126].

4.2.2 Splitting tensile strength

Tensile strength characteristics of SCCs are of considerable importance and the split tensile test is a simple and reliable method of measuring the tensile strength. The variation of split tensile strength with coarse aggregate replacements at different curing ages arepresented in Table 4.2 and Figure 4.7 respectively.

It was seen that tensile strength of the concretes decreased with increasing cold-bonded slag aggregate in the mixtures. The results indicated that the optimum replacement level being 20% for the tensile strength. The reduction in strength may be due to the presence of unfilled micro-voids in the concrete mixtures with increase of cold-bonded slag aggregate. These micro-voids might have acted as the weak zones for the initiation and propagation of tensile cracks offering a lower ultimate tensile strength for the hardened composites.

This phenomenon can be explained by the non-compatibility of natural and artificial gravels due to their chemical compositions and their physical characteristics. This situation is entirely consistent with the previous study conducted by Euro Light Concrete project (EuroLightCon) which had found that the splitting tensile strength of concrete mixture decreases with increasing artificial aggregate volume replacement [127].

Table 4.2 Mechanical properties of SCCs.

Mix NO	Mix Description	Compressive strength(MPa)		Splitting tensile strength(MPa)	
		28 days	56 days	28days	56days
M1	Control0%ASA	60.96	71.38	3.351	3.533
M2	20% ASA	64.38	72.92	3.395	3.638
M3	40% ASA	66.78	73.59	3.067	3.378
M4	60% ASA	69.74	78.84	3.317	3.44
M5	80% ASA	65.06	78.14	2.635	3.04
M6	100% ASA	64.27	77.2	2.696	2.942
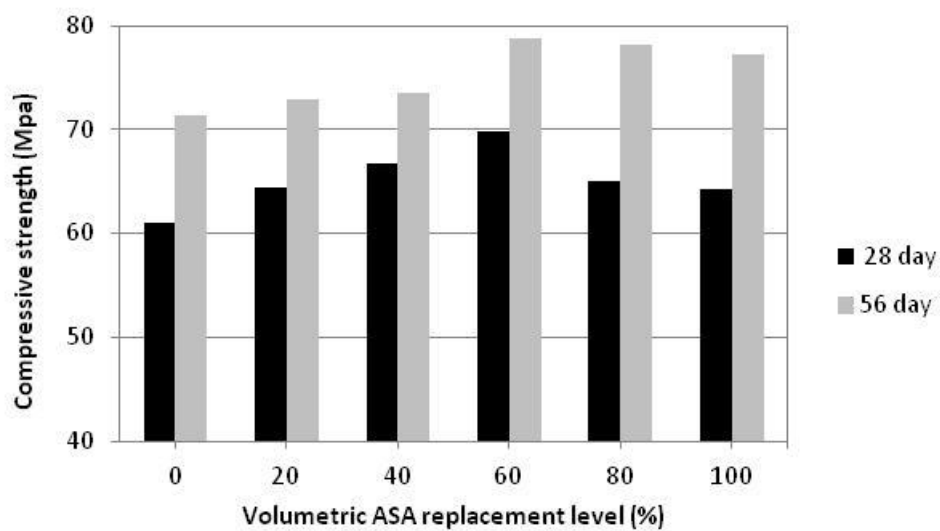
Figure 4.6 Variation of compressive strength with ASA replacement level
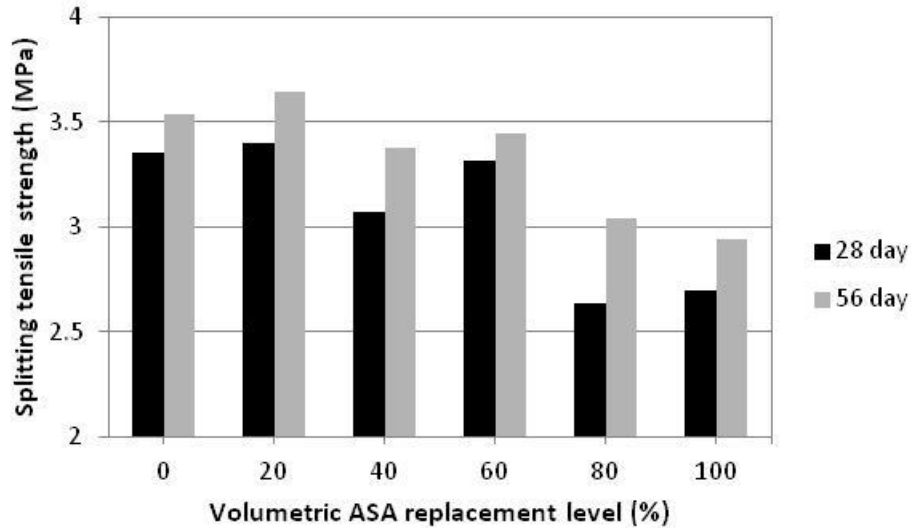
Figure 4.7 Variation of split tensile strength with ASA replacement level

4.4 Durability Related Properties

4.4.1 Chloride ion permeability (RCPT)

Incorporating cold-bonded slag aggregate at varying amounts in the concretes exhibited significantly lower permeability than the control mixture, irrespective of the testing age as presented in Table 4.3 and Figure 4.8 respectively. There was an asymmetric decrease in chloride-ion permeability with increasing cold-bonded aggregate content ranging from 1637.01 coulombs in the control mixture to 561.78 coulombs at 60% replacement level. The permeability classes of the concretes were reported between low to very low permeability concretes according to AASHTO T 277 [121] at 28 days. At 56 days, similarly, the control concrete had a low chloride ion permeability which shifted to be very low for all ASA modified concretes. As seen in the compressive strength, the concrete with 60 % ASA had better performance against chloride ion penetration. Moreover, a remarkable correlation can be concluded between the compressive strength and chloride ion permeability. The study of Mohr et al demonstrated that the changes in RCPT values are arrested

by changes in compressive strength. This is best described by the role the concrete microstructure has on both properties [128].

Table 4.3 Chloride ion permeability of SCCs

Mix NO	Mix Description	Chloride ion permeability (coulombs)	Rating	Chloride ion permeability (coulombs)	Rating
		28 days	28 days	56 days	56 days
M1	Control0%ASA	1637.01	Low	1052.06	Low
M2	20% ASA	1323.09	Low	850.32	very low
M3	40% ASA	895.14	very low	866.07	very low
M4	60% ASA	561.78	very low	379.08	very low
M5	80% ASA	738.09	very low	579.69	very low
M6	100% ASA	968.76	very low	714.24	very low
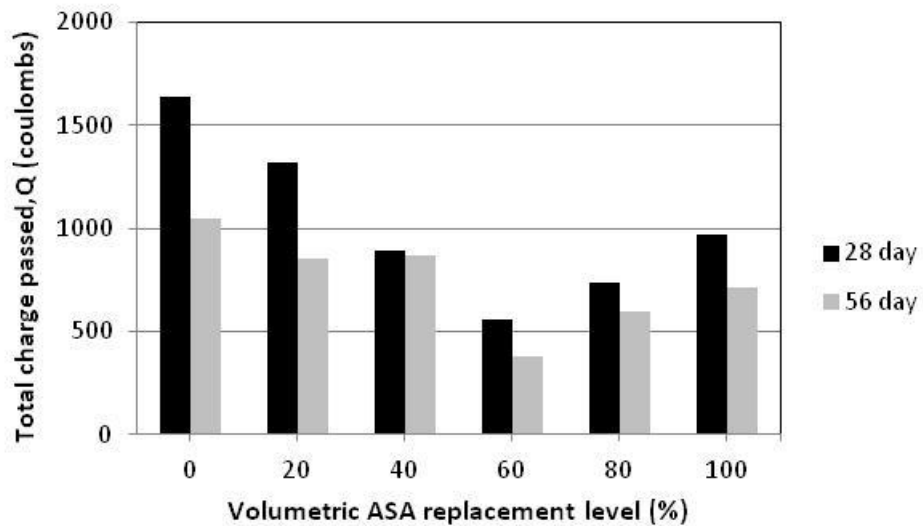
Figure 4.8 Variation of chloride ion permeability with ASA replacement level

4.4.2 Gas Permeability

According to equation (1), apparent gas permeability of each concrete has been obtained at the end of the 10 min interval for each stress level by using the volumetric gas flow rate. RILEM TC 116 [122] recommends the use of 150, 200, and 300 KPa inlet pressures for determining the average gas permeability coefficient. Thus, the coefficients of apparent gas permeability obtainedafter 28 and 56 days of curing are presented in Table 4.4 and Figure 4.9 respectively. It was observed that the permeability coefficients were found to be (10.97, 9.97, 11.69, 7.89, 4.92 and 3.51)$\times 10^{-16} m^2$at 0, 20, 40, 60, 80, and 100% ASA incorporated concretes, respectively,at 28 days.

The apparent gas permeability coefficient was increasing with increasing the ASA replacement rate of 20 and 40% compared to the control mixture, irrespective of the curing age. However, in the case of 60,80, and 100% ASA contents, the concretes exhibited lower gas permeability thancontrol mixture at both 28 and 56 days. This behavior may be attributed to the amount of ASA that giving the opportunity to proceed more pozzolanic reaction between interfacial transition zone and matrix that cause better hydration and filling the pores and existed void with sufficient hydration product. The study of Hui-sheng et al. discussed about gas permeability of high-performance concrete (HPC) with FA or GGBFS. It was notedthat compressive strength and gas permeability are greatly affected by w/b ratios and sensitive to the blended cementitious systems [129].

Pressure Level (KPa)	Table 4.4 Gas permeability coefficient according to ASA replacement ratio (%)											
	Control 0% ASA		20% ASA		40% ASA		60% ASA		80% ASA		100% ASA	
	28 days	56 days	28 days	56 days	28 days	56 days	28 days	56 days	28 days	56 days	28 days	56 days
150	1.45E-15	6.10E-16	1.45E-15	8.23E-16	1.74E-15	1.33E-15	1.22E-15	3.27E-16	7.58E-16	5.37E-16	4.72E-16	4.85E-16
200	9.62E-16	3.74E-16	8.75E-16	7.28E-16	1.04E-15	7.62E-16	6.92E-16	3.58E-16	4.41E-16	3.32E-16	3.90E-16	2.97E-16
250	7.10E-16	3.05E-16	6.93E-16	6.05E-16	8.00E-16	5.61E-16	5.23E-16	4.61E-16	3.38E-16	2.65E-16	3.23E-16	2.42E-16
300	9.92E-16	2.66E-16	6.64E-16	6.30E-16	7.10E-16	4.96E-16	4.53E-16	2.96E-16	2.75E-16	2.23E-16	1.93E-16	2.19E-16
350	7.56E-16	2.51E-16	7.05E-16	6.07E-16	6.77E-16	4.57E-16	4.21E-16	4.00E-16	2.47E-16	1.97E-16	1.83E-16	2.00E-16
400	9.37E-16	2.93E-16	8.39E-16	7.65E-16	7.32E-16	4.14E-16	4.96E-16	4.14E-16	2.49E-16	2.19E-16	1.73E-16	2.00E-16
450	1.24E-15	3.12E-16	8.02E-16	7.04E-16	6.67E-16	4.12E-16	4.24E-16	4.12E-16	2.43E-16	2.28E-16	1.74E-16	2.00E-16
500	1.71E-15	3.84E-16	1.98E-15	9.85E-16	6.80E-16	5.87E-16	6.21E-16	5.87E-16	2.42E-16	2.07E-16	1.86E-16	2.00E-16
Mean	1.13E-15	4.17E-16	9.96E-16	7.27E-16	1.16E-15	8.63E-16	7.88E-16	3.27E-16	4.91E-16	3.64E-16	3.52E-16	3.34E-16
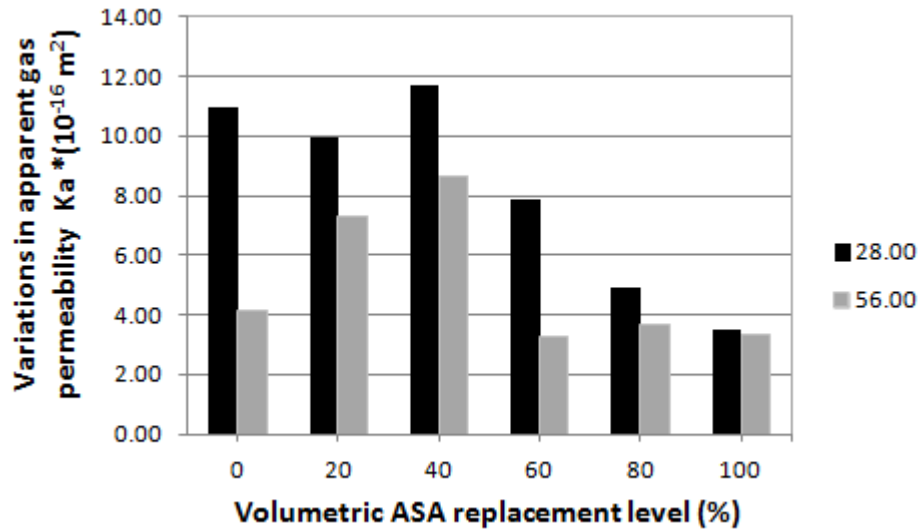
Figure 4.9 Variation of Gas permeability coefficient with ASA replacement level

4.4.3 Sorptivity index

Water sorptivity of a concrete surface relies on many factors involving concrete mixture proportions, attendance of chemical admixtures, supplementary cementitious materials, physical characteristics of aggregates and cementitious components as well as the placement method including consolidation and finishing. Table 4.5 and Figure 4.10 are presents the sorptivity coefficients of theSCCs depending on the contents of ASA as well as testing age.

Sorptivity displayed a marked decrease with increasing ASA. It can be observed that the sorptivity of 0.0787 mm/min$^{0.5}$of the control concrete at 28 days decreased to 0.0596 mm/min$^{0.5}$when the concrete included 100% ASA. Sorptivity coefficients measured at 56 days displayed a reduction as compared to those of the 28 days. Similar to the behaviour seen in the chloride ion permeability, increasing ASA provided gradual reduction in sorptivity coefficients especially at 60% replacement level and 56 days. As ASA replaced 60% of the natural coarse aggregates in SCC,the

56-day sorptivity of the concretesdiminished by as much as36%. Like chloride ion permeability and compressive strength, the concrete with 60% ASA displayed the best performance in terms of sorptivity. Beyond that level, sorptivity began to increase, especially at 56 days of testing age.

Table 4.5Sorptivity of SCCs

Mix NO	Mix Description	Sorptivity index ($mm/min^{0.5}$)	
		28 days	56 days
M1	Control 0% ASA	0.0787	0.0614
M2	20% ASA	0.0711	0.054
M3	40% ASA	0.0694	0.0522
M4	60% ASA	0.0711	0.0395
M5	80% ASA	0.0688	0.056
M6	100% ASA	0.0596	0.0556
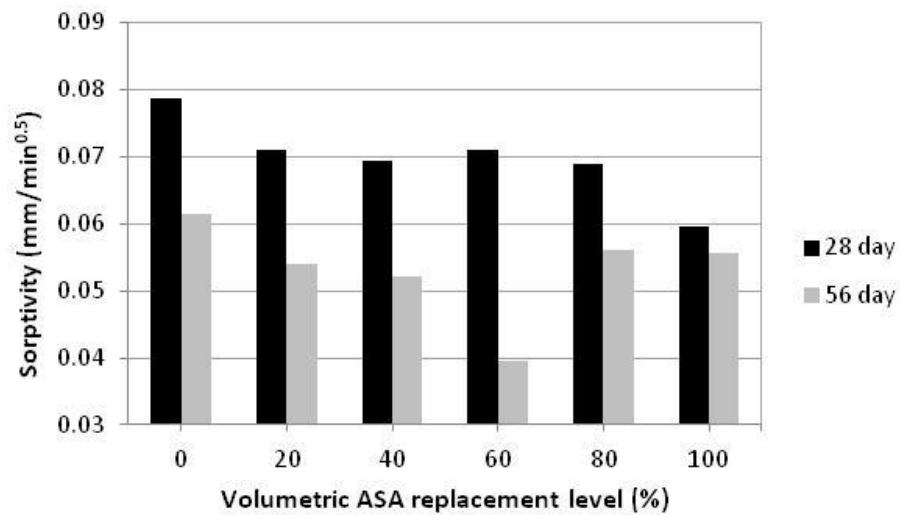
Figure 4.10 Variation of sorptivity coefficients with ASA replacement level

CHAPTER 5
Conclusions

Based on the findings of the study, the following conclusions may be drawn:

1. The artificial cold bonded slag aggregates was proved to be applicable in self compacting concrete production without any segregation and bleeding. Even at the most extreme level of replacement (100%), SCC without loss of uniformity and stability was produced.

2. All of the SCCs mixtures were designed to give a slump flow diameter of 700 ± 50 mm, which was achieved by adjusting the dosage of the super plasticizer used for the trial batches. In order to stay within the limits of the targeted slump flow diameter, the amount HRWRA was decreased with the increase in ASA replacement level.

3. Rounded shape and surface smoothness of the ASA particles provided enhancement in viscosity and flowability of the self compacting concretes. Increasing the rate of ASA provided the prevention of the interlocking the angular aggregate particles.

4. It was observed that increasing the replacement ratio of ASA resulted in a gradual increase in the L-box height ratio of SCCs mixes. Moreover, the height ratio reached to 1.0 for the mixtures with 80% and 100% replacement of ASA, revealing the highest fluid behavior.

5.   A systematic increase in compressive strength of the concretes was observed with increasing the percentage of ASA. All of the concretes containing ASA had greater compressive strength than that of the control concrete. The concrete with 60% ASA content had the highest compressive strength.

6.   However, the effect of incorporating ASA in SCC was to reduce the tensile strength. Higher the amount of ASA used the tensile strength of the concretes became lower.

7.   Using of ASA as a replacement for normal coarse aggregate enhanced the concretes against chloride penetration, especially at 56 days. The control concrete tested at that age had low rating according to AASHTO T 277 [121] while all of the concretes containing ASA displayed very low rating. The reduction in permeability and the resistance to chloride intrusion increased as the level of ASA increased in the concrete mixtures.

8.   Gas permeability and sorptivity tests reflect the permeability characteristics of the concretes. Lower permeability of the concretes enhanced higher durability. The concretes with higher content of ASA appeared to have relatively lower gas permeability coefficients. Similar to the behaviour seen in the chloride ion permeability, increasing ASA provided gradual reduction in sorptivity coefficients especially at 60% replacement level and 56 days.

9.   As a result of the tests conducted in this study SCC with 60% ASA content had generally better performance. The substitution of ASA made by cold-bonding process may be used as alternative of normal coarse aggregate in the production of SCCs.

REFERENCES

[1] Ozawa K., and Maekawa, K. (1989). Development of High Performance Concrete Based on Durability Design of Concrete Structure.*Proceeding of the Second East-Asia and Pacific Conference on Structural Engineering and Construction (EASEC-2)*, **V.1**, pp. 445-450.

[2] Persson B A. (2001).Comparison between mechanical properties of self compacting concrete and the corresponding properties of normal concrete. *Cement and Concrete research*, **V.31**,pp.193–8.

[3] Holton I.(2004). Self-compacting concrete.*BRE information Paper. Report IP 3/04, British Research Establishment*, Watford, UK.

[4] Sonebi M. (2004). Medium strength self-compacting concrete containing fly ash Modeling using factorial experimental plans. *Cement and Concrete Research*, **V.34**,pp.199–208.

[5] Nagamoto N, Ozava K. (1997). Mixture properties of self-compacting concrete.*In Proceedings of third CANMET/ACI International Conference on design and materials and recent advances in concrete technology, ACI SP 172, Kuala Lumpur, American Concrete Institute*, MI, USA: Farmington Hills, pp. 623–37.

[6] Okamura H, Onchi M. (1999). Self-compacting concrete: development, present use and future. *In Proceedings of First International Conference On Self-Compacting Concrete*, Stockholm, pp.13–14.

[7] Sari, M; Prat, E; and Labastire, JF.(1999). High strength self compacting concrete: original solutions associating organic and inorganic admixtures. *Cement and Concrete Research*,**V.29**, ,pp.813–818.

[8] Sakata, S.; Maruyama, K.; and Minami, M. (1996). Basic Properties and Effects of Welan Gum on Self Compacting Concrete.*Proceedings of RILEM International Conference on the Production Methods and Workability of Concrete, P. J. M. Bartos; D. L. Marrs; and D. J. Cleland, eds., E&FN Spon*, London, UK, pp. 1-24.

[9] Lachemi, M; Hossain, KMA; and Lambros, V; Nkinamubanzi, PC; Bouzoubaa, N. (2004). Performance of new viscosity modifying admixtures in enhancing the rheological properties of cement paste.*Cement and Concrete Research* ,**V.34**,No.2, ,pp.185–193.

[10] Saric-Coric, M.; Khayat, K. H.; and Tagnit-Hamou, A. (2003). Performance Characteristics of Cement Grouts Made with Various Combinations of High-Range Water Reducer and Cellulose-Based Viscosity Modifier. *Cement and Concrete Research*, **V. 33**, No. 12, pp. 1999-2008.

[11] Erdogan, T.Y.(1997). Admixture for Concrete.*METU Press*, Ankara, Turkey.

[12] Bouzoubaa, N., and Lachemi, M. (2001). Self-Compacting Concrete Incorporating High Volumes of Class F Fly Ash Preliminary Results. *Cement and Concrete Research*, **V. 31**, No. 3, , pp. 413-420.

[13] Bilgen, G.; Kavak, A.; Yıldırım, S.T.; and Çapar, O.F.(2010). Blast furnace slag and its importance in the construction sectors.*The Second National Solid Waste Management Conference*,.578, Mersin, Turkey.

[14] Su, N., Hsu, K.C. and Chai, H.W. (2001). A simple mix designs method for self compacting concrete. *Cement and. Concrete Research*, **V.31**, No.12, pp.1799-807.

[15] Kayali O. (2008). Fly ash lightweight aggregates in high performance concrete". *Construction and Building Materials*,**V.22**, pp.2393–2399.

[16] Gesoğlu ,M; Özturan, T., and Güneyisi, E. (2004). Shrinkage cracking of lightweight concrete made with cold-bonded fly ash aggregates. *Cement and Concrete Research*, **V. 34**, Issue 7, pp. 1121-1130.

[17] Zhang, M. H., and Gjorv, O. E. (1991). Characteristics of Lightweight Aggregates for High-Strength Concrete.*ACI Materials Journal*, **V. 88**, No. 2, pp. 150-158.

[18] Al-Khayat, H., and Haque, H. N. (1999). Strength and durability of lightweight and normal weight concrete.*Civil Engineering Material Journal*, **V.11**, No.3, pp. 231– 235.

[19] Kayali, O.; Haque, M.N., and Zhu, B. (1999). Drying shrinkage of fibre-reinforced lightweight aggregate concrete containing fly ash.*Cement and Concrete Research*, **V.29**, , pp.1835– 1840.

[20] Mayfield, M. Y. (1996). Composite action of foamed and lightweight aggregate concrete.*ASCE-Journal of Materials in Civil Engineering*, **V. 8**, No. 3, pp. 111-113.

[21] Arslan, H., and Baykal, G. (2006). Utilization of fly ash engineering pellet aggregates. *Environ Geol*, **V.50** , pp. 761–770.

[22] Baykal, G., and Döven, A.G. (2000). Utilization of fly ash as pelletization process; theory, application, areas and research results.*Resources Conservation and Recycling Journal*,**V.30** , pp. 59–77.

[23] Bui, Le Anh-tuan, Hwang, Chao-Lung, Chen, Chun-tsun, and Hsieh, Meng-Ying.(2012). Characteristics of Cold-Bonded Lightweight Aggregate Produced with Different Mineral Admixtures.*Applied Mechanics and Materials*, **V.174-177**, pp.978-983.

[24] Joseph, G., and Ramamurthy, K. (2009). Influence of fly ash on strength and sorption characteristics of cold-bonded fly ash aggregate concrete. *Construction and Building Materials*, **V.23**, pp.1862–1870.

[25] Gesoğlu, M.; Güneyisi, E.; and Öz, H. Ö. (2012). Properties of lightweight aggregates produced with cold-bonding pelletization of fly ash and ground granulated blast furnace slag. *Materials and Structures*, In press, Available online, DOI 10.1617/s11527-012-9855-9.

[26] Sivakumar A, Gomathi P.(2012). Pelletized fly ash lightweight aggregate concrete: A promising material. *Journal of Civil Engineering and Construction Technology*, **V.3**, No.2, pp.42-48.

[27] Wu, Z.; Zhang, Y.; Zheng, J.; and Ding, Y. (2009). An experimental study on the workability of self-compacting lightweight concrete.*Construction and Building Materials*, **V.23**, pp.2087–2092.

[28] Wang, H.Y. (2009). Durability of self-consolidating lightweight aggregate concrete using dredged silt.*Construction and Building Materials*, **V.23**, pp. 2332–2337.

[29] Khayat, K. H. (1999). Workability, testing, and performance of self-consolidating concrete, *ACI Materials Journal*, **V.96**, pp.346–353.

[30] Okamura, H. (1999). Self-Compacting High Performance Concrete.*Tokyo Social System Institute*.

[31] St John, D. A. (1998).Concrete Petrography. *A handbook of investigative techniques*, Wiley & Sons, New York

[32] Okamura, H., Ouchi, M. (2003). Self-compacting concrete.*Journal of Advanced Concrete Technology*.**V.1**, pp.5–15.

[33] EFNARC.(2005). Specification and guidelines for self compacting concrete.*Available at http://www.efnarc.org*.

[34] RILEM TC Final Report 188-CSC. (2006). Casting of self compacting concrete. *Materials and Structures*, **V.39**, pp.937–954.

[35] Mishima, N., Tanigawa, Y., Mori, H., Kurokawa, Y., Terada, K., Hattori, T. (1999). Study on Influence of Aggregate Particle on Rheological Property of Fresh Concrete.*Journal of the Society of Materials Science*, **V.48**, pp.858–863.

[36] Kurokawa, Y., Tanigawa, Y., Mori, H., and Nishinosono, K. (1996). Analytical Study on Effect of Volume Fraction of Coarse Aggregate on Bingham's Constants of Fresh Concrete.*Transactions of the Japan Concrete Institute*, **V.18**, pp.37–44.

[37] Grunewald, S, Walraven, J. C. (2001). Parameter-Study on the Influence of Steel Fibres and Coarse Aggregate Content on the Fresh Properties of Self-Compacting Concrete.*Cement and Concrete Research*, **V.31**, pp.1793–1798.

[38] O'Flannery, L. J., O'Mahony, M. M. (1999). Precise Shape Grading of Coarse Aggregate.*Magazine of Concrete Research*, **V.51**, pp.319–324.

[39] Nehdi, M. (2000). Why Some Carbonate Fillers Cause Rapid Increases of Viscosity in Dispersed Cement-Based Materials. *Cement and Concrete Research*, **V.30**, pp.1663–1669.

[40] Bosiljkov, V. B. (2003). SCC Mixes with Poorly Graded Aggregate and High Volume of Limestone Filler.*Cement and Concrete Research*, **V.33**, pp.1279–1286.

[41] Sedran, T., De Larrard, F. (1999). Optimization of Self Compacting Concrete Thanks to Packing Model.*Proceedings for first International RILEM Symposium on Self Compacting Concrete*, RILEM, pp.321–332.

[42] Senthil, V. K., Santhanam, M. (2003). Particle Packing Theories and Their Application in Concrete Mixture Proportioning.*Indian Concrete Journal*, **V.77**, pp.1324–1331.

[43] D. Ho, W. S., Sheinn, A. M. M., Ng, C. C., Tam, C. T. (2002). The Use of Quarry Dust for SCC Applications.*Cement and Concrete Research*, **V.32**, pp.505–511.

[44] Metha, K. (1986). Concrete: Structure, properties, and materials. *Ed. Prentice-Hall*, USA.

[45] Gagne, R., Boisvert, A. and Pigeon, M. (1996). Effect of Superplasticizer on Mechanical Properties of High - Strength Concretes with and without Silica Fume.*ACI Materials Journal*, **V. 93**, No. 2, pp.111-120.

[46] Whiting, D, and Dziedzic, W. (1979). Effects of Conventional and High-Range Water Reducers on Concrete Properties.*Portland Cement Association*, R & D Bulletin 107T.

[47] Hwang, S. D., Mayen-Reyna, D., Bonneau, O. and Khayat, K. H. (2003). Performance of Self-Consolidating Concrete Made With Various Admixture Combinations. *Proceedings of the 3rd International RILEM Symposium on Self-Compacting Concrete*, O. Wallevik and I. Nielsson, Ed., RILEM Publications, pp. 467 – 478.

[48] Ozyildirim, C. (2003). Investigation of Self-consolidating Concrete.*TRB*, **V. 345**, No.1.

[49] Mindess, S., Young, J. F. and Darwin, D. (2003). *Concrete, Second Edition, Prentice Hall.*

[50] Kosmatka, S. H., Kerkhoff, B. and Panarese, W. C. (2002). Design and Control of Concrete Mixtures.14th Edition, *Portland Cement Association*.

[51] Luke, K. (2002). Pulverized Fuel Ash as a Cement Extender.In Structure and Performance of Cements 2nd Edition, *Spon Press*, London.

[52] Mehta, P. K. (2000). Reflections on Recent Advancements in Concrete Technology.*Second International Symposium on Cement and Concrete Technology*, **V.1**, pp.43-57.

[53] Bayat, O. (1998). Characterization of Turkish Fly Ashes.*Fuel*, **V.77**, pp.1059–1066.

[54] Tokyay, M. (1998). Characterization of Turkish Fly Ashes.*Turkish Cement Manufacturers Association, Ankara.*

[55] ASTM C618–08. Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete.*ASTM International.*

[56] Naik, T. R., Singh, S.S., Hu, W. Y. (1992). High Volume Fly Ash Concrete Technology.*Research Project of Center for By-Products Utilization*, University of Wisconsin-Milwaukee.

[57] ACI Committee 232 (1996). Use of Fly Ash in Concrete.*American Concrete Institute*, USA.

[58] Lee, A. R. (1974). Blast furnace and Steel Slag: Production, Properties and Uses. *Edward Arnold Ltd*, London.

[59] Neville, A .M. (2004). Properties of Concrete.*Pearson Prentice Hall*, Essex.

[60] Regourd, M. M. (2004). Cements Made from Blast-furnace Slag. *In Leas Chemistry of Cement and Concrete*, Hewlett Edition, Elsevier, Oxford.

[61] Bijen, J., (1996)a. Blast Furnace Slag Cement. *Association of Netherlands Cement Industry.*

[62] ASTM C 989. (1999). Standard Specifications for Ground Granulated Blast–Furnace Slag for Use in Concrete and Mortars. *The American Society for Testing and Materials*, Pennsylvania.

[63] Bijen, J. (1986). Fly Ash Aggregates. ACI SP 79-26, *American Concrete Institute.*

[64] Ramamurthy, K., Harikrishnan, K. I. (2006). Influence of binders on properties of sintered fly ash aggregate. *Cement Concrete Composite*. **V.28**, pp.33-38.

[65] Bijen, J. M. (1986). Manufacturing processes of artificial lightweight aggregates from fly ash. *International Journal Cement Composite and Lightweight concrete*, **V.8**, pp.191-199.

[66] Yang, C. C., Huang, R. (1998). Approximate Strength of Lightweight Aggregate using Micromechanics Method. *Advanced Cement Based Materials*, **V.7**, pp.133-138.

[67] Gesoğlu, M. (2004). Effects of lightweight aggregate properties on mechanical, fracture, and physical behavior of lightweight concretes.*PhD thesis*, Istanbul, Bogazici University.

[68] Doven, A. G. (1996). Lightweight fly ash aggregate production using cold bonding agglomeration process.*PhD Thesis*, Boğaziçi University, Turkey.

[69] Jaroslav, S., Ruzickova, Z. (1987). Pelletization of Fines. Ore Research Instituted-Prague, *Elsevier Science Publishing Company*, New York.

[70] Pietsch, W. (1991). Size Enlargement by Agglomeration.*John Wiley and Sons.*New York.

[71] Goldstick, T. K. (1962). A Survey of the Literature Pertinent to Iron Ore Pelletizing.*In Agglomeration, Inter Science Publishers*, New York, pp. 1067-1104.

[72] Kapur, P. C. (1978). Balling and Granulation. Advances in Chemical Engineering, **V. II** ,*Academic Press*, New York, pp. 56-123.

[73] Sastry, K. V. S. and Fuerstenau, D. W. (1977). Kinetics and Process Analysis of Agglomeration of Particulate Materials.*It Agglomeration '77*, *AIME*, New York, pp. 381-402.

[74] Sastry, K. V. S. and Fuerstenau, D. W. (1973). Mechanisms of Agglomerate Growth in Green Pelletization.*Powder Technology*, **V. 7**, pp. 97-105.

[75] Rumpf, H. (1962). The Strength of Granules and Agglomerates.*Agglomeration Inter science*, New York, pp. 379-418.

[76] Kapur P. C. and Fuerstenau, D. W.(1964).Kinetics of Green Pelletization,*Trans AIME*,**V. 229**, pp. 348-355.

[77] Dhir, R. K. and Dyer, T. D. (1999). Modern Concrete Materials: Binders, Additions and Admixtures, *Thomas Telford Publishing*, London, UK.

[78] Barksdale, R. D. (1993). The Aggregate.*Handbook.National Stone Association.*

[79] Subramanian, S.(1999). Interfaces in concrete–Achieving performance.*International Conference on Concretes*, Dundee, Scotland.

[80] Bijen, J. M. and de Rooij, M. (1999). Aggregate–Matrix Interfaces.*International Conference on Concretes*, Dundee, Scotland.

[81] Detwiler, R. J., Wenk, R. and Monteiro, P. (1988). Texture of calcium hydroxide near the aggregate cement paste interface.*Cement and Concrete Research Journal*, **V. 18**, Issue 5, pp.823-829.

[82] Perry, C. and Gillott, J. E. (1977). The influence of mortar-aggregate bond strength on the behavior of concrete in uniaxial compression.*Cement and Concrete Research Journal*, **V. 7**, Issue 5, pp.553-564.

[83] ACI 232.2R-96. (1996). Use of Fly Ash in Concrete.*American Concrete Institute.*

[84] Bouzoubaa, N., Lachemi, M. (2001). Self-compacting concrete incorporating high volumes of class F fly ash Preliminary results. *Cement and Concrete Research*, **V.31**, pp.413-420.

[85] Sukumar B, Nagamani K, Srinivasa RR. (2008). Evaluation of strength at early ages of self compacting concrete with high volume fly ash.*Construction and Building Materials In Press, Corrected Proof:-1320.*

[86] Atis CD. (2003). High-volume fly ash concrete with high strength and low drying shrinkage.*Journal of Materials in Civil Engineering*,**V.15**, No.2, pp.153-156.

[87] Sekino, S., Narita, T. (2003). Study on mix design and properties of self-compacting concrete containing high volume fly ash. *Journal of the Taiheiyo Cement Corporation*, **V.145**, pp.18-35.

[88] Xie, Y., Liu, B., Yin, J., Zhou, S. (2002). Optimum mix parameters of high strength self-compacting concrete with ultra-pulverized fly ash.*Cement and Concrete Research*, **V.32**, pp.477–480.

[89] Kim, J. K., Han, S. H., Park, Y. D., Noh, J. H., Park, C. L., Kwon, Y. H. (1996). Experimental research on the material properties of super flowing concrete.Production Methods and Workability of Concrete*,E& FN Spon*, pp.271-284.

[90] Wood, K. (1981). Twenty Years of Experience with Slag Cement. *Symposium on Slag Cement*, University of Alabama, Birmingham.

[91] ACI 233R-95. (1995). Ground Granulated Blast-Furnace Slag as a Cementitious Constituent in Concrete. *American Concrete Institute*.

[92] Mehta, P. K. (1985). Influence of Fly Ash Characteristics on the Strength of Portland– Fly Ash Mixtures.*Cement and Concrete Research*, **V.15**, pp.669–674.

[93] Demir, M., Erenoglu, T., Ekim, H, Tasdemir, M. A. (2002). Effects of Fineness and Amount of Fly Ash on Strength Development of Concrete.*5th International Congress on Advances in Civil Engineering*, Istanbul, pp.1349-1358.

[94] McCarthy, M. J., Dhir, R. K. (1999). Towards Maximizing the Use of Fly Ash as a Binder.*Fuel*, **V.78**, pp.121 – 132.

[95] Oner, M. (2000). A Study of Intergrinding and Separate Grinding of Blast Furnace Slag Cement.*Cement and Concrete Research*, **V.30**, pp.473–480.

[96] Tasdemir, M. A., Tasdemir, C., Ozbek, E. Altay, B. (1997).Fineness Effect of GGBS on the Properties and Microstructure of Concrete.*First International Symposium on Mineral Admixtures in Cement*, Istanbul, pp.198-215.

[97] Hooton, R. D. (1987). The Reactivity and Hydration of Blast Furnace Slag, in Supplementary Cementing Materials for Concrete.*Malhotra Edition*, Canada.

[98] Tasdemir, C., (2003). Combined effects of mineral admixtures and curing conditions on the sorptivity coefficient of concrete, *Cement and Concrete Research*, **V.33**, pp.1637 – 1642.

[99] Li, S. and Roy, D.M., (1986). Investigation of Relations Between Porosity, Pore Structure, and Chloride Diffusion of Fly Ash and Blended Cements. *Cement and Concrete Research*, **V.16**, pp.749–759.

[100] McCarthy, M. J., Dhir, R. K. (2005). Development of high volume fly ash cements for use in concrete construction. *Fuel*, **V.84**, pp.1423-1432.

[101] Malhotra, V. M. (2000).Role of supplementary cementing materials in reducing Greenhouse gas emissions.*Concrete technology for a sustainable development in the 21st century*, London.

[102] Sengul, O. (2005).Effects of pozzolanic materials o the mechanical properties and chloride diffusivity of concrete.*PhD thesis*, Istanbul Technical University, Istanbul.

[103] Bijen, J. (1996)a. Blast Furnace Slag Cement. *Association of Netherlands Cement Industry*.

[104] Sivasundaram, V., Malhotra, V. M., (1992). Properties of Concretes Incorporating Low Quantity of Cement and High Volumes of Ground Granulated Slag. *ACI Materials Journal*, **V.89**, pp.554-563.

[105] Gjorv, O. E., Vennesland, O. (1979).Diffusion of Chloride Ions from Seawater into Concrete.*Cement and Concrete Research*, **V.9**, pp.229 – 238.

[106] Pal, S. C., Mukherjee, A., Pathak, S. R. (2002).Corrosion Behavior of Reinforcement in Slag Concrete.*ACI Materials Journal*, **V.99**, pp.521-532.

[107] Lang, E. (2004). Blast-furnace Cements, in Structure and Performance of Cements. *Ed. Hewlett*, Elsevier, Oxford.

[108] Bijen, J. (1996) b. Benefits of Slag and Fly Ash.*Construction and Building Materials*, **V.10**, pp.309–314.

[109] Neville, A. M. (1996). Properties of Concrete.*John Wiley and Sons,*New York.

[110] Gesoglu, M., Ozbay, E. (2007). Effects of mineral admixtures on fresh and hardened properties of self-compacting concretes: binary, ternary and quaternary systems. *Materials and Structures*, **V.40**, pp.923-937.

[111] Osborne, G. J. (1999).Durability of Portland – Blast Furnace Slag Cement Concrete.*Cement and Concrete Composites*, **V.21**, pp.11–21.

[112] Turkish Standard TS EN 197-1. (2002). *Çimento- Bölüm 1: GenelÇimentolar-Bileşim, ÖzelliklerVeUygunlukKriterleri*.

[113] ASTM C127.(2007).Standard test method for specific gravity and absorption of coarse aggregate. *Annual Book of ASTM Standards*.

[114] BS 812, part 110.(1990).Methods for determination of aggregate crushing value (ACV). *British Standards Institute*.

[115] ASTM C192.(2012).Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory. *International standards worldwide*.

[116] Khayat KH, Bickley J, Lessard M.(2000).Performance of self-consolidating concrete for casting basement and foundation walls. *ACI Materials Journal*,**V.97**, No.3, pp.374–380.

[117] Gesoğlu, M.; Özturan, T.; and Güneyisi, E.(2007). Effects of fly ash properties on characteristics of cold-bonded fly ash lightweight aggregates.*Construction and Building Materials*, **V. 21**, pp.1869-1878.

[118] Khayat, K.H., Manai, K. and Trudel, A. (1997). In situ mechanical properties of wall elements cast using self consolidating concrete. *ACI Materials Journal*, **V.94**, pp.492-500.

[119] ASTM C39.(2010).Standard test method for compressive strength of cylindrical concretespecimens. *Annual Book of ASTM Standards.*

[120] ASTM C496 / C496M - 11.(2012).Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. *International standards worldwide.*

[121] AASHTO T277.(2007). Standard Method of Test for Rapid Determination of the Chloride Permeability of Concrete.*http://engineers.ihs.com/document/abstract/YIDGIBAAAAAA.*

[122] RILEM TC 116-PCD.(1999).Permeability of concrete as a criteron of its durability. *Materials and Structures journal*.**V.32**, pp.174-179.

[123] Picandet V, Khelidj A, Bastian G.(2001). Effect of axial compressive damage on gas permeability of ordinary and high-performance concrete.*Cement and Concrete* Research,**V.31**, pp.1525–1532.

[124] ASTM C1585.(2012).Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes. *International standards worldwide.*

[125] Tobes, J M ;Anahi, L; Giaccio, G ;Zerbino, R. (2008). Effect of Coarse Aggregate Shape and Texture on Self-Compactability.*American Concrete Institute*, **V.253**, No. 2, pp 13-24.

[126] Mezghiche, B.; Guettela, A.; Chebili, R.; and Zeghichi, L. (1999).Study of the effect of alkalis on the slag cement systems.Proceedings of International Conferences on Modern Concrete Materials, Binders, *Additions and Admixtures*, Dundee. Scotland, pp. 287-293.

[127] EuroLightCon.(2000). Mechanical properties of lightweight aggregate concrete.*Economic Design and Construction with Light Weight Aggregate Concrete, Document BE96 3942/R23.*

[128] Mohr, P.; Hansen, W.; Jensen, E. and Pane, I. (2000). Transport properties of concrete pavements with excellent long-term in-service performance. *Cement and Concrete Research*, **V.30**, pp.1903-1910.

[129] Shi Hui-sheng, Xu Bi-wan, Zhou Xiao-chen.(2009). Influence of mineral admixtures on compressive strength, gas permeability and carbonation of high performance concrete.*Construction and Building Materials*, **V.23**.