DEVELOPMENT OF ECO-EFFICIENT SELF COMPACTING CEMENTITIOUS SYSTEM VIA SUCCESSFUL INTEGRATION OF WASTE BURNT BRICK POWDER MODIFIED THROUGH HYDRATED LIME

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ABSTRACT

Burnt Brick is a very abundant resource in Pakistan, with Pakistan being the third largest producer in South Asia. Of all the solid waste generated in country, 18% is burnt bricks. The recycling of waste and industrial byproducts from different industrial sectors leads to environmental and economic benefits. This study is aimed at development of eco-efficient self-compacting cementitious system via successful integration of waste burnt bricks (powder) modified through hydrated lime.

Six formulations were prepared and the parameters studied include water demand, super plasticizer demand, initial and final setting time, flow of self-compacting paste system, shrinkage test, water absorption and resistance to acid attack.

The Scanning Electron Microscopy analysis show that the particles of burnt bricks powder are irregular with rough porous surface which tend to increase the water demand and leading to more adsorption capacity compared to cement and thus has higher SP demand. The greater T25 cm time and T30 time of BBP sample indicate higher viscosity and thus will offer better segregation resistance. Results has shown lesser shrinkage in formulations than control sample and this is because of the lesser cement content in the paste phase which results in lesser consumption of water during hydration process. The shrinkage has been studied for first 24 hours. Decreased water absorption is due to better packing efficiency caused by smaller average particle size of Burnt Brick powder which reduce undesirable voids and discontinuous porosity. Strength improvement has also been noticed for up to 10% cement replacement.

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List of Notations

SCC	Self-Compacting Concrete
SCP	Self-Compacting Paste
SCM	Self-Compacting Mortar
SCCS	Self-Compacting Cementitious System
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence
EDS	Energy Dispersion X-Ray Spectroscopy
SEM	Scanning Electron Microscopy
PSD	Particle Size Distribution
BBP	Brunt Brick Powder
HL	Hydrated Lime
OPC	Ordinary Portland Cement
SP	Super Plasticizer
WD	Water Demand
Ti	Initial Setting Time
Tf	Final Setting time

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CHAPTER 1

Introduction

1.1 General

Concrete is the most widely used material for construction in the present era. Concrete is used in the constructing residential and commercial buildings, infrastructural facilities such as highways, dams and bridges, canals, ports and other important facilities. The earliest use of concrete predates to the Roman Empire. This large scale use of concrete compared to other construction materials like bricks, steel and wood is due to its various characteristics like economy, ability to be cast in any shape, readily available raw materials and most importantly durability. To achieve this durability proper compaction is required by skilled labor. Another solution to achieve this durability is using Self Compacting Concrete (SCC).

1.2 Self-Compacting Cementitious Systems

Three basic types of self-compacting concrete systems are known which include powder type, viscosity modifying agent type and combination type. These types basically differ from each other mainly in the way the segregation resistance is achieved. In powder type-self compacting cementitious system, a lower w/p ratio or higher powder content (cement as well as secondary raw materials) guarantees adequate segregation resistance while the same goal is achieved by viscosity enhancement agent in the viscosity agent type self-compacting cementitious system. The combination type SCC allows production of a robust self-compacting cementitious system and is believed to have excellent segregation resistance. Self-compacting cementitious systems can be broadly classified into the following systems

1.2.1 Self-Compacting Paste System

Self-compacting Paste (SCP) systems are the vehicles for aggregates present in self-compacting mortar (SCM) systems and self-compacting concrete (SCC) systems. The properties of modern concretes like high performance concrete (HPC) and SCC depend very significantly on the properties of SCP systems. In modern concretes, paste component usually contains suitable secondary raw materials (SRM’s) which improve or modify the properties of resulting SCM and SCC systems. It is used to understand the change in various fresh and harden properties of different types of self-compacting paste systems containing SRMs.

Self-compacting paste systems act as a binder between mortar and concrete systems. Therefore study of self-compacting paste system is essential in determining the properties of other systems i.e. SCM and SCC. To achieve self-compaction and produce highly flow able concrete without segregation various admixtures are used.

1.2.2 Self-Compacting Mortar System

Self-compacting mortar (SCM) is a new generation product and has prospective use as an independent material as well as an integral constituent of self-compacting concrete (SCC).

Self-Compacting mortar has higher content of powder materials to achieve the desired relative flow value. The mortar is a combination of powder, fine aggregate, admixture and water. The efficiency of the mortar mix depends on the synchronous flow behavior of all the ingredients of mortar during the mortar trial test.

1.2.3 Self-Compacting Concrete System

SCC was conceptualized in 1986 by Prof. Okamura at Ouchi University, Japan. Self-Compacting Concrete as defined by ACI 237R - 07 is “a highly flow able, non-segregating concrete that can spread into place, fill the formwork and encapsulate the reinforcement without any mechanical consolidation”.

1.2.4 Admixtures

Admixtures are defined as materials added in small quantities to improve the properties of concrete, mortar or paste systems. Super plasticizers are type of admixtures used in self-compacting cementitious system improve workability and durability due to effective packing of particles and decrease permeability issues because of the thorough mix and minimum use of cement. It also reduces the w/c ratio.

1.3 Secondary Raw Materials

Concrete as compare to other construction materials is one of the most sustainable materials. However as almost billion tons of concrete is being currently produced per annum around the globe which makes it the largest material flow on our planet. In near future concrete production should be responsible for about 10% of the total greenhouse gas emission on earth. In order to reduce CO_2 emissions, commonly practiced approach is the replacement of cement by secondary raw materials.

Secondary raw materials are the waste products that can be recycled and used as an ingredient of concrete. They are mineral admixture used to replace a part of cement in self-compacting concrete and to improve its properties by reducing early heat of hydration and shrinkage, improving rheological properties and microstructure, making concrete more durable and cost effective as well. Secondary raw materials in concrete may act as natural pozzolanic, artificial pozzolonic and as an inert filler material.

1.3.1 Pozzolans

As per ASTM C, Pozzolan may be defined as "A siliceous or aluminous and siliceous or aluminous and siliceous material, which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide (CH) produced by cement hydration at ordinary temperature to form compounds possessing cementitious properties".

1.3.1.1 Natural Pozzolan

The natural pozzolans include volcanic ashes, opaline, shales and cherts, calcined diatomaceous earth, and burnt clays. According to ASTM C618, these materials are described as Class N type pozzpolans. These materials are usually processed for producing pozzolan which involves drying, grinding and

1.3.1.2 Artifical Pozzolan

These are the by-products of industries producing them. According to ASTM C 618, these pozzolans are termed as Class C or Class F type pozzolans depending upon the silica content or lime content.

1.3.2 Waste Burnt Bricks

The secondary raw material which is used in this study is waste burnt bricks powder. The recycling of waste and industrial byproducts from different industrial sectors leads to environmental and economic benefits. This results from the production and disposal of less waste and also in a reduced consumption of raw materials. Clay brick is originated while manufacturing on brick kilns and from demolition of existing structures as well, which leads to large volume of waste to be disposed with resulting negative impacts on the environment.

1.3.2.1 Brick Kilns in Pakistan

1.3 trillion, bricks are manufactured each year worldwide. Pakistan is the **third largest** brick producing country in South Asia producing more than **45 billion bricks per year** and there are around **18,000 brick kilns** across the country and burnt brick waste per stock is 30%. From total solid waste generated in Pakistan 18% is clay bricks.

1.3.3 Hydrated Lime

Hydrated lime is an inorganic compound with the chemical formula $Ca(OH)_2$. It is a colorless crystal or white powder and is obtained when calcium oxide is mixed, or slaked with water. It has many names including caustic lime, calcium hydroxide, builders' lime, slack lime, or picking lime. Hydrated lime can contribute to strength development because the finely grounded particles act as a major source for providing nucleation sites for products of cement hydration, thus accelerating strength development during the early age.

It is known that hydrated lime improves the workability and water retention of Portland cement (PC) mortars.

PC-lime mixes can be reworked without increasing entrained air thus not undermining durability. In addition, lime lowers strength and stiffness making PC mortars more deformable. However, the use of hydrated lime in PC composites has largely decreased due to the use of plasticizers. These enhance workability and lower cement content reducing heat of hydration. As they are water reducers, they are expected to decrease permeability, minimize shrinkage, enhance ultimate strength and accelerate early-strength gain; leading to stronger, durable composite.

1.4 Research Objectives

Construction industry in Pakistan is rapidly growing so it is the time incorporate modern techniques in conventional construction methods. Now,it is the time to integrate such construction materials which are economical, durable and environment friendly. Concrete is the most widely used construction material in all over the world. Greater content of cement present in concrete results in high cost and emissions of carbon dioxide which helps increase in global warming. In the modern world to make the mega concrete structures economical and durable, it is a normal practice to use locally available secondary raw material as a replacement of cement. The primary objective of the research is to integrate successfully locally available waste burnt brick powder in self-compacting cementitious system modified through hydrated lime which is cost effective and eco efficient. The specific objectives are:

To study the behavior of fresh paste system and it’s rheological properties with and without burnt brick powder.

To keenly observe the effect of waste burnt brick powder on the early age shrinkage.

To assess the durability of self-compacting cementitious system with and without using secondary raw material.

- Effect of Burnt Brick Powder on Early age shrinkage
- Effect of Hydrated Lime on initial mechanical properties
- Make Self Compacted Concrete more economical using Burnt Brick Powder as Secondary Raw Material.

CHAPTER 2

Literature Review

2.1 General

A lot of research material is available on use of rice husk, fly ash, lime stone powder etc. as a Secondary Raw Material (SRM) in Self Consolidating Cementitious Systems (SCCS) but very little research has been done on use of Burnt Brick powder which is a very abundant resource in Pakistan as a SRM in SCCS.

2.2 Historic Background

In 1986, Professor Hajime Okamura proposed a solution to the problems faced by ordinary concrete, he proposed a powder type concrete that can fill the formwork without requiring any mechanical consolidation thus can be placed round the clock without producing any noise and also requires much less skilled labor [1]. Students of Professor Hajime Okamura, Ozawa and Maekawa in 1988 studied the workability of this type of concrete [2]. Later on Professor Okamura defined the properties of this type of concrete and named it Self-compacting High Performance concrete [3]. From then onwards Self compacting concrete started to be studied and used all over the world with the first ever paper presented in 1989 at the second East-Asia and Pacific Conference on Structural Engineering and Construction (EASEC-2).

2.1 Self-Consolidating Cementitious System

Self-Compacting Concrete is defined by ACI 237 as “A highly flowable, non- Self-Consolidating Cementitious System segregating concrete that can spread into places and fill formwork and encapsulate reinforcement without requiring any mechanical consolidation”.

Self-compacting cementitious system has three types: Self Compacting Paste system, Self-Compacting Mortar system and Self Compacting Concrete system. In order to study the effect of a particular SRM on properties of SCC sequential study of these three systems while understanding different parameters step by step is important.

Filling ability, passing ability and segregation resistance are the three essential fresh properties of SCC. Filling ability is the ability of SCC to fill the formwork completely by flowing under its own weight. Its ability to easily move through and around obstacles is known as passing ability and its ability to resist segregation and remain homogenous while being transported and during placement is known as segregation resistance.

Self-Compacting Concrete (SCC) offers faster construction time due to rapid rate of replacement, reduced noise and ability to flow around dense reinforcement [4]. The deformability and segregation resistance offers a high level of homogeneity, minimal voids, uniform strength, better surface finish and durability.

Numerous studies have been conducted to study the properties and behavior of self-compacting concrete. Few significant studies have been summarized below:-

Miao studied SCC with cement replacements of up to 80% in all mixes and examined their fresh properties. He found out that fly ash when used as a cement replacement acts as a lubricant; it doesn't react with super plasticizer and due to its lubricating behavior doesn't require extra super plasticizer. Thus larger amounts of fly ash replacements require lesser super plasticizer [5].

Payal and Itika report that "A systematic experimental approach has shown that if coarse and fine aggregate are partially replaced with fine materials, a self-compacting concrete having low segregation potential can be achieved as evident by V-Funnel test. The properties of SCC are governed by amount of aggregate, binder and mixing water and also by type and dosage of super plasticizer. The tests performed to examine the performance of SCC were Slump flow, V-funnel, L-flow, U-box and compressive strength. Addition of mineral admixture produces a better workable concrete" [6].

Rizwan conducted a study using different types of cements and mineral admixtures like rice husk ash (RHA) and silica fume (SF) on self-compacting paste systems (SCPS). The SCPS were characterized by water demand, SRM particle size, setting time, early volume stability, flow, microstructure and strength. The results showed that the addition of mineral admixtures increased the water demand which may be due to their smaller particle size, internal pores and higher surface area. Using mineral admixtures in SCPS also increases the strength of SCPS due to filler effect, pozzolanic action which translate into pore refinement and hydration. The results show that the resultant properties of self-compacting cementitious systems (SCCS) depend on the nature and type of mineral admixture used. The mineral admixture particle size, shape and morphology is very important in defining the properties of the resulting system [7].

Through above studies it is clearly visible that by using Secondary Raw Materials in SCC not only economy is achieved but flow, segregation resistance and strength properties are also enhanced.

2.2 Secondary Raw Materials

Secondary Raw Materials also known as Mineral admixtures are used as partial replacement of cement in SCC since all cement particles don't get hydrated in SCC. This consequently leads to more economical and environment friendly concrete. SRM are mostly industrial by products that require little or no processing. When used as a partial replacement in SCC they may act as filler, natural or artificial pozzolanic. When acting as filler they may only increase the flowability of SCC due to their fineness but when acting as artificial or natural pozzolanic they also contribute to the strength of SCC by reacting with Calcium Hydroxide or Hydrated Lime in the presence of moisture to form compounds possessing cementitious properties.

Ability of pozzolanic materials to enhance the strength of concrete includes physical as well as chemical effects. Physical affects are primarily associated with their influence of packing characteristics of the mixture which depend on size, shape and texture of particles. The chemical affects are associated with the percentage of Silica and Alumina present in the SRM which will react with Calcium hydroxide in the presence of water to give cementitious products [8]. Studies suggest that during the first 28 days the physical effects of fly ash contribute towards its strength development while beyond that the chemical effects become significant [9]. This may be due to the absence of excess Calcium Hydroxide in the initial stages of hydration. Smaller the particle size of SRM higher is its surface area increasing the pozzolanic activity and thus producing higher compressive strength [10].

2.3 Burnt Brick Powder

Every year tons of Brick waste is produced. The two major sources of Brick waste are construction and demolition waste and waste from Brick manufacturing plant. This waste Brick can be utilized in Self Compacting Concrete as a Secondary Raw Material. Brick here refers to Ceramic Brick obtained by firing clayey soil.

Research has shown that Burnt Brick has a high percentage of Alumina and Silica characterizing it as a pozzolanic material as per ASTM C 618. Wild et al. [12] studied eight different types of bricks from Denmark, Lithuania, Britain and Poland and carried out for pozzolanicity and compression test for strength development on mortar mixtures with up to 30% cement replacements using ground brick powder; they concluded that pozzolanic behavior was being shown by all the brick types used in the study. Studies have also revealed that ground brick replacements improve resistance of mortar to aggressive environment. O'Farrell et al. [13,14] studied effect of sulfate attack on mortar mixtures containing ground brick and found out that resistance to sulfate attack is improved; similarly, negative effects like expansion and reduction in strength due to exposure of mortar mixtures to seawater are also mitigated. A recent study on mortars with replacements up to 40% using ground brick powder has revealed that up to 20% replacements the compressive strength is not negatively affected and chloride ion penetration and sulfate attack resistance is also improved [15]. Another property which is improved by addition of ground brick to mortar mixtures is alkali-silica resistance [16,17]. There is lack of research in ground brick replacements in concrete mixtures and current study is only limited to compressive strength studies. Research done on the use of ground brick and tile material as partial cement replacement it was found that ground brick replacements lead to decrease in early age strength, however long term strength of these replacements was found to reach or even exceed that of the control sample; additionally, elastic modulus is also slightly reduced at all ages [16]. This research proves that although reduction in early strength might pose some challenges but due to adequate long term strength ground brick replacement mixtures can be used in actual construction. Research has shown that use of ground brick as a cement replacement improves the rheological properties (workability and stability) of the SCC [18].

Research has shown that ground brick increases the water demand of the self-consolidating paste, delays the setting time, causes reduction in temperature rise during hydration and reduces calcium hydroxide content due to its pozzolanic reactions. The reduction in temperature rise during hydration shows that Burnt Brick powder has a retarding effect on hydration conforming with the delayed time of setting. Research on concrete containing ground brick has shown that the mechanical properties like compressive, flexural and splitting tensile strength and modulus of elasticity are well comparable to that of control sample. Studies have shown that clay brick wastes from demolished buildings or other sources in finely ground form can be used as partial replacement of cement where it will act as a pozzolanic cementitious material. Tests have also revealed that ground brick used in mortar improves its chemical resistance like resistance to sulfate attack and alkali-silica reaction [19].

2.4 Hydrated Lime

The partial replacement of cement with Burnt Brick powder as a SRM has its limitations since the amount of portlandite (calcium hydroxide) generated by hydration is very limited. This problem can be solved by using hydrated lime which will provide portlandite (calcium hydroxide) for the pozzolonic Burnt Brick powder to react with and form cementitious product [20]. **Prasanna** and **Sanjaya** worked on using ferrochrome ash (FCA) as a partial replacement of cement in concrete. They found out that FCA acts as a pozzolanic material. Their tests revealed that using FCA alone as a partial replacement of OPC leads to decrease in compressive strength while using hydrated lime as a chemical modifier produced a positive impact. They found out that using FCA as a partial replacement in various percentages with 7% lime leads to increased 28 day compressive strength by 1.5 – 13.5% and flexural strength by 4.5 – 9% [21].

So in the light of literature it is obvious that secondary raw material mostly act as inert filler at start of hydration. However, at later stages of hydration secondary raw material react with calcium hydroxide in presence of moisture to give cementitious properties. It is also concluded that if we added hydrated lime in small content with secondary raw material then there are chances of improved mechanical properties at initial stages of hydration.

CHAPTER 3

Materials

3.1 General

The experimental program was carried out at structural laboratory of NUST Institute of Civil Engineering (NICE) Islamabad. To ensure reliability and validity of test results all material was stored in the laboratory at ambient temperature during the experimental program, mixing, sample preparing and testing. The required quantities of cement, secondary raw material, super plasticizer and hydrated lime were stored in the plastic jars with air tight caps to ensure no moisture or dust particles effect the homogeneity of materials used throughout the experimental program.

3.2 Materials used

3.2.1 Ordinary Portland cement

An ordinary Portland cement from Best Way cements conforming to Type 1 ASTM C150 was used throughout the research program.

Specific Gravity = 3.15

Avg. Particle Size = 8.77 micrometer

Normal Consistency = 26.5

3.2.2 Waste burnt bricks

Burnt bricks waste was collected from Nonagran kiln in the vicinity of I-8 Islamabad. At first, bricks were washed to remove dust particles and then air dried for one day. Bricks were then broken into small pieces with hammer. After that grinding was carried out in ball milling machine. Each batch of 5 kg was given revolutions for 30 minutes to maintain uniform fineness. After that, the powdered bricks were calcined by heating it at 100 degree Celsius for 24 hrs, and after cooling to r oom temperature, calcined brick powder was sieved through #200 sieve. The resulting sample after sieving was preserved in air-tight plastic jar and later on used for producing different mixes.

Figure 3.1 Brick powder preparation

3.2.3 Super plasticizer

Sika Viscocrete 3110 is a super plasticizer (**Aqueous Solution of modified poly_carboxylate co-polymer**) developed for the production of high flow concrete with exceptional flow retention properties. It is suitable for use in hot climatic conditions. Viscocrete 3110 conforms to the requirements of ASTM C494-86 Type GF, BS 5075: Part 3 and EN 934-2. It is available in the liquid form having density approx. 1.085 kg/lt with appearance clear, colorless to yellowish.

3.2.4 Hydrated lime

Hydrate lime was commercially available in Taxila and therefore purchased from there.

Mean size = 10.94 micrometer

3.2.5 Water

As water used in concrete should be clean drinkable water, therefore tap water at 25±1 degree Celsius is used conforming to WHO guidelines. Attach properties table

3.3 Secondary raw material preparation

Waste burnt bricks were collected from Nonagran kiln in the vicinity of Islamabad. Burnt bricks were then further broken into smaller pieces using hammer and further crushed to fine particles using Ball Milling machine. Fine powder was then pulverized and sieved through sieve 200. 16 kg sample was prepared which was utilized in further experimentation.

3.4 Hydrated lime preparation

As mentioned before that hydrated lime was collected from Taxila which is then further pulverized and sieved through no. 200 sieve.

CHAPTER 4

Experimental Program

4.1 General

The Secondary Raw Material i.e. burnt brick powder was prepared by first milling in Los Angeles Abrasion machine and then passing through sieve number 200. A comprehensive experimental program was adopted to carry out necessary tests pertaining to Self-Compacting Paste Systems. The chemical composition of hydrated lime and cement was obtained by X-Ray Florescence analysis. The chemical composition of burnt brick powder was determined using EDS. X-Ray Diffraction was also used to characterize cement, burnt brick powder and hydrated lime. XRD of certain select samples was also done after 28 days. Particle size distribution of cement, burnt brick powder and hydrated lime was determined through laser technology .The water demand of all formulations was determined through consistency test in Vicat apparatus. Flow of 30 ± 1 cm was achieved by using Sika Viscocrete 3110 super plasticizer in Hagerman's mini slump of 6x7x10 cm^3 cone. Durability of samples against acid attack was also determined. Mechanical properties after exposure to 25°C, 100°C, 150°C and 200°C were also analyzed.

4.2 Materials

All the experimental programs were held in Structural and Geotechnical laboratory of NICE, Surface treatment, Heat treatment and Material testing laboratory of SCME, Combined lab CASEN and Central research laboratory of University of Peshawar.

4.2.1 Cement

Ordinary Portland Cement (OPC) conforming to ASTM C150 standard was used. The cement was kept in controlled environment according to requirements of research to keep it moisture free. Chemical composition of Cement determined through XRF analysis is shown below.

Constituents	Percentage by weight
CaO	61.80
SiO_2	19.19
Al_2O_3	4.97
Fe_2O_3	3.27
MgO	2.23
P_2O_5	0.68
Na_2O	0.57
K_2O	0.51
Ti_2O_2	0.29

Cement Properties

Brand : Bestway Cement

Type : Type I (ASTM C150)

Specific Gravity : 3.15

Avg. Particle Size : 8.34 µm

Normal Consistency : 26.5% (ASTM C187) using standard Hobart mixer and EN-197

4.2.2 Burnt Brick Powder

Burnt Brick was obtained from Nonagran Kiln in the vicinity of I8. It was milled in Los Angeles Abrasion machine to get Burnt Brick powder. Burnt Brick powder passing through sieve number 200 was used. The chemical composition of Burnt Brick powder determined through EDS is shown below.

Constituents	Percentage by weight
SiO_2	69.85
Al_2O_3	5.83
Fe_2O_3	4.43
CaO	15.67
K_2O	1.04
MnO	0.18
ZnO	0.30
SrO	0.62
SO_3	0.23
MgO	1.04
LOI	4.3

Burnt Brick Properties

Source : Nonagran Kiln

Avg. Particle Size : 3.17 µm

Moisture Content : 2.5%

4.2.3 Hydrated Lime

Hydrated lime was obtained in powder form from commercial market in Taxila. The powdered hydrated lime was passed through sieve 200 before being used. The chemical composition of hydrated lime obtained through XRF analysis is tabulated below.

Constituents	Percentage by weight
CaO	92.53
Fe_2O_3	4.23
SrO	3.24

Hydrated Lime Properties

Source : Commercially available in Taxila

Avg. Particle Size : 10.94 µm

4.2.4 Viscocrete 3110

Sika Viscocrete 3110 is a third generation super plasticizer for concrete and mortar. It is particularly developed for the production of high flow concrete with exceptional flow retention properties. It has a yellowish color and is supplied in liquid form. It conforms to ASTM C494-86 Type GF requirement.

Viscocrete 3110 Properties

Brand	**:** Sika
Standard	**:** ASTM C494-86 Type GF, BS 5075: Part 3 and EN 934-2
Form	**:** Yellowish liquid
Water Reduction	**:** 30%
Density	**:** 1.085 kg/L

4.2.5 Water

Tap water obtained from NICE lab was used. The temperature of water used was maintained at 25±1°C.

Water Properties

pH	**:** 6.9
Turbidity	**:** 0.7 NTU
TDS	**:** 460 mg/L
Chlorides	**:** 78 mg/L
Hardness	**:** 330 mg/L

4.3 Mixing Regime and Mix Proportions of SCP Formulations

All mixings were done using a 5L capacity Hobart Mixer. Mixing regime adopted was such that first 90% water and cement were fed to the mixer and mixed for 30 seconds at slow speed (145 rpm). Then paste from sides and blade of mixer was scraped for 15 seconds and remaining 10% water with super plasticizer mixed, was added. Now slow mixing was done for 30 seconds and finally after fast mixing (285 rpm) was done for 120 seconds as per EN-D/N 197.

Time(s)	Regime
0-30	Wet slow mixing in 90% water
30-60	Adding 10% remaining water with SP at slow mixing
60-180	Rapid Mixing for 120 seconds

The mix proportions used for various self-compacting formulations are given below.

Sr #	Formulation	Notation
1	C100-WD-SP-BB0-HL0	C100
2	C95-WD-SP-BB5-HL0	C95
3	C90-WD-SP-BB10-HL0	C90
4	C90-WD-SP-BB10-HL2.5	C90-HL
5	C80-WD-SP-BB20-HL0	C80
6	C80-WD-SP-BB20-HL2.5	C80-HL

- C Cement
- WD Water Demand
- SP Super Plasticizer
- BB Burnt Brick Powder
- HL Hydrated Lime

4.4 Water Demand and Setting Time

Water demand and initial and final setting time of all the formulations was determined using Vicat apparatus. For initial setting time the needle should penetrate up to 5±2mm from the bottom and for final setting time the final set needle should leave no circular impression on the cement paste. ASTM C187 was followed to determine standard consistency while ASTM C191 was followed to determine initial and final setting time.

Figure 4.1 consistency test

Figure 4.2 vicat apparatus for setting time

4.5 Super plasticizer demand

Super plasticizer demand was determined using Hagerman mini slump cone. The slump cone had an upper diameter equal to 70mm and lower diameter equal to 100mm with a height of 60mm. The spread from Hagerman cone should be 30±1 cm. Spread value was taken as average of diameter in orthogonal direction.

The amount of super plasticizer required for each formulation to give a spread of 30±1cm is determined.

Figure 4.3 Hagerman mini cone apparatus for SP demand

4.6 Flow Time

T25 and T30 are the times the paste takes to reach 25cm and 30cm after the paste leaves the Hagerman mini slump cone. T25 and T30 are used to measure yield stress and viscosity respectively.

Figure 4.4 Flow time measurement

4.7 Strength

The casting, curing and testing of all samples were carried out as per EN 196-1 of 1994. After mixing the paste was poured in to prisms of 40 x 40 x 160 mm size. After 24 hours the samples were taken out and placed in water bath for curing. The samples were then taken out after 3, 7, 28, 60 and 90 days for compression and flexure testing. Flexure test was done on three prisms measuring 40 x 40 x 160 mm of each formulations while compression test was done on six samples obtained from broken pieces of flexure test with cross section 40 x 40 mm.

4.8 Water Absorption Test

Water absorption was performed according to ASTM C642 – 97 specification, but instead of 100 mm cubes, prisms of 40 x 40 x 160 mm were used. After 28 day curing the samples were transferred to laboratory oven at 100° C for 24 hours. After 24 hours oven dried samples were weighed and then immersed in water for 48 hours after which samples were removed and weighed in SSD condition. Water absorption was thus calculated from difference between oven dried and SSD weight.

4.9 Resistance to acid attack

For determining resistance to sulfate attack two of each formulation was dried and weighted after 28 day curing and then half the samples were immersed in 2.5% HCL solution and other half in 2.5% H_2SO_4 solution for 30 days. Both the solutions were renewed after 15 days. After 30 days the samples were weighted and reduction in weight was determined. Then each specimen was tested in compression and flexure and compared with control sample readings to determine durability of SCPS with and without secondary raw material against acid attack.

4.10 Exposure to different temperatures

After 28 day curing samples were removed from curing tank and placed in oven where one sample of each formulation was heated at 25°C, 100°C, 150°C and 200°C respectively. The rate of temperature increase was 5°C per minute and samples were exposed to their respective high temperatures for 1.5 hours. After which they were cooled to room temperature and weighted for weight reduction. Each sample was then tested for compression.

4.11 Early Shrinkage

German Schwindrine apparatus measuring 4 x 6 x 25 cm interfaced with a computer was used to measure linear early shrinkage at 20±1°C. The samples were tested only in uncovered condition. The frontal end of the apparatus was fixed while the rear end was moveable and capable of recording 0.31 microns displacement due to shrinkage or expansion. Shrinkage was observed for 24 hours and then readings were exported to excel and analyzed.

Figure 4.5 Shrinkage apparatus

4.12 X-Ray Diffraction

X-Ray Diffraction is used to identify the crystalline phases in materials. XRD of cement, burnt brick powder and hydrated lime was done to determine their mineral characterization. XRD of certain select samples was also done after 28 days.

XRD is widely used to identify various crystals present in the cementitious systems. CH, CSH and ettringite are the common hydration products which can be detected by XRD technique at different 2Ɵ angles typical of such crystals which are crystalline in nature. The presence of aggregates which are crystalline in nature in the SCC makes it complicated which makes it difficult to identify the hydration products, therefore, most of the study is done on pastes.

4.13 X-Ray Fluorescence

X-Ray Fluorescence is a experimental technique used to determine the complete chemical analysis of a sample by giving the types and percentages of compounds present in a sample. It uses X-Rays and Gamma rays bombardment to excite the material under experimentation thereby resulting in production of characteristic X-

Rays from the material. XRF analysis of cement and hydrated lime was carried out to determine the corresponding percentages and types of oxides present in them.

4.14 Scanning Electron Microscopy

Scanning Electron Microscopy is used to analyze the microstructure and identify hydration progress. In Back Scattered Electron mode, it is able to identify different phases of hydration and even unhydrated cement grains. It was done to investigate the change in phases of hydration products due to presence of Burnt Brick powder, SEM was carried out for certain formulations after 28 day curing. SEM of Burnt Brick powder was also done to determine its morphology.

4.15 Energy Dispersion X-Ray Spectroscopy

EDX or EDS is an analytical technique used for elemental or chemical characterization of a sample. To stimulate the emission of characteristic X-rays from a specimen, a high-energy beam of charged particles such as electrons or protons (see PIXE), or a beam of X-rays, is focused into the sample being studied which excites them releasing X-rays in the process. As the energies of the X-rays are characteristic of the difference in energy between the two shells and of the atomic structure of the emitting element, EDS allows the elemental composition of the specimen to be measured. EDX of burnt brick powder was done to determine its chemical composition.

CHAPTER 5

Results

5.1 Tests on Secondary Raw Material

5.1.1 Particle characterization by Scanning Electron Microscopy

The particle shape, size and morphology are very important parameter to understand their role in the workability, yield strength, viscosity, mechanical properties, shrinkage, setting time, water demand, super plasticizer demand and microstructure of Self Compacting Cementitious System.

The Figure 5.1(a) and Figure 5.1(b) are the SEM images of Burnt Brick powder at resolution 10 µm and 5 µm respectively.

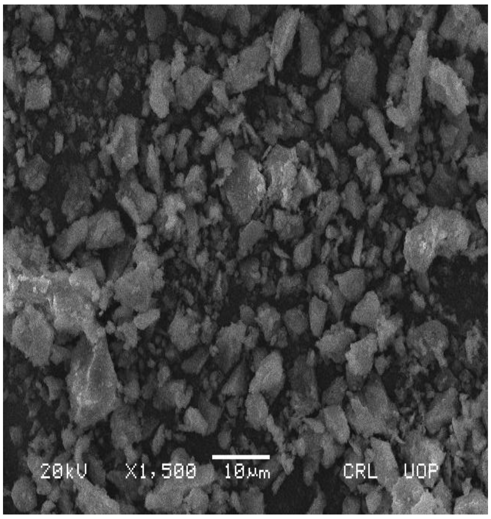


Figure 5.1(a) SEM of BBP

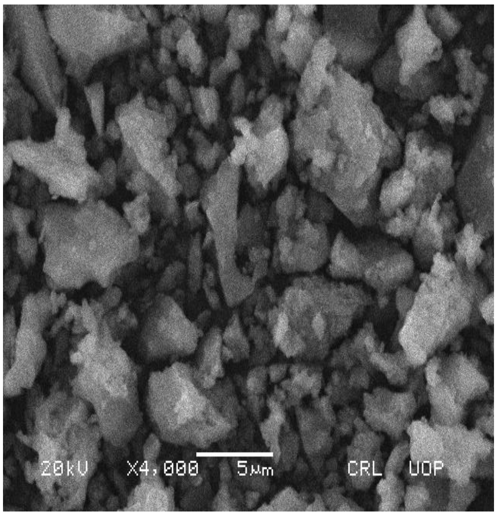


Figure 5.1(b) SEM of BBP

The SEM images indicate that Burnt Brick powder particles are irregular in shape, size and have abrasive texture.

5.1.2 X-Ray Diffraction of Burnt Brick powder

According to XRD data shown in Figure 5.2 the Burnt Brick powder is rich in Quartz, Hematite and Albite mineral. The peaks show the crystalline behavior and the white bands in the XRD pattern indicates amorphous phase.

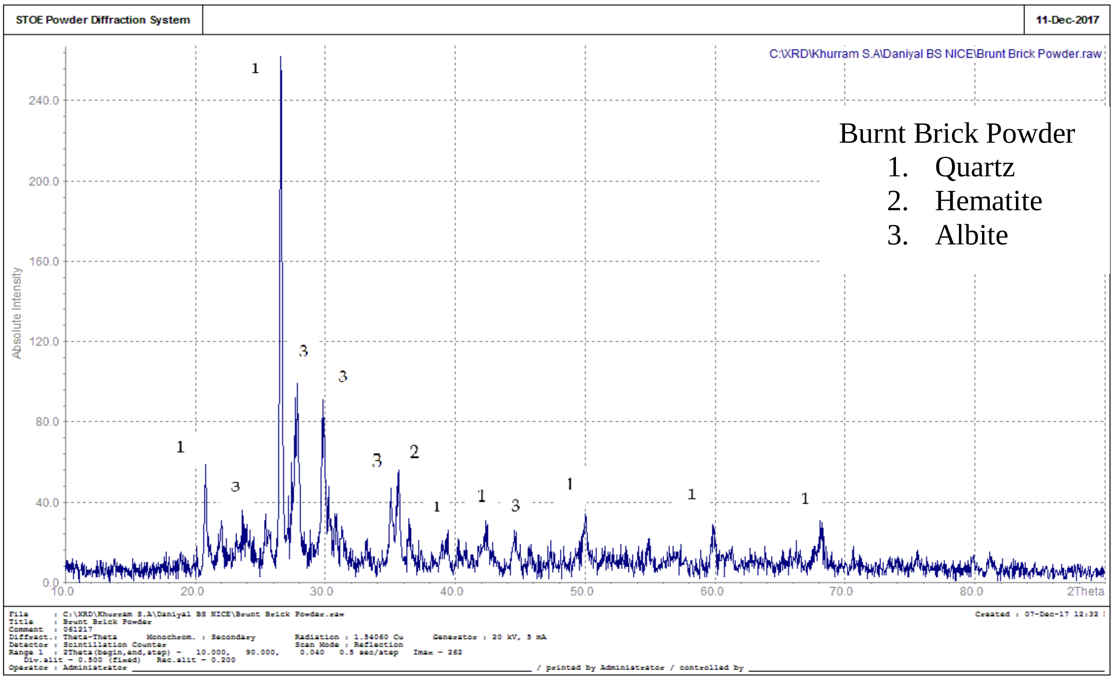


Figure 5.2 XRD pattern of BBP

5.1.3 EDAX of Burnt Brick powder

The table gives the different oxides present in the Burnt Brick powder which is determined through EDAX.

Constituents	**Percentage by weight**
SiO_2	69.85
Al_2O_3	5.83
Fe_2O_3	4.43
CaO	15.67
K_2O	1.04
MnO	0.18
ZnO	0.30
SrO	0.62
SO_3	0.23
MgO	1.04
LOI	4.3

5.1.4 Particle size distribution of Burnt Brick powder

The Figure 5.3 indicates the particle size distribution of Burnt Brick powder.

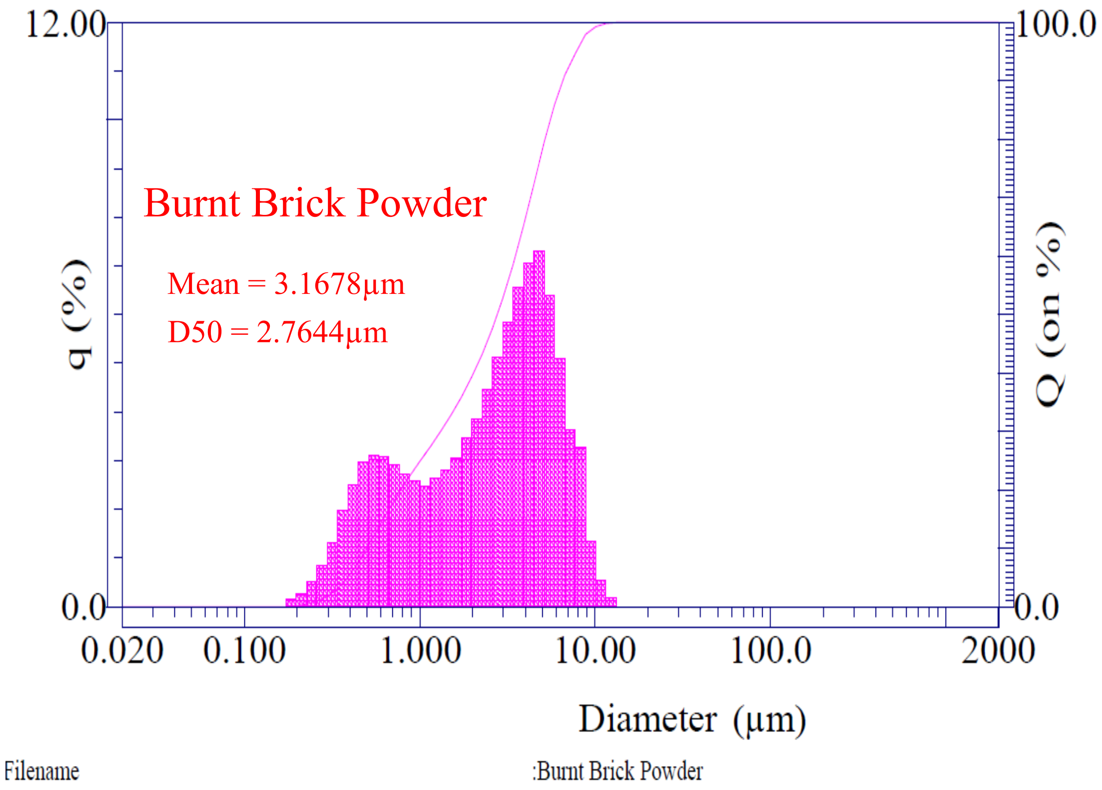


Figure 5.3 PSD of BBP

5.2 Tests on Hydrated Lime

5.2.1 X-Ray Diffraction of Hydrated Lime

Figure 5.4 shows the XRD pattern of Hydrated Lime.

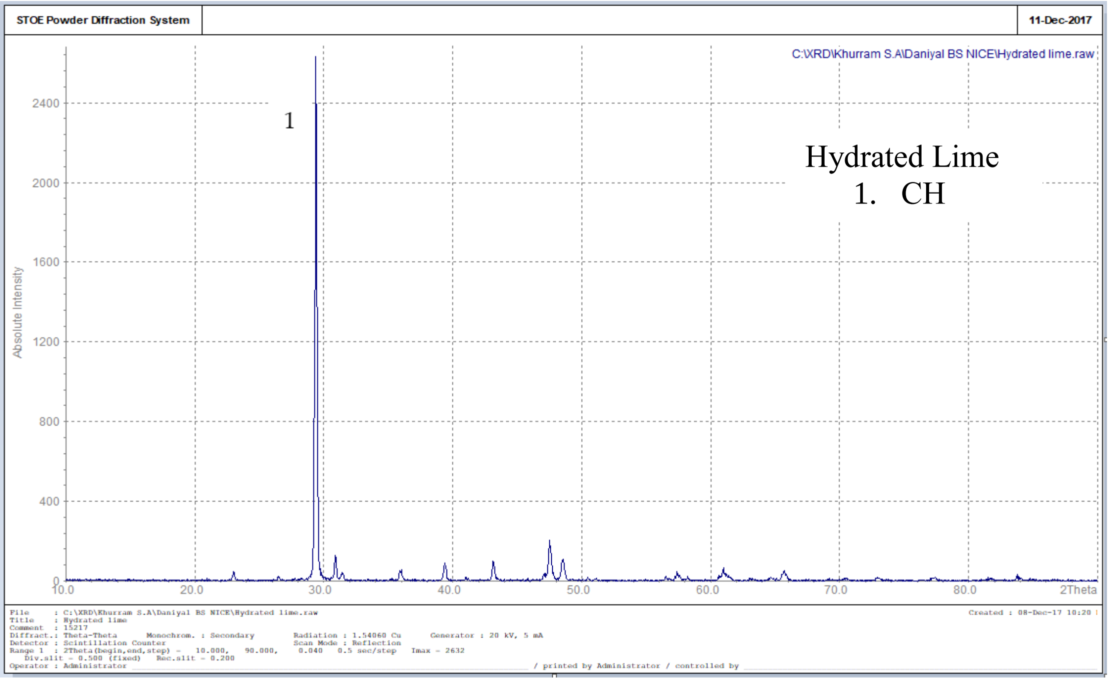


Figure 5.4 XRD pattern of HL

5.2.2 X-Ray Fluorescence of Hydrated Lime

The table below shows the XRF results of Hydrated Lime.

Constituents	Percentage by weight
CaO	92.53
Fe_2O_3	4.23
SrO	3.24

5.2.3 Particle Size Distribution of Hydrated Lime

The particle size distribution of Hydrated Lime is given below.

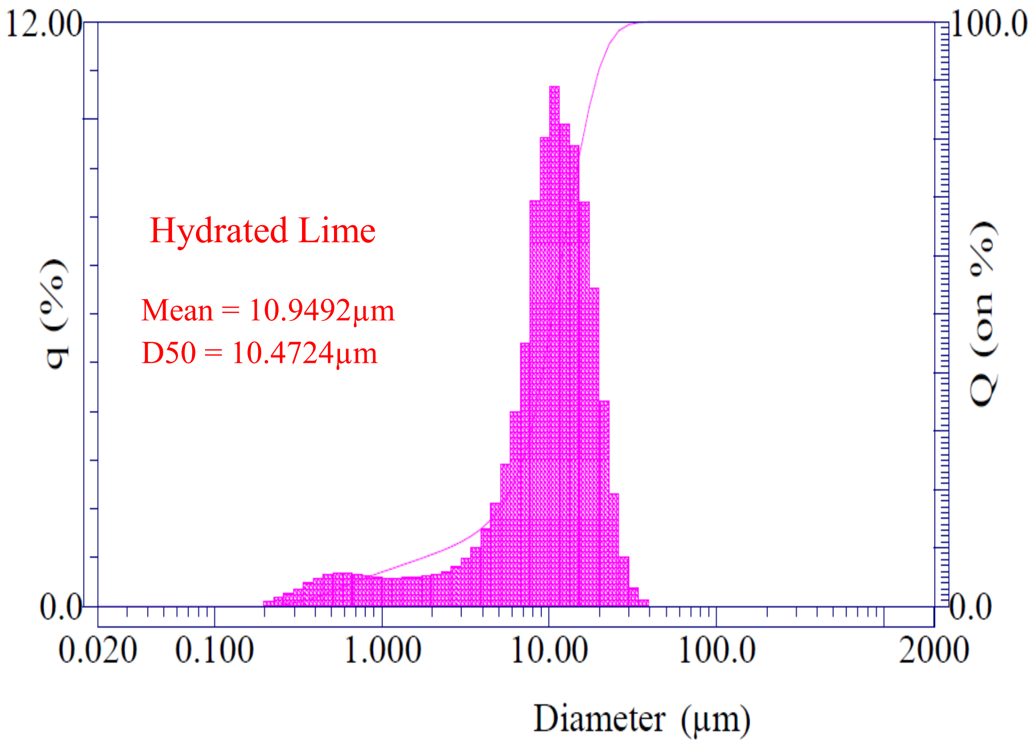


Figure 5.6 PSD of HL

5.3 Tests on Cement

5.3.1 XRD of Cement

The XRD pattern of Cement is shown below.

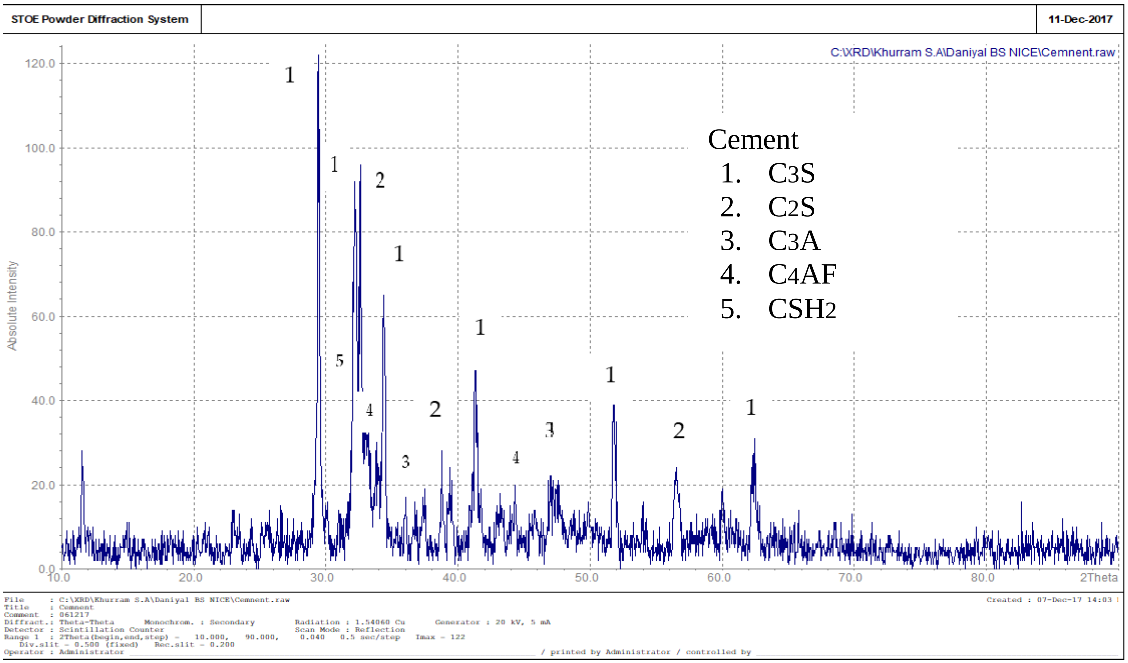


Figure 5.7 XRD pattern of OPC

5.3.2 XRF of Cement

The XRF results of Cement are shown below.

Constituents	Percentage by weight
CaO	61.80
SiO_2	19.19
Al_2O_3	4.97
Fe_2O_3	3.27
MgO	2.23
P_2O_5	0.68
Na_2O	0.57
K_2O	0.51
Ti_2O_2	0.29

5.3.3 Particle Size Distribution of Cement

The particle size distribution of cement is shown below.

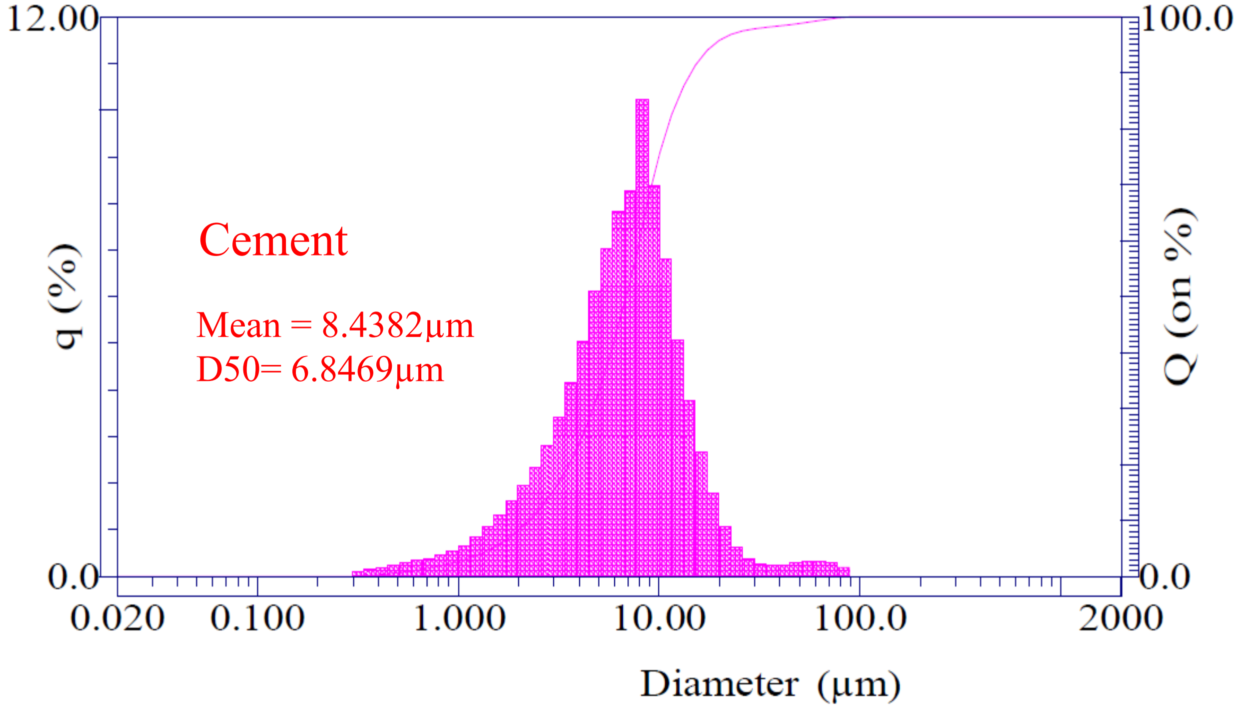
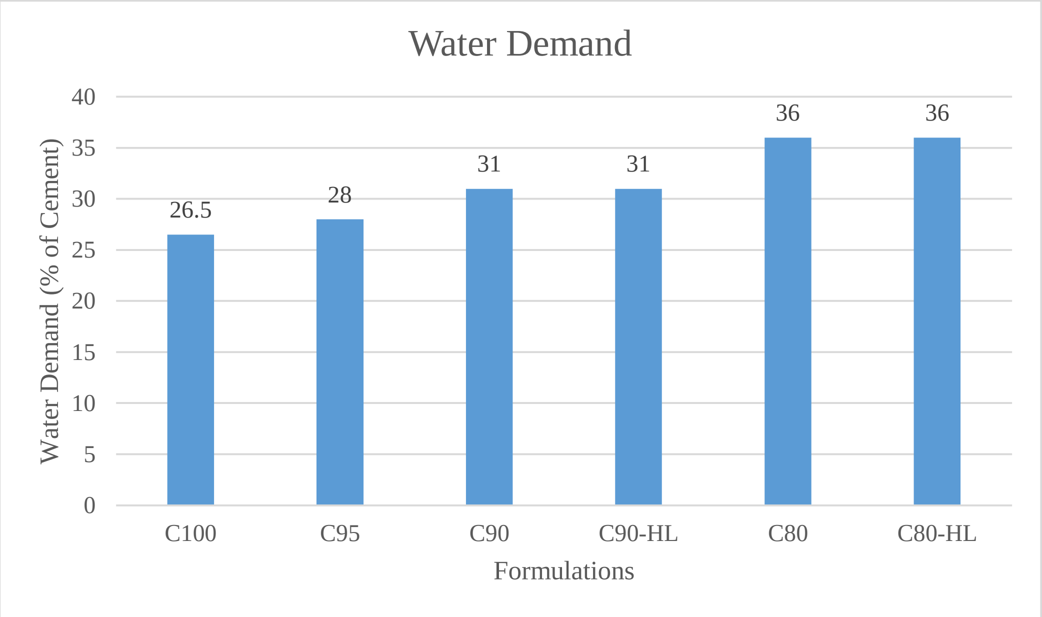


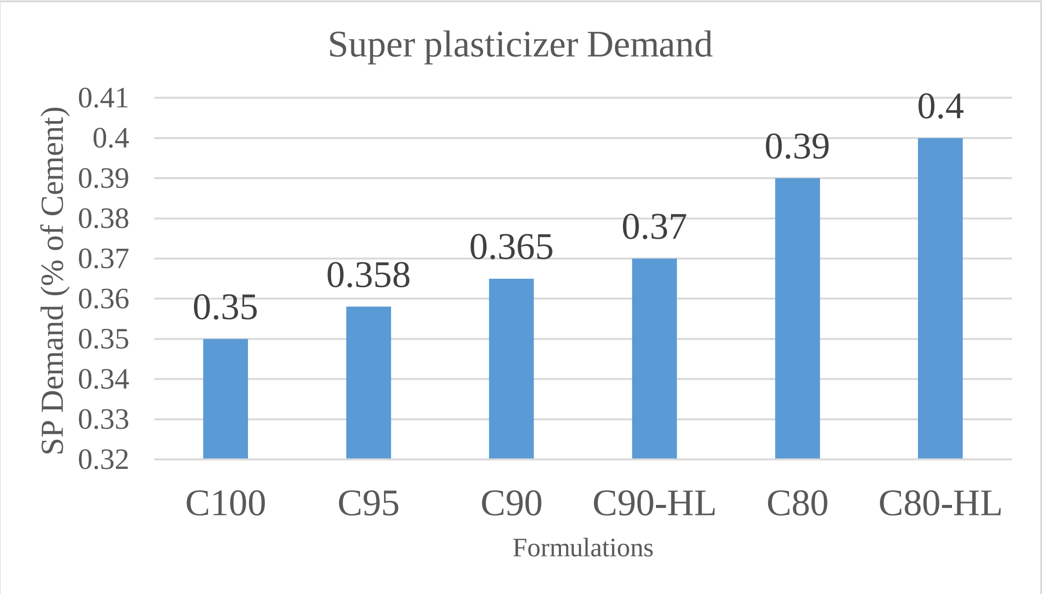
Figure 5.8 PSD of OPC

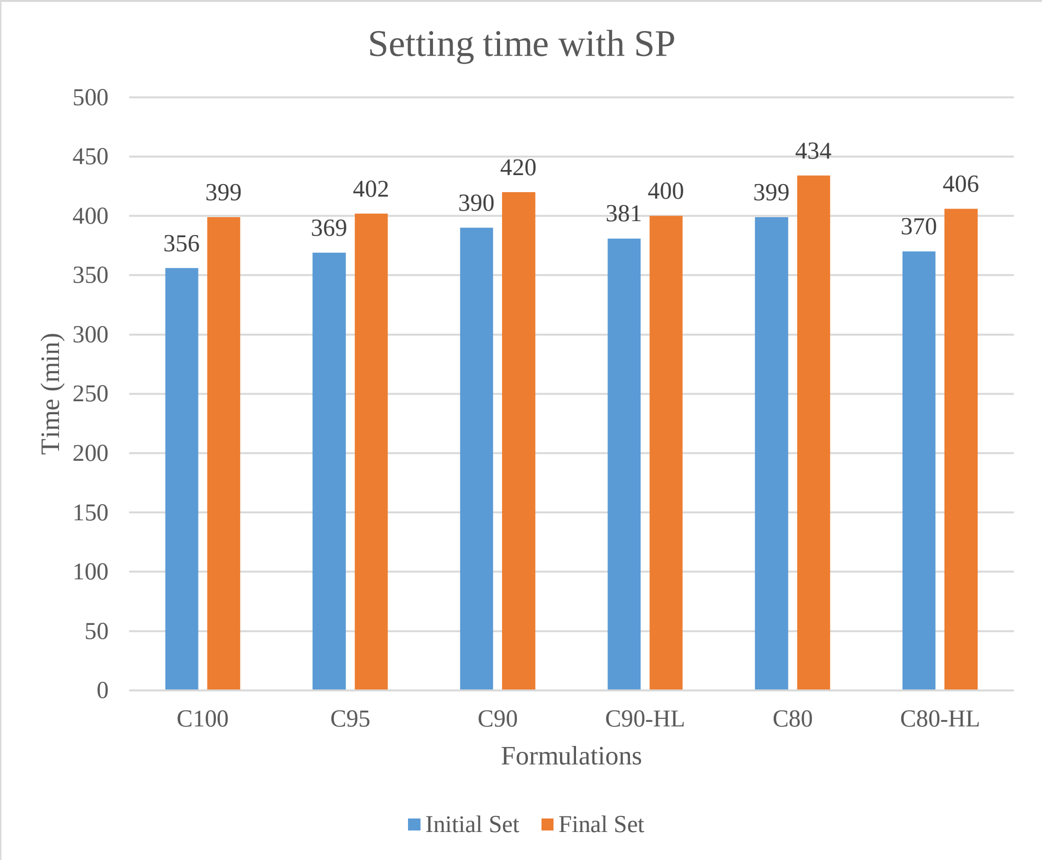
5.4 Tests on Self Compacting Cementitious System

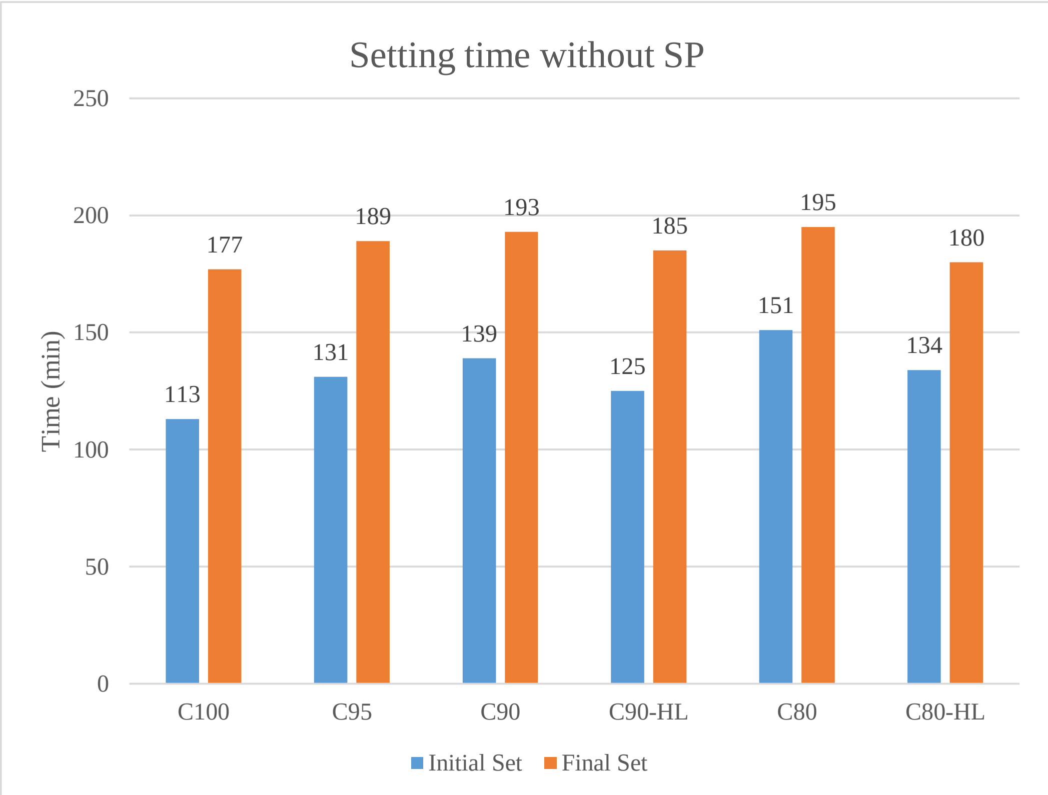
5.4.1 Water demand, super plasticizer demand and setting time

The bar charts show the water demand, super plasticizer demand for a target flow of 30±1cm, setting time without SP and setting time with SP. The water demand increases by increasing percentage of secondary raw material. The super plasticizer demand also increase with increase in secondary raw material percentage. The delay in setting time with and out super plasticizer is observed.



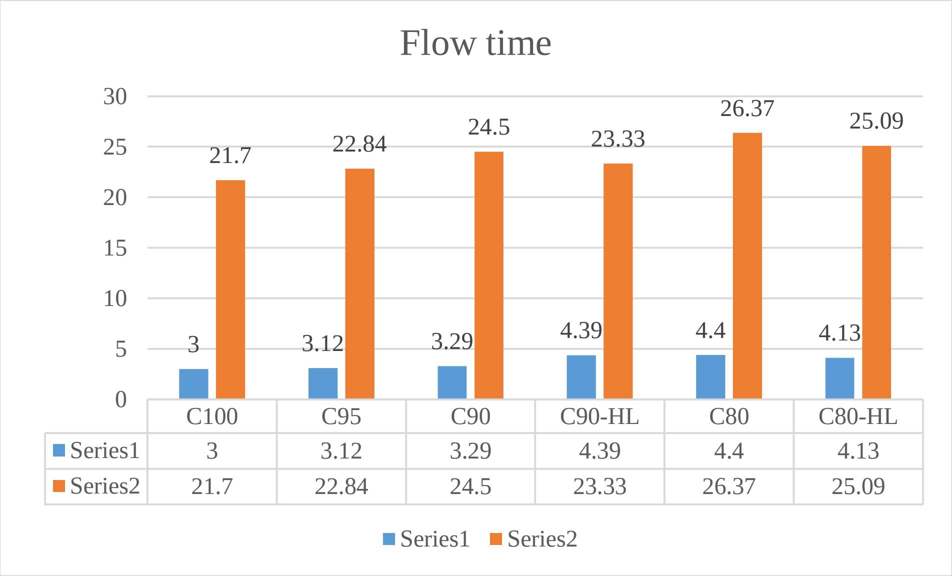



Setting time with SP
500
450
400
350
300
250
200
150
100
50
0
Time (min)
356
399
369
402
390
420
381
400
399
434
370
406
C100
C95
C90
C90-HL
C80
C80-HL
Formulations
Initial Set
Final Set


Setting time without SP
250
200
150
100
50
0
Time (min)
113
177
131
189
139
193
125
185
151
195
134
180
C100
C95
C90
C90-HL
C80
C80-HL
Initial Set
Final Set

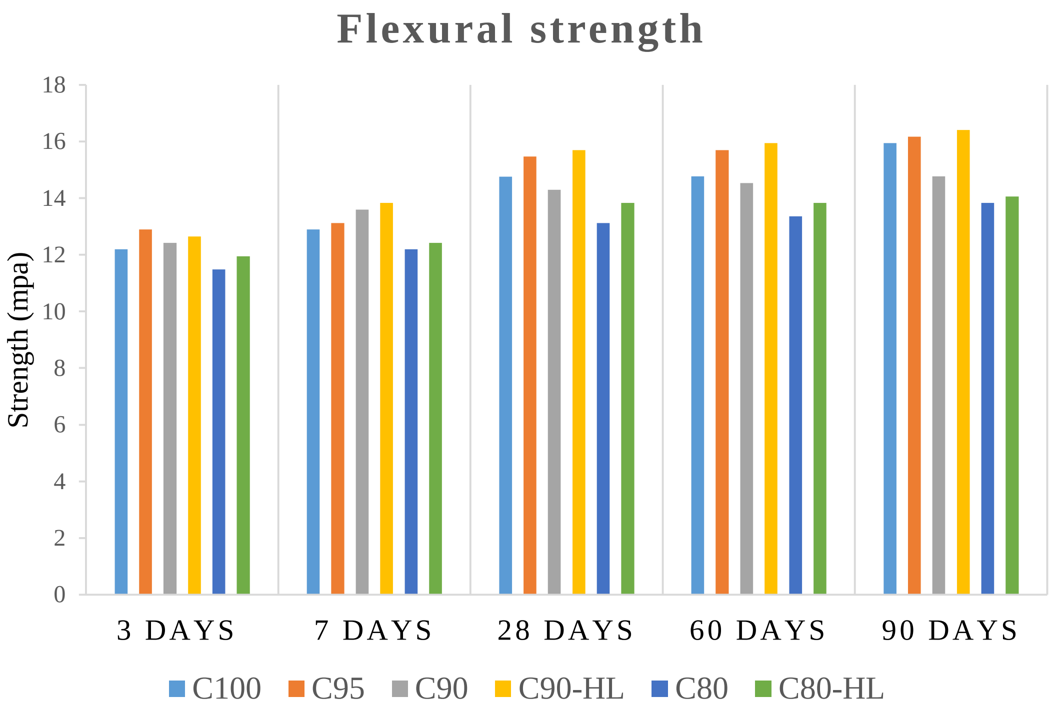
5.4.2 Flow of SCP Formulation

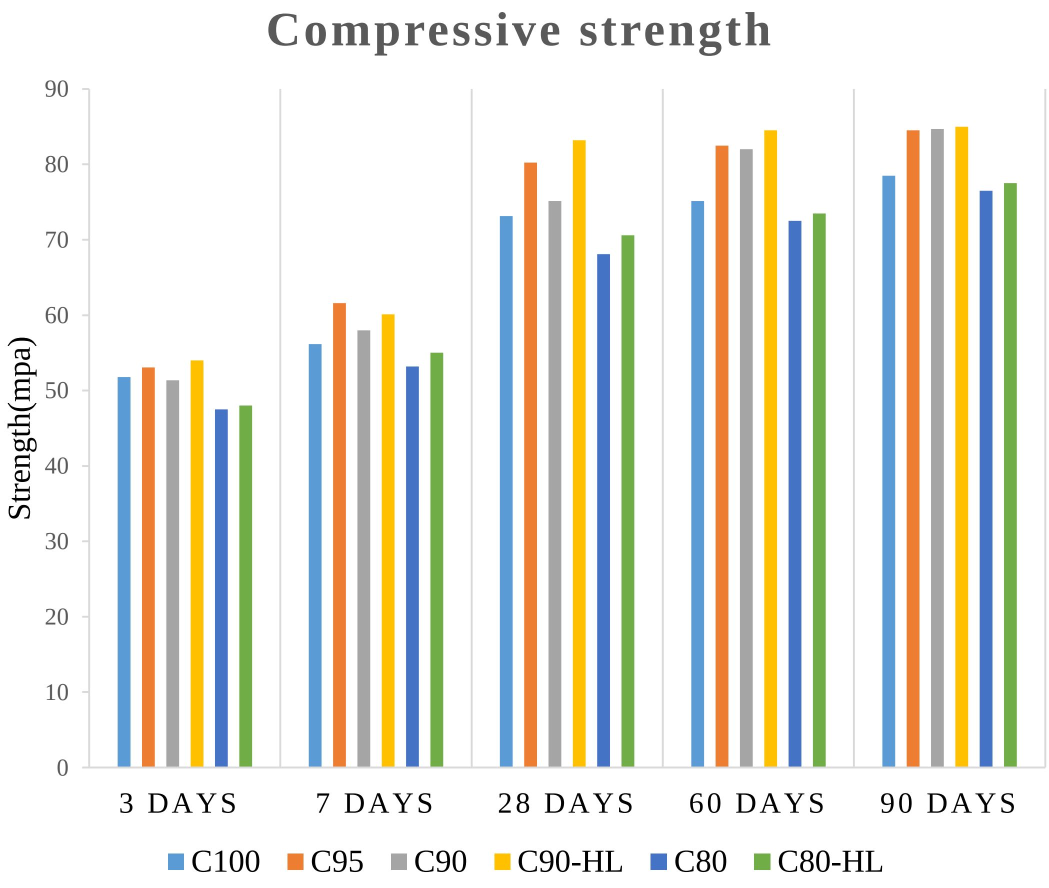
Bar chart shows the Hagerman's mini slump cone for T 25 cm and T 30 cm.



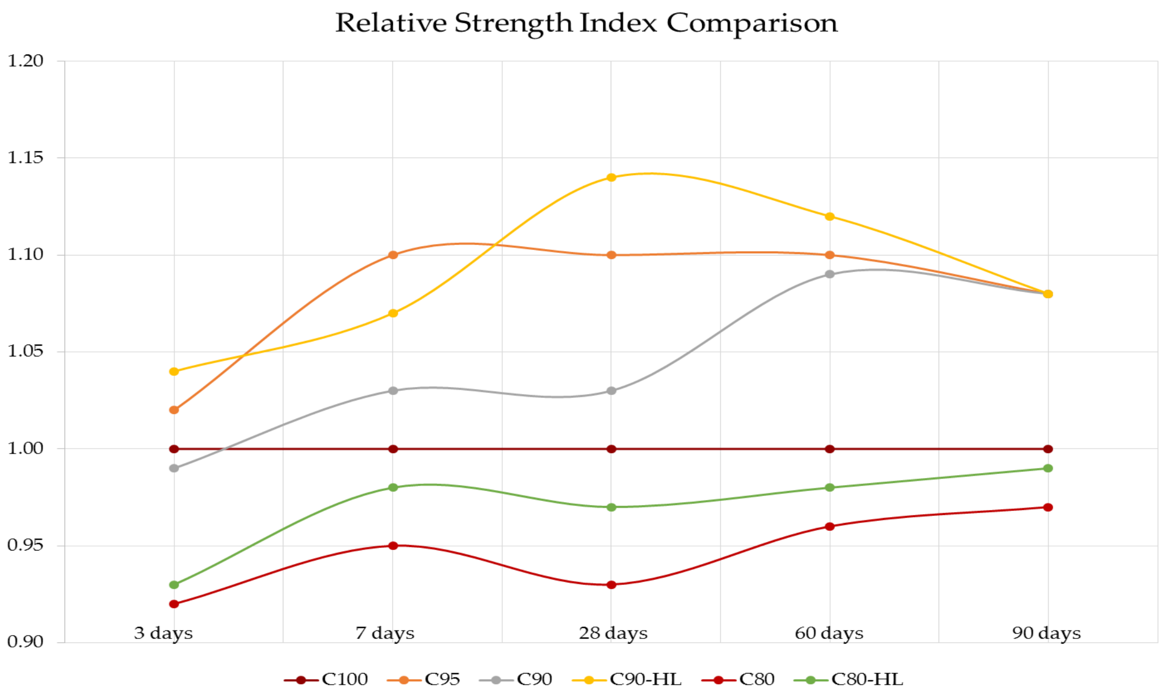
5.4.3 Strength of SCP Formulation

The results for flexure and compression strength for each respective formulation are shown by bar chart in figure 1 and 2 at day 3, 7, 28, 60 and 90.



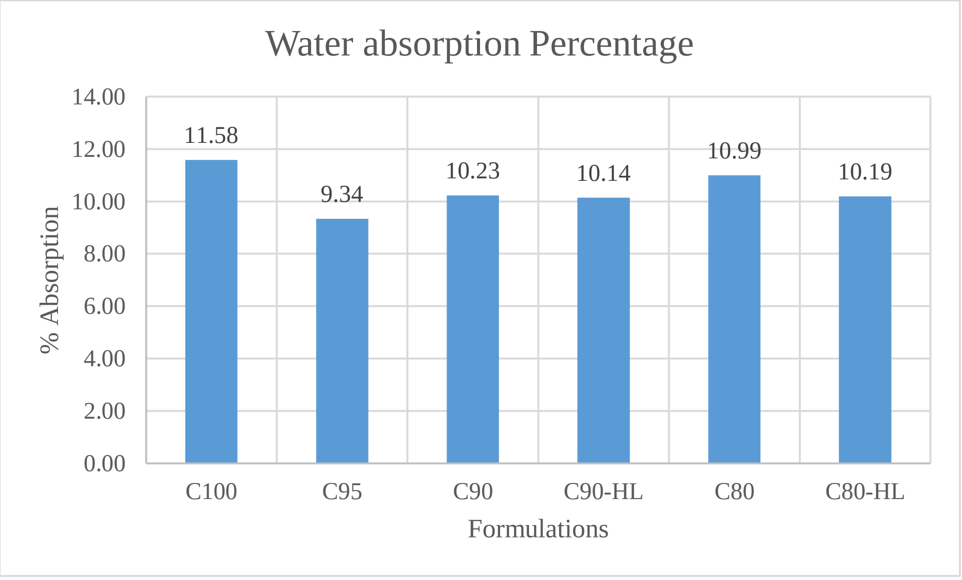


The graph below gives the information about the strength index at the age of 3, 7, 28, 60 and 90.



5.4.4 Water absorption

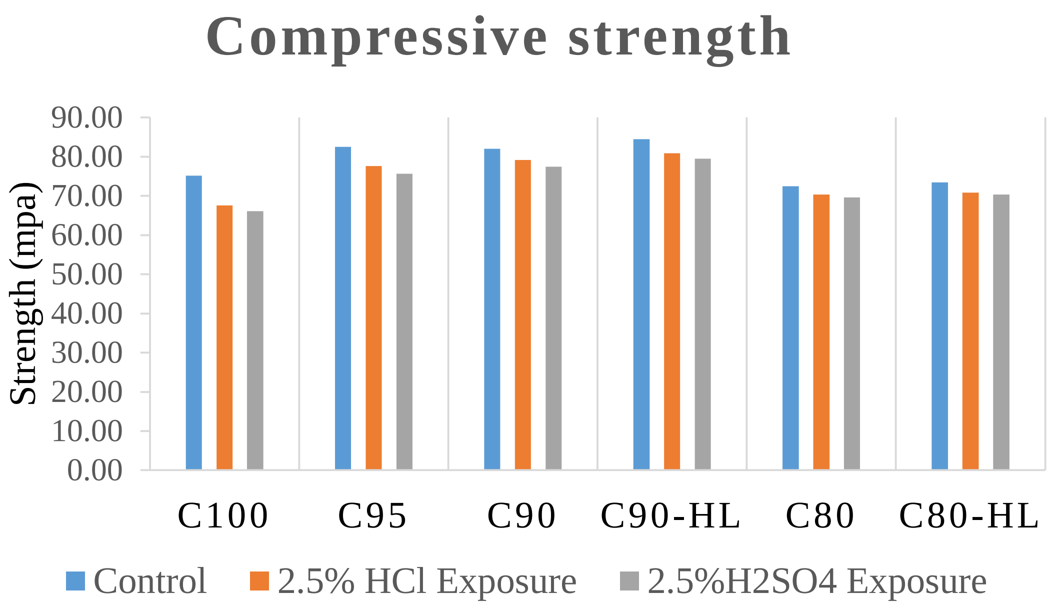
The water absorption test results indicates that there is decrease in water absorption by incorporating secondary raw material in self-compacting paste system.



5.4.5 Resistance to acid attack

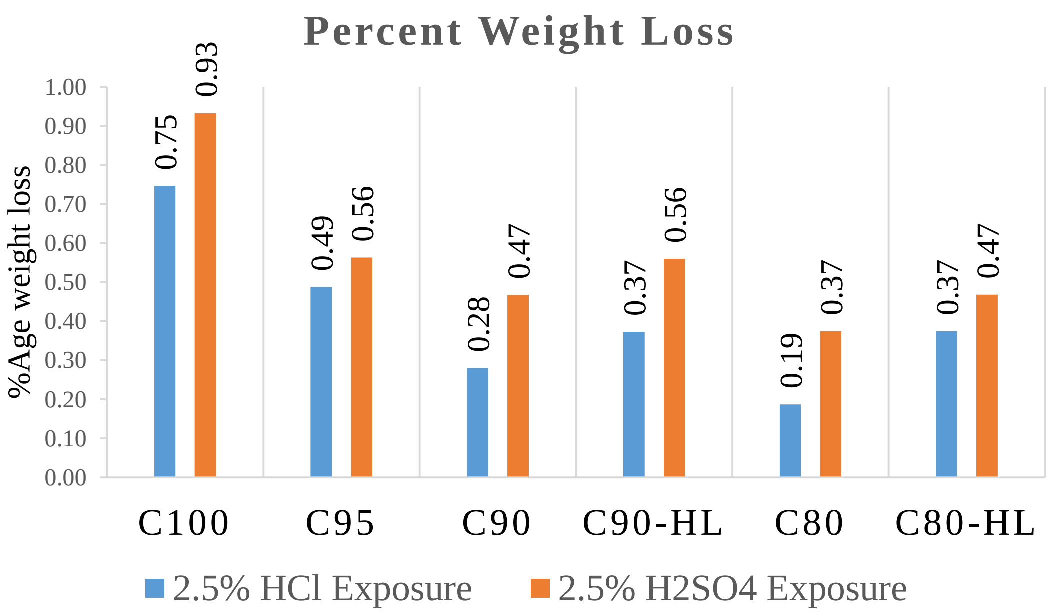
Resistance against acid attack of SCP formulation with and without secondary raw material has been measured in term of weight loss and strength after immersed in 2.5

% of dilute sulphuric acid and 2.5% dilute HCL solution for 30 days. The figure indicates compressive strength after exposure to acidic environment.



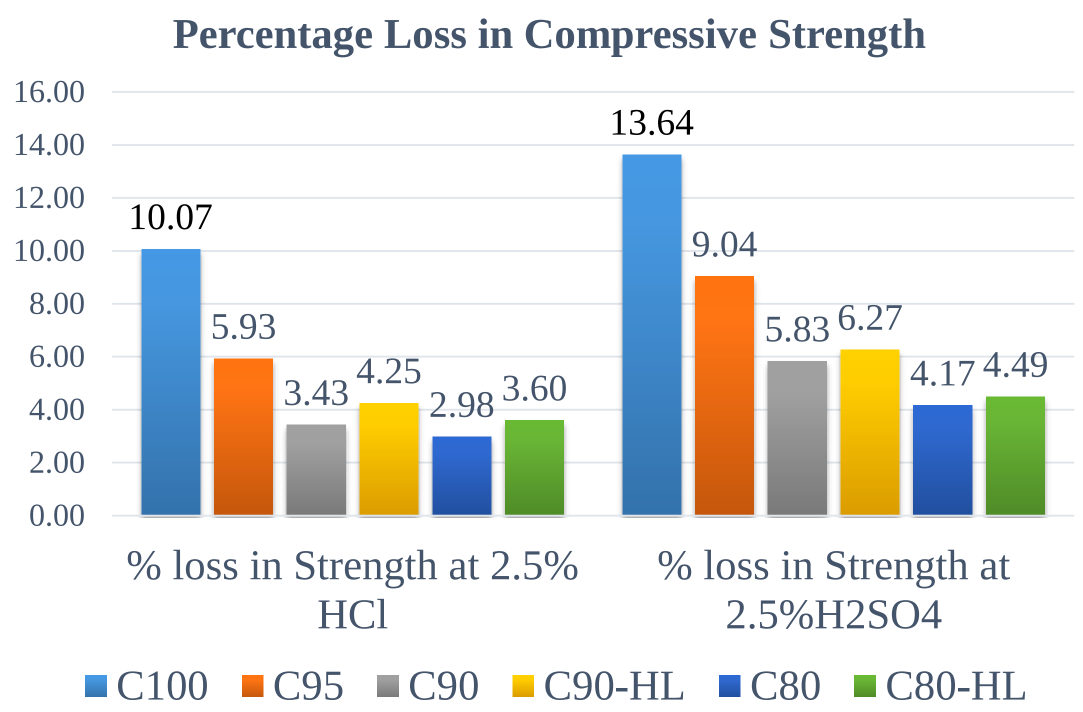
5.4.5.1 Percentage reduction in weight

The percentage reduction in weight for each respective formulation after exposed to acidic environment for 30 days is shown in bar chart below. Bar chart indicates that weight loss in control sample is maximum as compared to formulation having SRM's. Also the percentage reduction in weight is maximum in sulphuric acid as compared to HCL and the reduction in weight is due to reaction of hydration product calcium hydroxide present in each formulation.



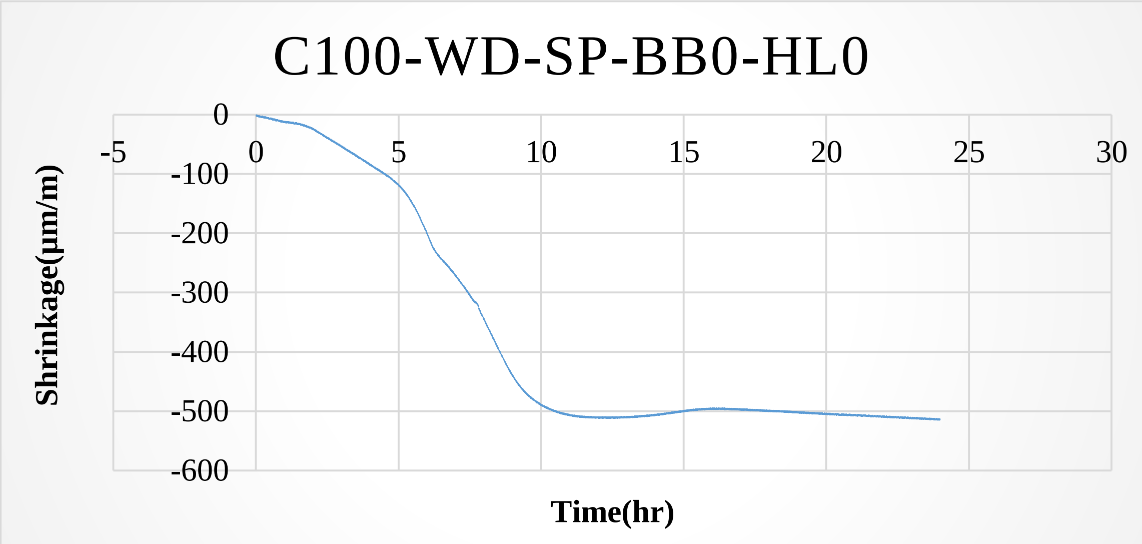
5.4.5.2 Percentage reduction in strength

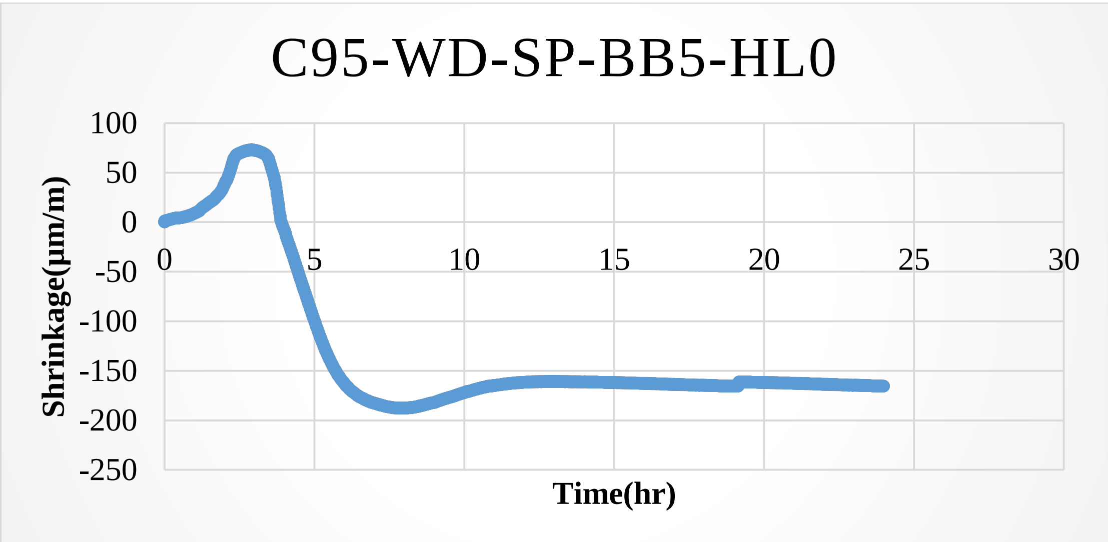
The percentage reduction in strength for each respective formulation after exposed to acidic environment for 30 days is shown in bar chart below. Bar chart indicates that strength loss in control sample is maximum as compared to formulation having SRM's. Also the percentage reduction in strength is maximum in sulphuric acid as compared to HCL and the reduction in strength is due to reaction of hydration product calcium hydroxide present in each formulation.

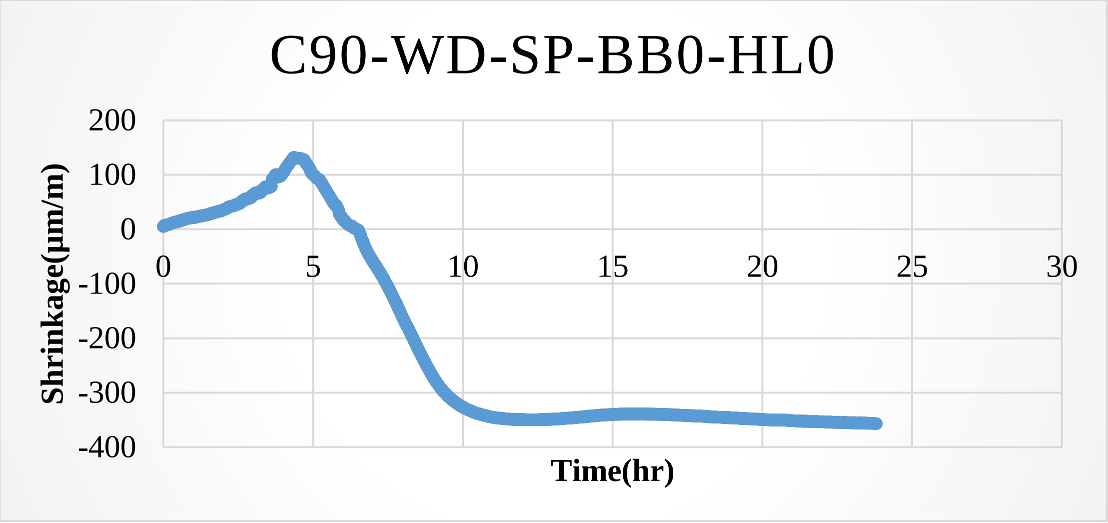


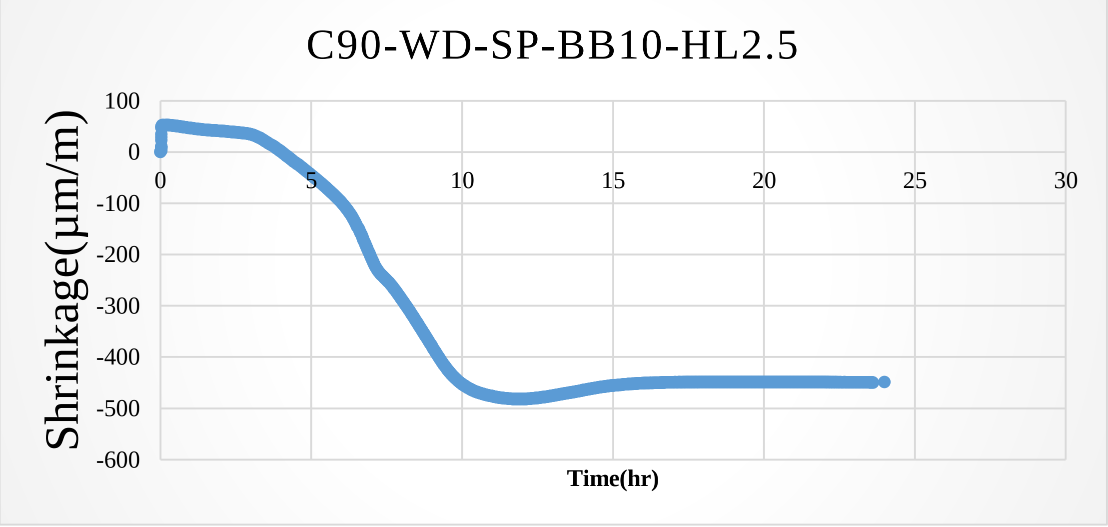
5.4.6 Early shrinkage

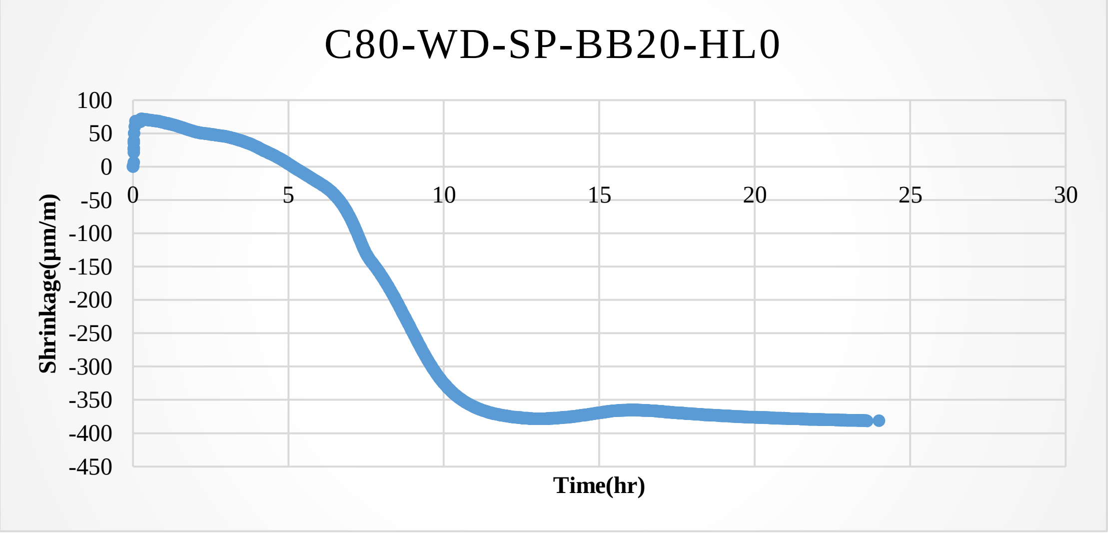
Figure shows the early shrinkage of each formulation study in the research. The maximum shrinkage value is observed in a control sample.

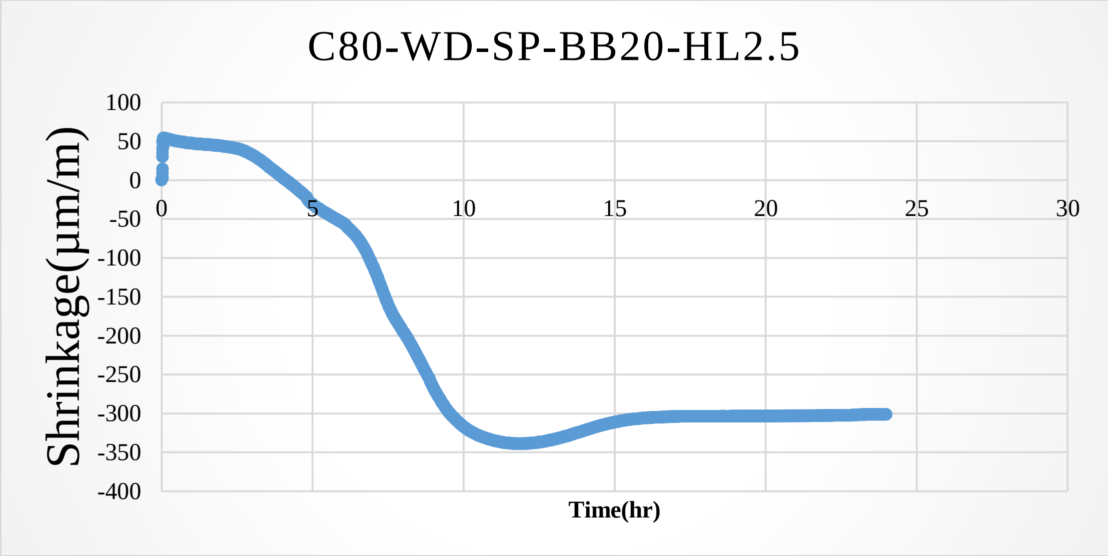





C90-WD-SP-BB0-HL0
Shrinkage(μm/m)
200
100
0
-100
-200
-300
-400
0
5
10
15
20
25
30
Time(hr)

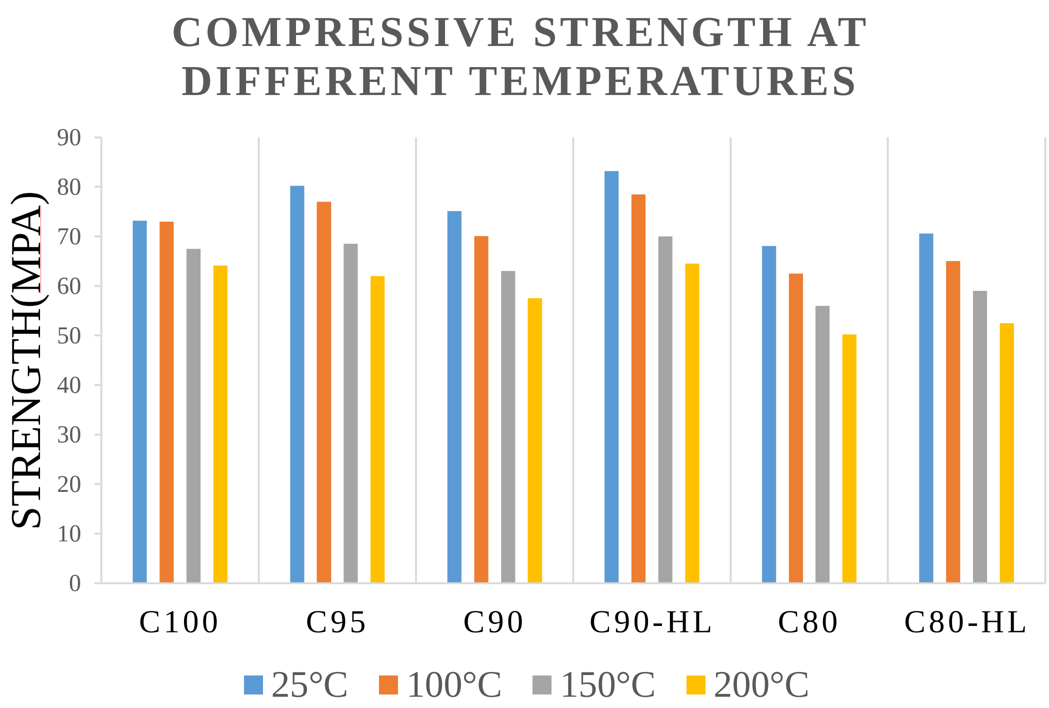

C90-WD-SP-BB10-HL2.5
Shrinkage(μm/m)
100
0
-100
-200
-300
-400
-500
-600
0
5
10
15
20
25
30
Time(hr)


C80-WD-SP-BB20-HL0
Shrinkage(μm/m)
100
50
0
-50
-100
-150
-200
-250
-300
-350
-400
-450
0
5
10
15
20
25
30
Time(hr)



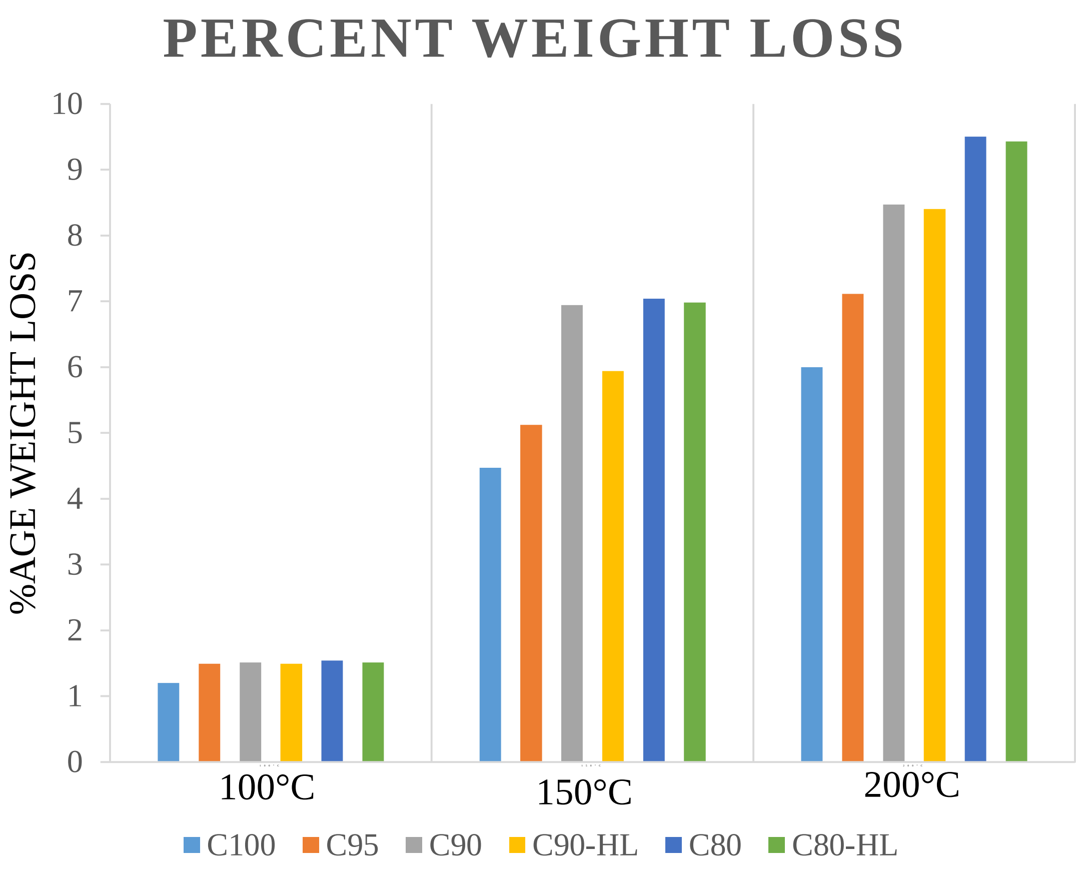
5.4.7 Exposed to temperature

At 25°C, 100°C, 150°C and 200°C temperature the behavior of each formulation is observed. It has been noticed that percentage reduction in weight is minimum in control sample as compared to other formulations having secondary raw material. Figure below shows compressive strength at different temperatures.



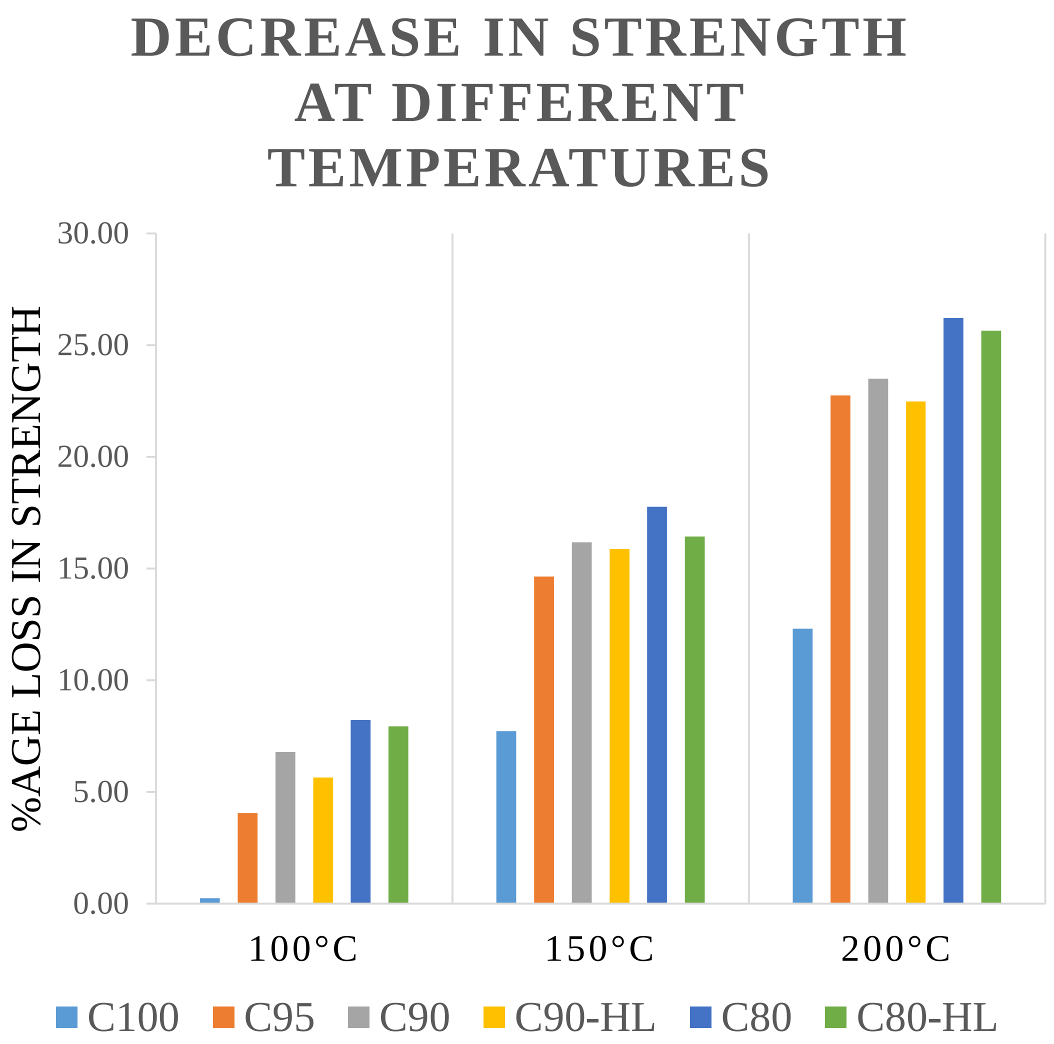
5.4.7.1 Percentage reduction in weight

The percentage weight reduction is minimum in control sample as compared to other formulation having secondary raw material.



5.4.7.2 Percentage reduction in compressive strength

The percentage reduction is minimum in control sample as compared to other samples as shown in the figure.



5.5 Scanning Electron microscopy

At age of 28 days for certain selected formulation such C100, C90 and C90-HL the SEM images are taken. The figure 5.9, figure 5.10 and figure 5.12 show the C100, C90 and C90-HL hydrated paste SEM images.

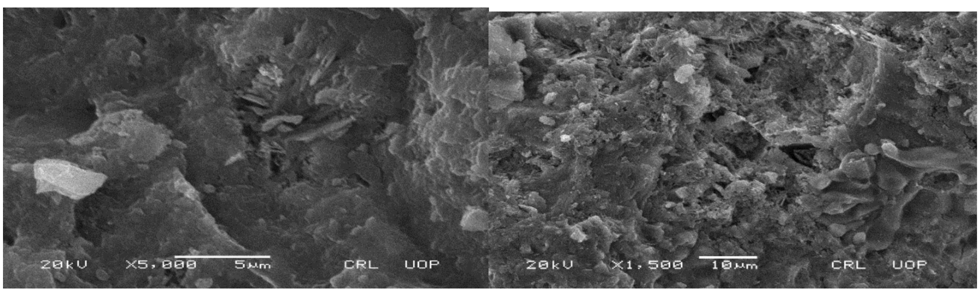


Figure 5.9 SEM of C100 at 28 day

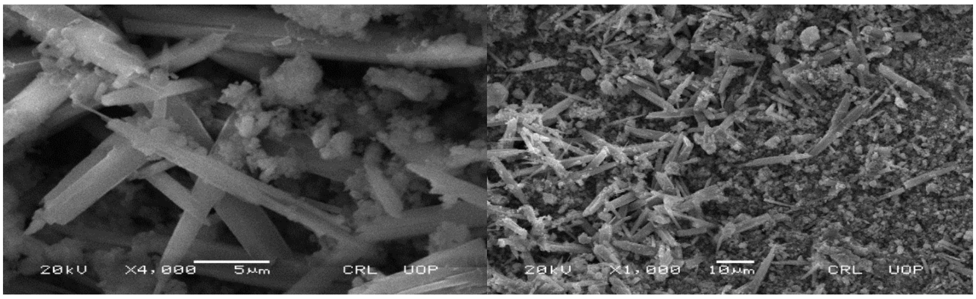


Figure 5.10 SEM of C90 at 28 day

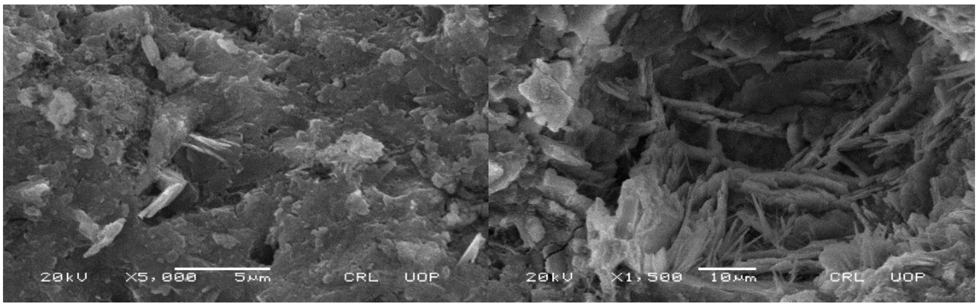


Figure 5.11 SEM of C90-HL at 28 day

5.6 X-ray diffraction

At age of 28 days for certain selected formulation such C100, C90 and C90-HL XRD test was performed. The figure 5.12, figure 5.13 and figure 5.14 show the C100, C90 and C90-HL hydrated paste XRD pattern.

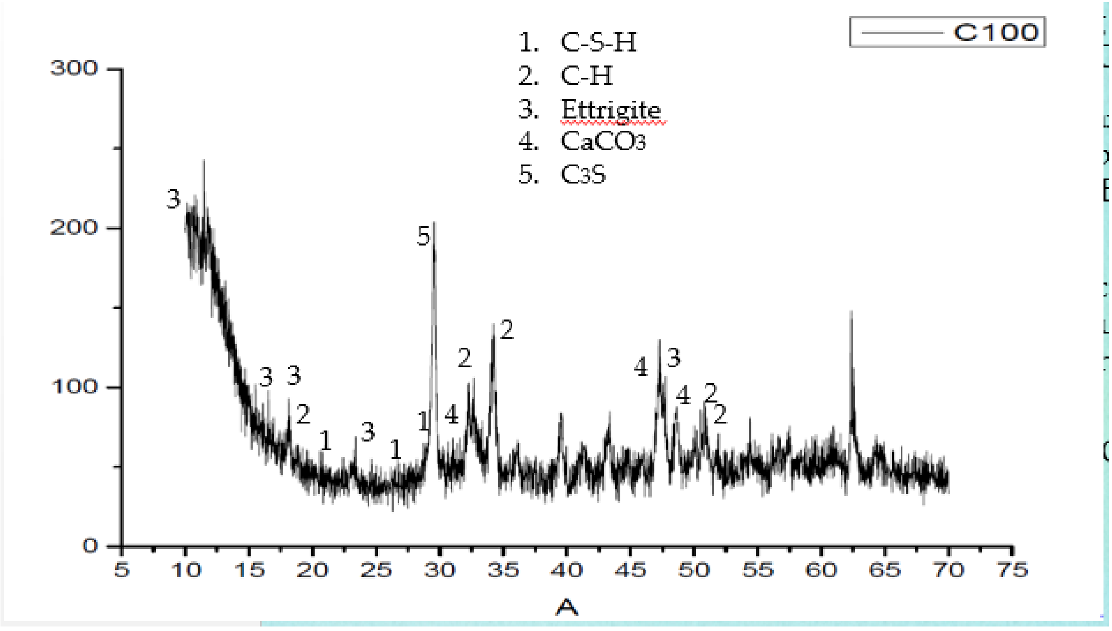


Figure 5.12 XRD of C100 at 28 day

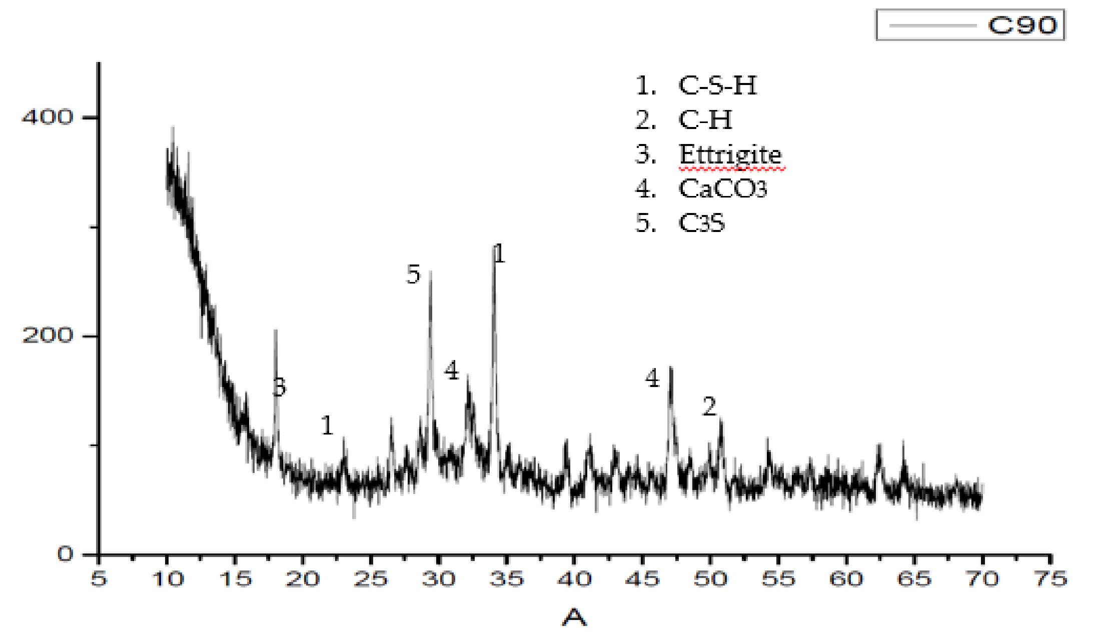


Figure 5.13 XRD of C90 at 28 day

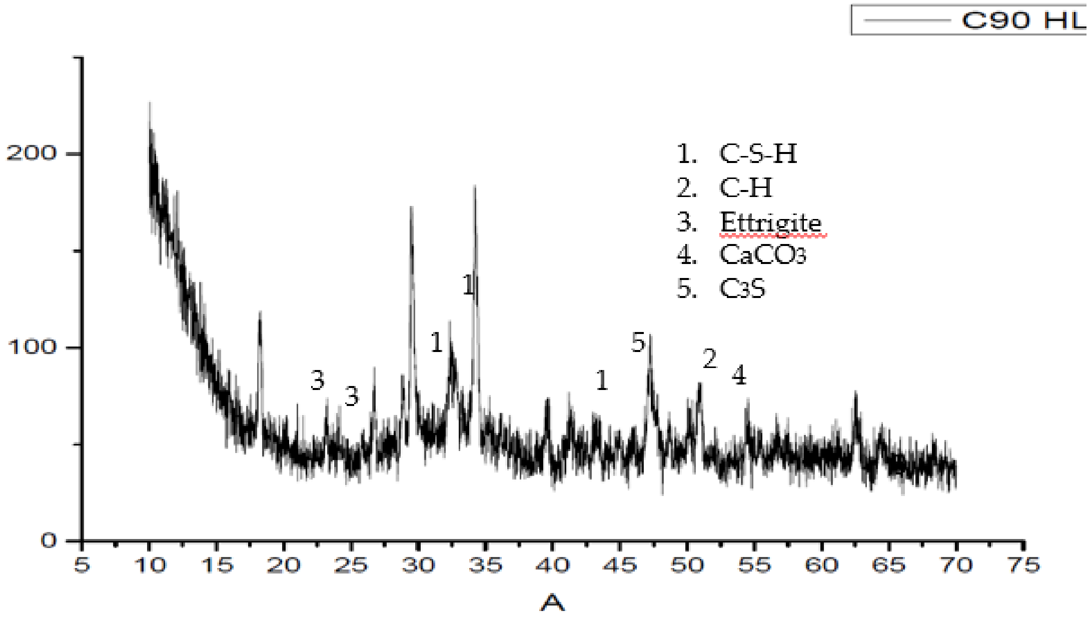
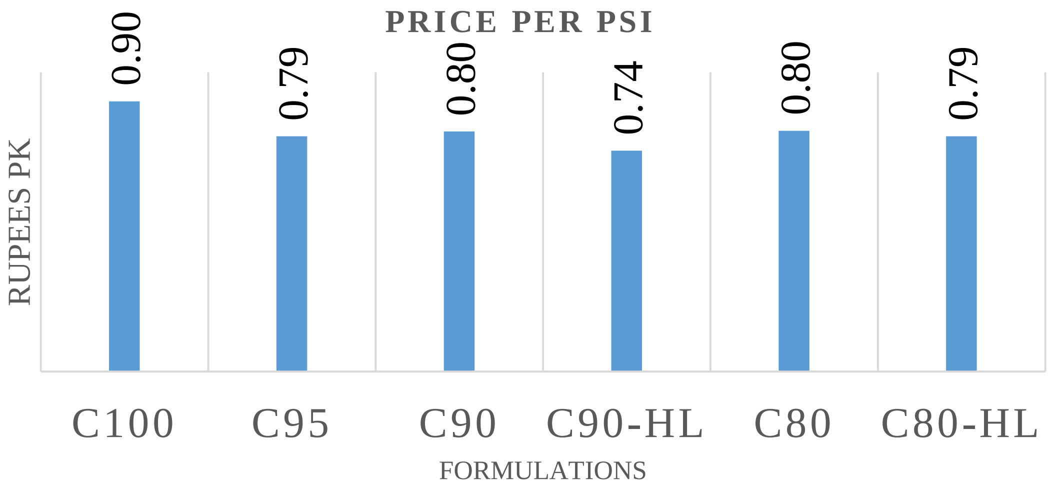
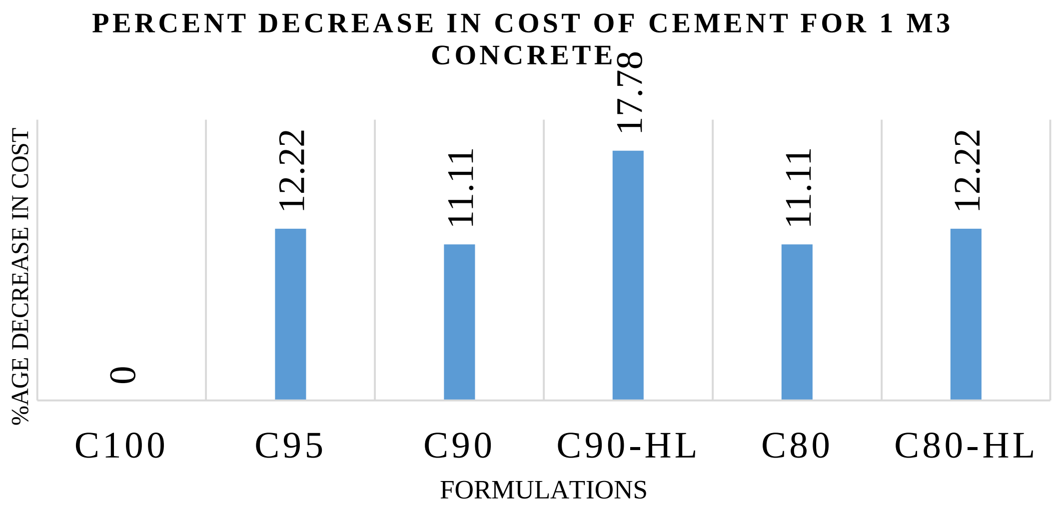


Figure 5.14 XRD of C90-HL at 28 day

5.7 Cost Analysis

For 1 cum M-30 concrete quantity of cement require 7.5 bag (1 bag 50 kg). M 30 grade (1:1.5:3). The fig and fig indicate the price per unit psi and percentage decrease in cost of cement required in one cubic meter of 4000 psi respectively.




PERCENT DECREASE IN COST OF CEMENT FOR 1 M3 CONCRETE
%AGE DECREASE IN COST
0
12.22
11.11
17.78
11.11
12.22
C100
C95
C90
C90-HL
C80
C80-HL
FORMULATIONS

CHAPTER 6

Discussion

6.1 Brunt Brick powder

The physical as well as chemical properties of waste brunt brick powder meets the ASTM C-618 requirement, so classified as artificial pozzolanic material.

Parameters	Brunt Brick powder	ASTM C-618 Requirement
$SiO_2 + Al_2O_3 + Fe_2O_3$	80.11 %	Min 70 %
SO_3	0.23 %	Max 4 %
Moisture Content	2.5 %	Max 3 %
Loss on ignition	4.3 %	Max 10 %
Strength index 7 days strength (20 % replacement)	0.98	Min 0.75

The SEM images of brunt brick powder indicate that its particles are irregular, rough and porous. The particles size of brunt brick powder are much smaller as compared to cement and hydrated lime particles which will cause increase water and super plasticizer demand due high specific area. The XRD pattern shows that brunt brick is composed of quartz, hematite and albite minerals.

6.2 Water Demand

The water demand of SRM depends on their shape, size and Morphology. Because of the smaller size of Burnt Brick powder its specific surface area is large so more water is required to wet its surface. The SEM analysis show that the particles of Burnt Brick powder are irregular with rough porous surface which tend to increase the water demand.

6.3 Super plasticizer Demand

Super plasticizer is adsorbed not only by cement but also by SRM. The Burnt Brick powder (BBP) has an irregular and angular surface leading to more adsorption capacity compared to cement and thus has higher SP demand.

6.4 Initial and Final setting time

Setting time of paste depends on particle size and Calcium Oxide (CaO) content. Smaller the particle size and Greater the CaO content the lesser will be the setting time. The initial setting time of control sample is lesser than the setting time of samples containing Burnt Brick powder because of the higher amount of CaO in the control sample. However the final setting time doesn't show much variance which may be due to smaller particle size of Burnt Brick powder.

6.5 Flow of Self Compacting Paste Systems (SCPS)

The particle shape, size and morphology of SRM play an important role in deciding the response of Self Compacting systems. The purpose of flow test using mini slump cone is to investigate yield stress, deformability and unrestricted filling ability of Self Compacting systems. So, the flow test basically measures two parameters total flow spread and flow time. In flow time we observe T25 cm and T30 cm. T25 cm indicates yield strength and T30 indicates rate of deformation within a defined flow distance. Smaller the flow time lesser is the internal friction offered by powder particles so higher will be the deformation. T25 time of control sample is smaller than that of samples with BBP. This is due to the fact that control samples only contain cement particles which have a smooth shape and thus offer lesser resistance to deformation. The greater T25 cm time of BBP sample indicate higher yield strength which indicates that they will offer better resistance to segregation. T30 time of BBP samples is also greater than control samples which indicate higher viscosity of these samples and thus will offer better segregation resistance.

6.6 Shrinkage Test

Volume stability is the change in volume of the final hydrated product with the initial volume during casting. Mostly shrinkage is observed however, in few rare cases expansion may also be observed. Shrinkage depends on consumption / loss of water which includes water consumed during hydration process and pozzolanic reaction, water suction by porous secondary raw materials and evaporation. The expansion occurs due to growth of expansive species like calcium hydroxide and ettringite, thermal gradient and may also be due to absorption of bleed water in the system.

Shrinkage is the sum of autogenous shrinkage, chemical shrinkage, autogenous shrinkage and drying shrinkage. The rate of autogenous shrinkage is highest up till day 1 and is quite significant for SCCS using low w/c ratio. Measurement technique of shrinkage includes volumetric and linear method.

Shrinkage or expansion in volume is caused by chemical reactions during and after hydration process due to removal of water from the pores within the system. The lower the W/C ratio, the greater the number of capillaries of smaller diameter in the concrete in hardening phase which accelerates the development of autogenous shrinkage. The paste phase is mainly responsible for the shrinkage / expansion of the cementitious systems. Greater the cement content in the paste phase greater would be the shrinkage due to higher consumption of water during hydration process. The shrinkage has been studied for first 24 hours.

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6.7 Water Absorption

Decreased water absorption is due to better packing efficiency caused by smaller average particle size of Burnt Brick powder which reduce undesirable voids and discontinuous porosity. Reduced water absorption dictates reduced permeability and reduced porosity. Reduction is more due to high efficient pozzolanic activity.

6.8 Resistance to Acid Attack

The weight and strength loss for control sample is highest among all formulations for both acid solutions of hydrochloric acid and sulfuric acid. The poor performance of control Mix is due to the fact that it contains 61 percent lime which upon hydration produces considerable portion of free calcium hydroxide which reacted with acid and a soft and mushy mass was left behind. In case of formulations with Burnt Brick powder, the calcium hydroxide reacted with Silica in Burnt Brick powder to form another kind of silica gel resulting in reduced amount of calcium hydroxide making these samples more resistant to acid attack.

The weight and strength loss is more for sulfuric acid than hydrochloric acid. This is because in case of sulfuric acid a product called sulfoaluminate (Ettringite) is formed which occupies large volume and hence its expansive nature causes disruption of the set cement paste whereas no such product is formed in case of hydrochloric acid.

6.9 Response at different temperature

At 25°C, 100°C, 150°C and 200°C compressive strength and reduction in weight were studied. The control sample performed better and incorporation of hydrated lime improve the properties in temperature range 25°C to 200°C as compared to formulation without hydrated lime. The better performance of control sample in temperature range 25°C to 200°C is due to the less available water content in hydration products. The removal of water from hydrated paste disturb the chemistry of hydration product which cause reduction in compressive strength. Since due to the water retention of brunt brick powder the water content in replacement sample were more, so therefore weight reduction in replacement samples were noted greater than control sample.

6.10 Microstructure of Self compacting Paste Systems

The SEM images of various formulation at age 28 day gave the idea about the microstructure. The microstructure of hydrated paste of replacement were more dense and compacted. The needle shape crystals in SEMs images indicate the growth of ettringite, the hexagonal crystals show the presence of CH and CSH gel is found as rough crystalline in form.

The XRD patterns of various formulation show the presence of hydration product such as CSH gel, CH, $CaCO_3$ and ettringite. The anhydrate cement grains also observed such as C_3S.

CHAPTER 7

Conclusion and Recommendation

7.1 Conclusions

The following conclusions were derived from the available data collected in the research project.

- The waste brunt brick powder is classified as artificial pozzolanic material.
- The waste brunt brick powder is classified as silica-aluminate on basis of XRD patter.
- Smaller the particles of SRM as compared to cement grains, higher will the pozzolanic activity.
- The water demand and super plasticizer demand increased with increasing percentage of BBP.
- There was increased in 28 days strength by replacement of BB up to 10%.
- At 90 days the 20% replacement show strength almost equal to control sample.
- By incorporating hydrated lime there is increase in initial strength.
- The shrinkage value reduced in other formulations as compared to control formulation.
- The Absorption capacity decreases using BB as SRM thus the durability of paste increases.
- The resistance against sulfate attack improved using BB as SRM.
- The control sample show better performance in temperature range 25-100.

7.2 Recommendations

The following are some recommendation to carry out further research activity.

- The idea of using BB as SRM must be extended to SCM and SCC.
- The mechanical and rheological properties must be determined for replacement of BB at greater than 20%.
- Work should be carried out to determine optimum hydrated lime content with burnt brick replacement.
- The potential of Over Burnt Brick as SRM should be assessed.

CHAPTER 8

Application

8.1 Advantages of Waste Brunt Brick Powder as SRM

8.1.1 Eco-Efficient

Using self-compacting cementitious system having BB as SRM is eco-efficient due to the following two reasons.

- Reduce cement quantity in concrete and reduction in cement content means reduction in carbon foot print.
- Reduce the solid waste brunt brick which has no commercial use.

8.1.2 Resource Conservation

In 2017 cement production of Pakistan was about 149 million tons. Also 18% solid waste in Pakistan is waste brunt bricks. So if we use brunt brick powder as SRM, we can easily conserved our resources.

8.1.3 Cost Effective

The cost analysis showed that using brunt brick powder as SRM we can save in cost of cement.

8.1.4 Readily Available

Bricks is most widely use construction material in Pakistan. So, waste bricks are easily available from brick kilns, construction industry and demolition of old masonry to use as SRM.

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Annexures

Annexure-A Chemical properties of material

Constituents	Cement (%age by weight)	Burnt Brick Powder(%age by weight)	Hydrated Lime (%age by weight)`
SiO_2	19.19	69.85	-
Al2O3	4.97	5.83	-
Fe2O3	3.27	4.43	4.23
CaO	61.8	15.67	92.53
K2O	0.51	1.04	-
MnO	2	0.18	-
ZnO	0.68	0.30	-
SrO	0.29	0.62	3.24
SO3	-	0.23	-
MgO	2.23	1.04	-
Na2O	0.57	0.81	-
LOI	-	4.3	

Chemical Base	Aqueous Solution of modified poly carboxylate co-polymer
Form	Liquid
Color	Colorless-yellowish
Water reduction	Upto 30%
Shelf life	12 months
Density	1.085kg/lt
Chloride content	Nill
Max Dosage	1.7%

Sr#	Parameters	Units	Sample Results	WHO Guidelines
1	pH	--	6.9	6.5-8.5
2	Turbidity	NTU	0.7	<5.0
3	TDS	mg/L	460	<500
4	Chlorides	mg/L	78	<250
5	Hardness	mg/L	330	<500

Chemical properties of SP and Water

Annexure-B Water Demand, Super plasticizer Demand, setting time and flow times

Formulation	Water demand (w/c)	Sp demad (% of c)	Sp demad (% of powder)	T 25 (sec)	T30 (see)	Ti with out Sp (min)	Tf with out sp (min)	Ti with Sp (min)	Tf with sp (min)
C100	26.5	0.35	0.35	3	21.7	113	177	356	399
C95	28	0.358	0.34	3.12	22.84	131	189	369	402
C90	31	0.365	0.329	3.29	24.5	139	193	390	420
C90-HL	31	0.37	0.333	4.39	23.33	125	185	381	400
C80	36	0.39	0.312	4.4	26.37	151	195	399	434
C80-HL	36	0.4	0.32	4.51	26.6	134	180	370	406

Annexure-C Strength Results

Compressive Strength

Formation	3 days (MPa)	7 days (MPa)	28 days (MPa)	60 days (MPa)	90 days (MPa)
C100	51.8	56.18	73.15	75.15	78.50
C95	53.1	61.6	80.25	82.50	84.5
C90	51.35	58	75.15	82	84.7
C90-HL	54	60.1	83.2	84.5	85
C80	47.5	53.2	68.1	72.5	76.5
C80-HL	48	55	70.6	73.5	77.5

Flexure Strength

Formation	3 days (MPa)	7 days (MPa)	28 days (MPa)	60 days (MPa)	90 days (MPa)
C100	12.18	12.89	14.76	14.77	15.94
C95	12.8	13.1	15.46	15.7	16.17
C90	12.42	13.59	14.29	14.53	14.17
C90-HL	12.65	13.82	15.7	15.94	16.41
C80	11.48	12.18	13.12	13.36	13.83
C80-HL	11.95	12.42	13.82	13.83	14.06

Annexure-D Resistance against acid and absorption

Percentage loss in compressive strength

Formulation	% loss at HCl	% loss at H2SO4
C100	10.07	13.64
C95	5.93	9.04
C90	3.43	5.83
C90-HL	4.25	6.27
C80	2.98	4.17
C80-HL	3.60	4.49

Water Absorption

Formulation	% Absorption
C100	11.58
C95	9.34
C90	10.23
C90-HL	10.14
C80	10.99
C80-HL	10.19