EXPERIMENTAL INVESTIGATION ON GGBS ADDED CONCRETE WITH PAPER SLUDGE AS SELF-CURING AGENT

A THESIS

Submitted by

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ABSTRACT

Cement is a widely used versatile material in the area of construction. Engineering construction in all parts of the world is rapidly growing now. Meanwhile, the quality of constructing structures are going down as the monitoring during constructions is not upto the mark. This could also be resulted in the alteration of durability in concrete. For poor durability of concrete improper curing of concrete is one of the factors. Hence, the present study has been carried out to produce self-curing concrete preloaded with compacting agents. Curing of concretes provides the preservation of sufficient moisture in concrete at its initial stages to develop and maintain the desired properties. The purpose of using self-curing agent is to minimize the evaporation of water from concrete, and thereby enhance the water retention ability of the concrete than that of control concrete. From the literature, it is clear that, paper sludge can effectively be used as self-curing agent. Self-curing concrete plays a crucial role in the development of concretes microstructure and pore structure, and hence it will effectively influence its durability.

A very large amount of Portland cement is needed at present since, construction industries are increasing at a global level. Manufacture of Portland cement is an energy intensive process and emits huge amount of greenhouse gases into the atmosphere lead to the alteration of the earth’s ecosystem. Various efforts are being practiced to conserve energy in terms of encouraging the use of industrial wastes such as Granulated Blast furnace Slag (GGBS) and Paper sludge (PS), which exhibit similar chemical properties as cement. In the present work, the solid waste materials from industries such as GGBS and PS were used as partial replacement of cement for M_{25} grade concrete to prepare all the test mixes, to find the optimum percentage of the replacement level to the cement with GGBS and paper sludge. In addition, an optimum percentage level of the paper sludge as self-curing agent has also been determined.

The entire research work carried out is divided into three distinct phases. In the first phase, tests on compressive strength, split tensile strength and flexural strength of M_{25} grade concrete were conducted with the addition of 10%, 20%, 30%, 40% and 50% GGBS. From the experimental results, it was found that, upto 40% replacement of cement by GGBS, the compressive strength, split tensile strength and flexural strength values were comparatively higher than the control concrete values (water curing).

In the second phase the tests on compressive strength, split tensile strength and flexural strength of M_{25} grade concrete with 5%, 10%, 15%, 20%, 25%, 30% and 40% PS were conducted. The results showed that, 10 to 25% of cement replacement by PS at 28 days have increased relatively higher than the control concrete for different self curing days (28, 60, 90, 120, 180 and 365 days) and it was optimum at 25% of cement replacement by PS.

In the third phase, M_{25} grade concrete specimens were prepared by the addition of PS with various dosages of GGBS having an interval of 5% were subjected to compressive strength, split tensile strength and flexural strength for different curing days by self curing methods. The obtained results revealed that, partial replacement of cement with 15% of PS including 25% of GGBS had the better compressive strength, split tensile strength and flexural strength values when compared to control concrete.

In addition, the micro structural analyses have been carried out for specimens of optimum level using the Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD). The rate of hydration of PS and GGBS added

Self curing concrete have also been analyzed using Thermogravimetry and DSC (Differential Scanning Calorimetry). In addition, the durability tests viz., acid attack, sulphate attack, water absorption, water sorptivity and rapid chloride permeability have been conducted based on Indian standards.

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Al_2O_3	-	Aluminium oxide
CaO	-	Calcium oxide
C-S-H	-	Calcium-Silicate-Hydrate
CO_2	-	Carbon dioxide
CLSM	-	Controlled Low Strength Material
f_{ck}	-	Cube Compressive Strength of HFRC
DTG	-	Derivative Thermogravimetry
DSC	-	Differential Scanning Calorimetry
DD	-	Distilled Deionized Water
EDX	-	Energy-dispersive X-ray spectroscopy
Fe_2O_3	-	Ferric Oxide
FA	-	Fine aggregates
GGBS	-	Ground Granulated Blast Furnace Slag
MgO	-	Magnesium Oxide
Mn_2O_3	-	Manganese Trioxide
OPC	-	Ordinary Portland Cement
PS	-	Paper sludge
PRCM	-	Partial Replacement Cement Material
K_2O	-	Potassium Oxide
RCPT	-	Rapid Chloride Ion Penetration Test
SEM	-	Scanning Electron Microscope
SiO_2	-	Silica dioxide
Na_2O	-	Sodium Oxide
TG	-	Thermogravimetry
TiO_2	-	Titanium Dioxide
WPSA	-	Waste Paper Sludge Ash
XRD	-	X-ray diffraction

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Cement concrete is the widely used material in construction throughout the world, which consists of cement, fine aggregate, coarse aggregate and water. Among the ingredients that are used in concrete, cement is the most important ingredient, which in contact with water, makes a paste and this paste binds the aggregates together into a solid mass (Ishak *et al.* (2015), Song *et al.* (2016) and Leeson *et al.* (2017)). In the production of cement, large amount of CO_2 is emitted which produces adverse effects on the environment such as global warming and green house effects (Ali *et al.* (2011), Hasabeigi *et al.* (2012)). 0.5 ton of CO_2 is emitted per 1 ton of cement production, which has a significant effect on global warming. There is also a great need to minimize the production and use of cement with respect to environmental protection (Rahman *et al.* (2013) and Morrow *et al.* (2014)).

Nowadays, significant attention is given to the use of waste materials of either industrial or agricultural processes as supplementary cement replacement materials (Zhnwei *et al.* (2013)). Some of the industrial wastes such as Ground Granulated Blast Furnace Slag (GGBFS), Paper Sludge (PS), marble powder, fly ash, silica fume and agricultural waste consist of rice husk ash wheat straw ash, coconut waste and sugarcane bagasse ash etc. are being commonly used as partial replacement cement materials in the recent past (Hanifi Binici *et al.* (2007), Mohammed Nadeem *et al.* (2012)). The utilization of such waste materials as cement replacement not only reduces the cost of concrete but also minimizes the negative environmental impacts that are associated with the disposal of these waste materials and reduction in CO_2 emission gas by reducing the cement content in concretes (García-Segura *et al.* (2014), Kashef-Haghighi *et al.* (2015)).

1.2 ROLE OF ADMIXTURES

During hydration of cement in concrete tricalcium silicates (C_3S) and dicalcium silicates (C_2S) react with water and produce calcium silicate hydrates and calcium hydroxide (Hwang *et al.* (1991), Brooks *et al.* (2000)). The calcium hydroxide ($Ca(OH)_2$) is not a desirable product in the concrete mass and it constitutes 20 to 25% of the volume of solids in the hydrated paste which is soluble in water. This may get leached out and makes the concrete porous, weak and non durable. $Ca(OH)_2$ also reacts with sulphates present in water or soil to form calcium sulphate which further reacts with Tricalcium Aluminates (C_3A) and cause deterioration of concrete.

Mineral admixtures such as GGBS, PS, marble powder, fly ash and silica fumes are used to overcome the adverse effect of calcium hydroxide which is produced during the hydration of cement in concrete (Hui-sheng Shi *et al.* (2009)). These mineral admixtures produce less percentage of calcium hydroxide when compared to Ordinary Portland Cement (OPC).

The pozzolanic reaction of mineral admixtures improves the durability of concrete. Hence, the mineral admixtures in optimum proportion improves the quality of concrete by various ways (Bai *et al.* (2009), Nijland *et al.* (2010)).

They are,

- Lowering the heat of hydration and thermal shrinkage.
- Increasing water tightness.

- Reducing the alkali-aggregate reaction.
- Improving chemical resistance.
- Improving the corrosion resistance.
- Improving the early strength, workability and durability.
- Improving the rate of strength development.

1.3 GROUND GRANULATED BLAST FURNACE SLAG

Ground Granulated Blast furnace Slag is a by-product of iron manufacturing industry. Iron ore, coke and limestone are fed into the furnace, and the resulting molten slag floats above the molten iron at a temperature of about 1500ºC to 1600ºC (Ujhelyi *et al.* (1991), Wang *et al.* (1997)). The molten slag has a composition of 30% to 40% Silicon Dioxide (SiO_2) and approximately 40% Calcium Oxide (CaO), which is close to the chemical composition of Portland cement. After the molten iron is tapped off, the remaining molten slag, which mainly consists of siliceous and aluminous residues, is then rapidly water- quenched, resulting in the formation of a glassy granulate (Isa Yuksel *et al.* (2018). This glassy granulate is dried and ground to the required size which is known as Ground Granulated Blast furnace Slag.

It has been reported that for manufacturing one ton of Portland cement would require approximately 1.5 tons of mineral extractions together with 5000 MJ of energy, and would generate 0.95 tons of CO_2 equivalent (Mahdy *et al.* (2002). At the same time production of one ton of GGBS would generate only about 0.07 tons of CO_2 equivalent and consume only about 1300 MJ of energy. Thus, the replacement of Portland cement with GGBS will lead to a significant reduction of CO_2 gas emission and disposal of GGBS can also be minimized.

Some of the recent studies in various parts of the world have revealed that GGBS can be efficiently used as supplementary cementitious material in concrete (ASTM C 989-940). GGBS when used in concrete can act as a partial substitution for Portland cement without significantly compromising the compressive strength. It would also provide environmental and economic benefits with required workability, durability and strength necessary for the concrete structures.

1.4 REACTION MECHANISM OF GROUND GRANULATED BLAST FURNACE SLAG

The hydration mechanism of GGBS and Portland cement is slightly more complex than that of a Portland cement. This reaction involves the activation of the GGBS by alkaline and SO_4 to form its own hydration products. Some of these products combine with the Portland cement products to form hydrates which have a pore blocking effect. The result is a hardened cement paste with more very small gel pores and fewer larger capillary pores for the same total pore volume. The rate of strength development for GGBS added cement mortar is slower than for a Portland cement mortar.

GGBS is a hydraulically latent material, in the presence of lime contributed from cement, (a secondary reaction involving glass (Calcium Alumino Silicates)) a component sets in. As a consequence of this, cementitious compounds are formed. They are categorized as secondary C-S-H gel. The interaction of GGBS and Cement in presence of water is described below:

Product of hydration of OPC:

$$\mathrm{OPC(C_3S/C_2S) + H_2O \longrightarrow C-S-H + Ca(OH_2)} \qquad (1.1)$$

Product of hydration of GGBS

$$\mathrm{GGBS(C_2AS/C_2MS) + H_2O \longrightarrow C - S - H + SiO_2} \qquad (1.2)$$

Reaction of pozzolanic material

$$\mathrm{SiO_2 + Ca(OH_2) + H_2O \longrightarrow C - S - H} \qquad (1.3)$$

The generation of secondary gel results in a formation of additional C-S-H, a principal binding material. This is the main attribute of GGBS, which contributes to the strength and durability of the structure (Yi *et al.* (2014), Yaolin *et al.* (2016)).

1.5 PAPER SLUDGE

A large amount of sludge is produced during the paper production process. This sludge is called paper mill sludge or fibre clay (Niutanen & Korhonen, 2002), which generated at the chemical wastewater treatment plant of the paper mill and is purged from the process prior to entering the paper machine. The amount and chemical composition, as well as the geotechnical properties of paper mill sludge depend on the paper grade being manufactured, fresh water consumption, the wastewater cleaning technique applied and the type of raw materials. Thus, the chemical composition of paper mill sludge produced by one mill is often significantly different from that of another (Jackson & Line 1997; Battaglia *et al.* 2003). The main organic components in the paper mill sludge are wood and cellulose fibres of different lengths, lignin and to some extent also organic binders. The main inorganic components in the paper mill sludge are kaolinite (clay) and calcium carbonate, which are paper additives, as well as heavy metals present as impurities, which mainly originate from the wood raw material (Voundi Nkana *et al.* 1999; Zhang *et al.* 2004).

Paper mill sludge is usually disposed of in landfills. Several studies have shown that, paper mill sludge can be compacted in such a way to have a very low hydraulic conductivity (permeability). Paper fibres can be recycled only a limited number of times before they become too short or weak to make high quality paper. It means that, the broken and low-quality paper fibres are separated out to become waste sludge which consumes a large percentage of local landfill space. To reduce disposal and pollution problems emanating from these industrial wastes, it is most essential to develop profitable building materials from them. Keeping this in view, investigations were undertaken to produce low cost concrete by blending various ratios of cement with paper sludge.

About 300 kg of PS is produced from each ton of recycled paper. These PS contains, low Calcium (CaO) and maximum Calcium Chloride ($CaCl_2$) and minimum amount of Silica (SiO_2). The shiny finish on glossy magazine-type paper is produced using a fine kaolin clay coating, which also becomes solid waste during recycling.

Worse yet, some of the wastes are land spread on cropland as a disposal technique, raising concerns about trace contaminants building up in soil or running off into area lakes and streams. Some companies burn their sludge in incinerators, which contributing to serious air pollution problems. To reduce disposal and pollution problems arising from this industrial waste, which contains ingredients, chemicals similar to the OPC, it is most essential to develop cost-effective building materials from them. Regarding this, investigations are needed to be undertaken to produce low cost concrete by blending various ratios of cement with PS.

1.6 PAPER SLUDGE (PS) CONCRETE

As PS includes cementitious properties, there are possibilities to partially replace the cement with PS, which is called PS added concrete.

Advantages of PS concrete

- It provides a most effective option for production of economical concrete.
- It minimizes the degradation of environment due to cement production (produces CO_2 emission) and safeguards the ozone layer from greenhouse gases to some extent.
- It can be an easily adopted for partial replacement of cement in field.
- Paper industry waste is utilized in an effective manner.
- It reduces the cost of the construction for concrete members.
- It promotes better option for development of low cost housing to the Economically Weaker Section (E.W.S.) group people.

1.7 DURABILITY OF CONCRETE

When we build any structure using concrete, we expect it to be long lasting, that is, we expect it to be durable. Durability of a concrete structure is not only related to its structural design but also to the various properties of the constituents of the concrete of which it is made and its resistance to actions of various natural and atmospheric agents. It is also related to the efficiency with which the concrete mix is made, transported, placed, compacted, finished and cured. In short, a concrete structure durable has the ability to resist all weathering actions, chemical attacks and all other forces of deterioration and maintains its original quality form and its utility (Sikdar *et al.* (2007)).

The durability of concrete is the resistance it can offer against deteriorating influences to which it is exposed (Sullerey *et al.* (2011)). Durability is related to a number of properties like strength, shrinkage, water tightness and surface condition of concrete, the structural design, the materials, workmanship and exposed conditions. It is clear that, concrete tends to undergo deterioration with age as it is put to continued service or exposed continuously to the action of weather. It should be not only strong enough to resist the various types of loadings likely to act upon it, but should also be able to offer satisfactory resistance against various weathering actions and should stay stable serving efficiently (Ghafoori *et al.* (2010)).

1.8 CURING OF CONCRETE

Curing is the process of controlling the rate and extent of moisture loss from concrete during cement hydration. This can be achieved by different methods such as supplying the water from outside (Ponding & Spraying), continuously wetting the exposed surface thereby preventing the loss of moisture from it, leaving formwork in place, covering the concrete with an impermeable membranes, application of a suitable chemical (wax etc.), mixing a suitable chemical in fresh concrete for internal curing or a combination of above methods.

The properties of hardened concrete, especially the strength and durability, are greatly influenced by curing since it has a remarkable effect on the hydration of the cement. The advancements in the construction industry have paved way for the development of the new curing techniques such as membrane curing, self curing agents, wrapped curing, accelerators, water proofing compounds etc. With the growing scale of the construction industry conventional curing methods have proven to be a costly affair as there are many practical issues (ACI Committee 330 (1997)) of the above self-curing agents can be used in inaccessible areas, vertical structures, water scarce areas etc.

1.9 SELF CURING CONCRETE

The ACI-308 (1997) Code states that “internal curing refers to the process by which the hydration of cement occurs because of the availability of additional internal water that is not part of the mixing water.” ‘Internal curing’ is also referred as ‘Self– curing’.

When the mineral admixtures react completely in a blended cement system, the demand for curing water (external or internal) can be much greater than that in a conventional ordinary Portland cement concrete. For these type of concretes self-curing can be used to provide additional moisture in concrete for more effective hydration of cement and reduced self-desiccation. In the present research work, it has been accomplished to find the combined effect of addition of GGBS for partial replacement of cement and paper sludge as cement replacement material and self-curing agent, respectively.

1.10 NEED FOR THE RESEARCH

The Ordinary Portland Cement (OPC) is one of the main ingredients used for the production of concrete, as there is no alternative in the construction industry. Unfortunately, production of cement involves emission of large amounts of CO_2 gas into the atmosphere, a major contributor for green house effect and global warming. Hence, it is inevitable to search for alternate material for partly replacing cement. The material, which can be used as an alternative for cement should lead to global sustainable development and lowest possible environmental impact.

A number of researchers were investigating the impact of using these pozzolanic materials as substitutions for cement. Many researchers have studied the properties of ordinary Portland cement concrete using fly ash, silica fume, GGBS and PS as cement replacement materials.

1.11 LIMITATIONS AND SCOPE

The various limitations and scope of this research is listed below.

1. There are a variety of concrete challenges relevant to social, economic and environmental concerns.

2. Hence, the need of green, sustainable, stable and economical concretes are in great demand and are being practiced in all around the world, nowadays.

3. Addition of waste materials as admixtures in concrete is not only economic, but also a great remedy for the environmental pollution as well as strength enhancers for concrete.

4. In this present research, the industrial waste materials, GGBS and paper sludge was used as a partial replacement for cement. M_{25} grade concrete was used to prepare all the test mixes in order to achieve an optimum percentage of the partial replacement for cement with GGBS and paper sludge.

5. The addition of GGBS and paper sludge in concrete could result in the development of green, sustainable and stable concrete.

1.12 OBJECTIVES OF THE RESEARCH

The present research is aimed to study the behaviour of the combination of GGBS and Paper sludge in M_{25} grade of concrete mix. By finding out

1. To check the suitability of using GGBS and PS as PRCM based on physicochemical properties
2. To check the workability of concrete using PRCM by GGBS, PS and GGBS with PS and to find its optimum percentage.
3. Determination of mechanical properties of concrete specimens with and without various percentages of GGBS, PS and GGBS with PS under normal and self-curing conditions to obtain the optimum replacement percentage.
4. To analysis the durability properties of concrete with PRCM (GGBS, PS and GGBS with PS) at optimum percentage under normal and self-curing conditions.
5. To study the micro structural properties of concrete with PRCM (GGBS, PS and GGBS with PS) at optimum percentage under normal and self-curing conditions.
6. To estimate the rate of hydration of Paper Sludge and GGBS added Self curing concrete by Thermogravimetry (TG) and DSC (Differential Scanning Calorimeter) analyses.

1.13 ORGANIZATION OF THE THESIS

The thesis has been arranged to contain six chapters. A brief description of each chapter is illustrated below:

Chapter 1 provides an overview of the different types of construction materials. The necessity of developing alternative construction materials with the aid of industrial wastes and by-products is discussed. It also presents the overall need for the study and the objectives of the proposed research.

Chapter 2 discusses a detailed review of literature about the utilization of wastes as construction materials and their performances in various aspects.

Chapter 3 discusses about the methodology and properties of materials used in the present research work.

Chapter 4 deals with the experimental investigations carried out to determine the strength and durability properties of M_{25} grade concrete with GGBS, PS and CC. It also explains the development of self-curing in PS added concrete.

Chapter 5 summarizes the results and discussions of the experimental investigations of control concrete and Partial Replace Cement Material (PRCM) with GGBS, PS and GGBS added with PS subjected to mechanical and durability properties.

Chapter 6 presents a concise summary of the work carried out, conclusions and scope for further research. The list of references is given at the end of the thesis.

CHAPTER 2

REVIEW OF LITERATURE

2.1 INTRODUCTION

In the cement industry, the use of pozzolanic materials is attaining the remarkable importance due to their beneficial effect on various properties of the cement. In this chapter, a brief review of literature about the influence of mineral admixtures (GGBS and PS) and self-curing in concrete and their effect on strength and durability behaviour of concrete is discussed in detail.

2.2 STUDIES ON POZZOLANO MATERIALS IN CONCRETE

Osborne (1999) has used GGBS as cementitious material and evaluated the performance and long-term durability of concrete. Where ground glassy blast-furnace slag (granulated and pelletized) has been used as a cementitious material. They compared the properties and performances of the slag cement concretes. And monitored for carbonation, permeability and strength. With slag contents of more than 50%, providing good sulphate resisting. Water: cement ratio of 0.5, and with 70% slag performed well in sea-water but suffered surface damage from severe frost action in the tidal zone. Higher levels of slag (70%) can be usefully employed where chemical resistance to sulphates, chlorides and sea-water is required. In mass concrete pours, with high cementitious contents, substantial reductions in the rate of temperature rise, overall heat release and peak temperatures in concretes can be achieved by using GGBS at higher levels of replacements, thereby minimizing the risk of thermal cracking and providing economic benefits.

Mailvaganam (2001) reported the interaction of mineral and chemical admixtures with cement. The need to manufacture more durable structures, there is significant interest in chemical concrete additives such as super plasticizers and additional cementing materials such as silica fume and fly ash. Chemical additives to concrete, such as super plasticizers and supplementary cementing materials such as silica fume and fly ash, attract significant interest due to the need to manufacture more durable structures. The author reported the characteristics of rheological, structural and durability. The results indicate that, mixtures affect both hydration and packing quality in fly ash or silica smoke concrete, resulting in significant changes in concrete that could not be best obtained if the materials were used individually.

Pal *et al*. (2003) used GGBS as a replacement material and studied its effects on concrete. Granulated slag of fine, granular near non-crystalline and glass structure is formed by coiling down the molten slag. It is then finely ground and mixed well with Portland cement, exhibits better cementitious properties. Ground granulated blast furnace slag (GGBFS), a by-product of the steel manufacturing industry, being used as an effective partial cement replacement material, the reactivity of GGBFS has been found to depend on the properties of slag, which vary with the source of slag, type of raw material used, method and the rate of cooling. Novel relationship between the Hydraulic Index (HI) of slag at 7 and 28 days (HI7 and HI28) and the influencing properties of slag, namely, glass content, fineness and chemical composition by employing multiple regression analysis on 37 slag samples from various sources. HI7 and HI28, thus obtained, have been mapped onto a Slag Activity Index (SAI) plot, giving an indication of the ranges of strength of slag.

Raghu *et al*. (2004) reported that, both the initial and final setting times get delayed on the following situations, i) the development of slow pozzolanic reaction developed and ii) the addition of admixtures to the cement or concrete mixing process. This delayed setting is quite advantages during the hot weather concreting. The blended cement concrete exhibited reasonable strength development and continues for longer period beyond 28 days.

Matsuda *et al*., (2005) evaluated the applications of GGBS in terms of reducing seismic earth pressure. GGBS is actually closely resembles its structure to natural sand with light weight, high shear strength, good permeability and especially a latent hydraulic property. Experiments were conducted on metal walls in order to evaluate various responses such as earth pressure, wall friction and the earth pressure distribution at the wall surface, and the obtained test results were compared with those of standard sand. It is very clear from the observed results that, the resultant earth pressure obtained for GGBS was smaller than sand, especially in the active-earth pressure side.

Gauld and Jasen (2006) pointed out that the latent hydraulic binder that can be used in conjunction with cement is GGBS, to produce Portland slag or blast furnace cements. The material is an ideal choice in both general and specialized concretes due to the merits of GGBS within concrete. They had concluded that if certain level of cement is replaced with GGBS in concrete, it gives greater resistance to sulfate attack, reduced chloride ion diffusion, lower early-age temperature rise and benefits from longer-term strength development.

Chen *et al.,* (2007) conducted experiments on the mortar made up of ground granulated blast furnace, gypsum, clinker and steel slag sand. The experimental results showed that the application of steel slag sand reduced the dosage of cement clinker and increased the content of industrial waste product using steel slag sand.

Ganesh and Dinakar (2008) proposed that the percentage replacement of pozzolana is the basic parameter in deciding the amount of water for good flow and not the super plasticizer. It was observed that in the case of GGBS there was a continuous increase of flow with increase in the percentage, whereas in case of GGBS and silica fume there was an optimum percentage beyond which there was a decrease in the flow. For both GGBS and silica fume the highest flow ability that can be achieved is around 45% and 10% respectively. Also, compressive strength variation was also observed with water to binder ratio of all pastes with 2% super plasticizer dosage resulting in strengths of around 20 to 80 N/mm^2 for the different paste 13 mixtures. This serves as a guideline for the strength of different concretes under investigation.

Feng *et al.,* (2009) studied the influence of steel slag powder on the workability and mechanical properties of concrete. The results showed that mechanical properties can be improved on the addition of compound mineral admixtures with steel slag powder and blast furnace slag powder in concrete.

Yunus and Graham (2009) had investigated the properties of concrete prepared with GGBS, condensed silica fumes and ground granulated blast furnace slag, blended with Portland cement in proportions ranging from 5% to 80%. These mixes were subjected to heat of hydration tests under adiabatic conditions and the results were used to assess and quantify the effects of the supplementary cementing materials in altering the heat rate profiles of concrete. The authors had also proposed a simplified mathematical form of the heat rate curve for blended cement binders in concrete to allow a design stage assessment of the likely early-age and time–temperature profiles in large concrete structures. Such an assessment would be essential in the case of concrete structures where the potential for thermally induced cracking is of concern

Elsayed *et al*., (2011) investigated experimentally in his studies, the effects of mineral admixtures on water permeability and compressive strength of concrete containing Silica Fume (SF) and GGBS (FA). The results were compared to the control concrete, ordinary Portland cement concrete without admixtures. The optimum cement replacement by FA and SF in this experiment was 10%. It was concluded that the strength and permeability of concrete containing silica fume, GGBS and high slag cement could be beneficial in the utilization of these waste materials in concrete work, especially in terms of durability

Netinger *et al*., (2011) established the aggregate properties on coarse slag fractions by following relevant European Standards. Results revealed that coarse slag fractions and suitable for concrete applications. Hence, concrete specimens were cast using coarse slag fractions in the study and the properties viz., compressive strength and flexural strength, static modulus of elasticity, volume changes and corrosion susceptibility were then compared with that of control concrete specimens. The results of the study indicated that, the slag was substitute for natural aggregate and performed better.

Anand *et al*., (2012) Raichur fly ash (Class F) and GGBS were used as partial replacement of cement. Supplementary cementitious materials were replaced for various levels from 10% to 70% for constant workability of 100 mm slump and by varying superplasticizer dosage. Durability of concrete is monitored against resistance to acid attack for various concentrations. The author also concluded that the cost of concrete may reduce up to 20% for high strength concrete, and about 45 % for lower strength concrete.

Mojtaba *et al*., (2013) reviewed in their research the specifications, production method and degree of effectiveness of some industrial byproducts such as GGBS, Silica Fume and Pulverised Fly Ash (PFA) as cement replacement to achieve high performance and sustainable concrete which can lead not only to improving the performance of the concrete but also to reduce the emission of CO_2 by reducing the amount of Portland cement showing how they affect economic, environmental and social aspects positively.

2.3 STRENGTH PROPERTIES OF GGBS CONCRETE

Fulton (1974) investigated the workability of concrete containing GGBS in greater detail and suggested that the cementitious matrix containing GGBS exhibited greater workability due to the increased paste content and increased cohesiveness of the paste. He also reported that the water demand for normal concrete is generally 3 to 5% lower than concrete with GGBS.

Wu and Roy (1982) reported that the amount of high-range water reducing admixtures required to produce flowing concrete is usually 25% less than that used in concretes containing non GGBS. They also found that pastes containing GGBS exhibits different rheological properties compared to paste of Portland cement alone. Their results indicate a better particle dispersion and higher fluidity of the pastes and mortars, both with and without water reducing admixtures.

Ganesh Babu & Sree Rama Kumar (2000) reported the effect of concrete properties by using GGBS as partial replacement cement material. The study focused on the replacement levels in the concrete studied, varied from 10% to 80% and the strength efficiencies at 28 days were calculated.

The evaluations had shown that at 28 days, the overall strength efficiency factor (k) varied from 1.29 to 0.70 for percentage replacement levels varying from 10% to 80%. It was also observed that for obtaining equal strength in concretes at 28 days, an average of 8.5% and 19.5% cementitious materials has to be added at 50% and 65% cement replacement levels.

Huiwen *et al.*, (2004) examined the geometric characteristics of GGBS, including Particle Size Distribution (PSD), shape and their effect on cement properties. Three various methods such as a ball mill, an airflow mill and a vibro mill have been carried out to prepare concrete samples of various PSD. The surface characteristic of GGBS and PSD were analyzed by scanning electron microscope and Laser Particle Analyzer (LPA), respectively. Results indicated that, the PSD of GGBS processed using an airflow mill is concentrated on a narrow range, whereas the size of GGBS prepared using a ball mill is distributed in a large range. The morphology of GGBS processed through vibro mill is mostly spherical with smooth surface. Further, it is observed that fluidity of mortar comprising GGBS has been improved.

Gao *et al.*, (2005) investigated the Interfacial Transition Zone (ITZ) microstructure of concrete containing GGBS using X-Ray Diffraction (XRD), Scanning Electron Microscope (SEM) and micro-hardness measurements. The experimental results demonstrated that the GGBS significantly decreases both the quantity and the orienting arrangements of CH crystal at the ITZ. The weak ITZ between aggregate and cement paste was strengthened as the result of the pozzolanic reaction of GGBS. The pozzolanic reaction rate was in direct proportion to the specific surface area of GGBS. The weak zone at the 18 ITZ almost vanishes when 40% cement was replaced by GGBS with a specific surface area of 425 m^2/kg and the weak zone completely vanishes when GGBS with a specific surface area of 600 m^2/kg replace 20% of cement.

Oner and Akyuz (2007) studied the optimum level of ground granulated blast furnace slag on the compressive strength of concrete. According to their test results, the compressive strength of ground granulated blast furnace slag concrete increases as the granulated blast furnace slag content is increased up to an optimum point about 55-59%, after which the compressive strength decreases. Furthermore, they concluded that as the ground granulated blast furnace slag content increases, the water to binder ratio decreases for the same workability and thus, the ground granulated blast furnace slag has positive effects on workability. Finally they stated that the early age strength of ground granulated blast furnace slag concretes was lower than the control concretes with the same binder content, but, as the curing 19 period is extended, the strength increase was higher for the ground granulated blast furnace slag concretes. They explained this conclusion by the fact that the pozzolanic reaction is slow and the formation of calcium hydroxide requires time.

Shariq et al (2008) studied the effect of curing procedure on the compressive strength development of cement mortar and concrete incorporating ground granulated blast furnace slag. The compressive strength development of cement mortar incorporating 20, 40 and 60% replacement of GGBS for different types of sand and strength development of concrete with 20, 40 and 60% replacement of GGBS on two grades of concrete were investigated. Tests results showed that incorporating 20% and 40% GGBS is highly significant to increase the compressive strength of mortar after 28 days and 150 days, respectively.

Venu & Rao (2010) had evaluated the characteristics of M_{30} concrete manufactured by partial replacement of cement with GGBS and sand with crusher dust. All the specimens were subjected to both the compressive and tensile strength tests. It has been found that, by the partial replacement of cement with GGBS and sand with ROBO sand helped in the development strength of the concrete substantially compared to control concrete.

Rafat & Rachid (2011) reported that, the mechanical properties of concrete prepared by GGBS and subjected to temperatures upto 350ºC. The cement was replaced with 0%, 20%, 40% & 60% of GGBS and the compressive strength has been established at 28 and 56 days. Further, determining the mass loss, compressive strength, splitting tensile strength and moduli of elasticity were also carried out. The modulus of elasticity of concrete containing 20%, 40% and 60% GGBS are 22.5%, 39.98% and 41.7% respectively lower than the control concrete at room temperature. It was concluded that, the compressive strength increased at 20% slag content and decreased afterwards.

Suvarna Latha *et al*., (2012) had studied the behavior of concrete with GGBS with high volume GGBS at different curing period. The authors had experimentally found that the strength of concrete with the addition of GGBS at early age is less but continues to gain strength over a long period due to its delayed hydration process. The strength efficiency factor ‘k’ of GGBS in concrete mixes of all grades at 90 and 180 days was found to be between 1.2 to 2.85 and for high volume GGBS, ‘k’ is between 1.45 to 2.14 which showed that the strength efficiency factors for GGBS were higher than high volume GGBS replaced concrete. It was observed that there was an increase in the compressive strength for different concrete mixes made with GGBS and fly ash.

Arivalagan *et al*., (2014) reported that, the strength efficiency factors of hardened concrete by partially replacing cement with various percentages of GGBS for M_{35} grade of concrete at different ages. The author concluded that, since the grain size of GGBS is less than that of ordinary Portland cement, its strength at early ages was low, but it continued to gain strength over a long period. As a cementitious material, the optimum GGBS replacement influences high compressive strength, low hydration heat, chemical attack resistance, better workability, good durability and cost-effectiveness.

2.4 DURABILITY ASPECTS OF GGBS IN CONCRETE

Hogan and Meusal (1981) conducted experiments on development of strength and durability properties on concrete and reported that the compressive and flexural strength-gain characteristics of concrete containing GGBS can vary over a wide range. They further concluded that, the early stage strength of control concrete is higher than GGBS added concrete whereas at later stage the strength of GGBS added concrete was greater than control concrete (1 to 3 days) and increased strength at later ages (7 days and beyond).

Swamy and Lambert (1984) analyzed the flexural behaviour of reinforced concrete T beams made with GGBS coarse aggregates and sand. Data on deflection, rotation, cracking, concrete and steel strains, design service and ultimate loads were presented. The results showed that GGBS aggregate concrete beams can satisfy the service-ability requirements of deflection and cracking. They also possessed adequate ductility and load factor against flexural failure. It was found that a better estimation of short term deflection can be obtained if the contribution of the concrete in tension is 25 neglected. Some of the beams may not fully satisfy long-term deflection requirements and this aspect should be considered in design.

Pane and Hansen (2002) investigated the key properties that influence the stress development in concrete at early ages and the effect of using blended cements. Mineral additives and amount by weight of total binder used in the blended cements were GGBS (25%), ground granulated blast furnace slag (25%), and silica fume (10%). The properties investigated include tensile creep, elastic modulus, split tensile strength, and autogenous shrinkage. The relaxation modulus used for stress prediction was obtained from the creep data fitted using a log-power creep function. These findings showed that tensile creep and stress relaxation are important properties of Portland cement concrete. It was found that blended cements affected the early age strength and elastic modulus moderately but significantly alter the autogenous deformation.

Yun feng *et al.*, (2004) had evaluated the performance of concrete manufactured using GGBS. The effect of GGBS on fresh as well as hardened concrete has been analyzed. Results shows that, strength of GGBS added concrete has been found to be at first day higher than reference concrete at raising temperature. So curing of GGBS concrete was control under particular constant temperature and in wet condition. Further, the study suggested that, GGBS concrete is more sensitive towards curing condition than that of Portland cement concrete. The reason could be the lower hydration rate of slag and curing time was also prolonged when compared to Portland cement concrete.

Guo *et al.*, (2006) evaluated the flexural strength of concrete specimens prepared using 50% and 80% proportions of GGBS by mass of total cementitious material. Samples were cured for more than 90 days and results showed that, the ratio of static flexural strength and compressive strength is found to be 0.1. The average value of static flexural strength is observed to be increased for 50% replacement whereas it was decreased in 80% replacement of GGBS in mortars.

Li-Ping *et al.*, (2007) investigated the flexural fatigue performance of concrete with 50% and 80% proportions of ground granulated blast-furnace slag by mass of total cementitious materials in concrete. The effect of different proportions of GGBS on concrete fatigue performance was investigated by experiments and was estimated by the fractal theory from five aspects, i.e. the 1-D fractal dimensions of critical surface cracks, the prediction area of fractured profiles, the ratios between the area of debonded coarse aggregates and the area of fractured profile, fracture energy modified by fractal theory, and the brittleness index. They had proposed a grey model to estimate these fractal parameters on-line. Those experimental and numerical results showed that the brittleness of concrete was impaired by the incorporation of GGBS, which contribute to higher fracture energy and more complicated characteristics on fractured profiles of concrete.

Alessandra *et al.,* (2008) studied the behavior of slag blended cement pastes when exposed to high temperatures and the consequences in the structure of these pastes. Thermogravimetric analyses made it feasible to identify the occurrences of transformations occurred and the changes of mechanical strength in the cement paste. A unique outcome of this work is the leaser possibility in slag blended cements after exposure to high temperatures.

Tarek & Jay (2008) investigated the influence of gypsum added in slag blended cement on free and restrained shrinkage condition of concrete at various curing conditions. The addition of gypsum in slag-blended cements increased the autogenous shrinkage of concrete upto 56 days of curing periods. This caused small reduction in the long-term shrinkage at the time of concrete exposed to drying. Slag concretes with 3% addition of gypsum (24 hours) drying, exhibited more cracking tendency than slag concrete without gypsum.

Yogendra *et al.,* (2013) experimentally investigated the effect of GGBS (0-40%) in flexural strength of concrete. The study further compared the flexural strength of control concrete and GGBS concrete at 90 days of curing period. Results showed that, the strength of concrete is inversely related to the percentage of replacement of cement with GGBS i.e. the strength is decreased with increase in GGBS content. Further, they added that, for 20% of GGBS replacement at 90 days of curing period, maximum strength has been achieved.

Madheswaran *et al.,* (2014) investigated the flexural behaviour of reinforced Geo Polymer Concrete (GPC) incorporating synthetic light weight aggregate. Four sets of reinforced GPC beams (two specimens each) having different mix composition incorporating GGBS aggregate and having reinforcement equal to 1.33 and 2.17% of balanced section were tested for flexural behaviour under two point loading up to failure. The deflection, cracking load, failure load, and crack pattern at failure load were recorded. The ultimate load capacities ranged from 53.3kN to 64.85kN for 100% reinforcement and 24kN to 32.6kN for 50% reinforcement and about 10% difference was observed due to mix variations. The ratio of experimental to theoretical moment capacity ranged from 0.92 to 1.0. The ultimate moment carrying capacity of beams tested was calculated from the first principles using strain compatibility methods and provisions of IS 456:2000.

2.5 PAPER SLUDGE

The various researches in the above the said area are documented in the succeeding paragraphs.

Pera *et al.*, (1998) found that, the paper industry in Western Europe produces approximately 6 million tons of sludge per year, which contains up to 60% dry matter, primarily composed of cellulose fibers, kaolinite and calcite. The original way of using such waste: the production of metakaolin in the temperature range of 700 ° C to 800 ° C by calcinating paper sludge. After calcination, pastes containing 50% calcium hydroxide and 50% burnt sludge were hydrated and the lime consumption investigated by differential thermal analysis. The results show that a very reactive pozzolan is produced by calcining paper sludge at 700°C or 750°C for 2 or 5 hours. Despite a smaller kaolinite content, the burnt paper sludge exhibits more pozzolanic activity than commercially available metakaolins, especially at early ages. Thermo desorption analyses show that this higher activity is due to the presence of superficial defects that occur during the sludge calcination.

Ishimoto *et al.* (2000) reported that various measure taken to actively recycle paper have resulted in increase of the amount of paper making sludge steadily every year, with discharge of 3,000,000 tons appear annually throughout Japan. The Nippon Telegraph and Telephone Corporation have successively converted the ash derived from incineration process of paper making sludge into a new porous material with high caution exchange capacity through alkali treatment. The derived new material could be successively employed as admixture in concrete.

Albinas Gailius *et al.,* (2003) tested the workability and strength of concrete prepared using various proportions of waste paper sludge ash (WSA) and GGBS as binder, at following two w/b ratios: 0.5 and 0.4. The rate of development of strength of concrete made with WSA-GGBS binder attained 1-day strength of about 2-6 % of its 28-day strength, while the 7-day strength was in the range 53-64 % of the 28- day strength.

Bai *et al.,* (2003) investigated the Compressive strength and hydration characteristics of wastepaper sludge ash-ground granulated blast furnace slag (WSA-GGBS) blended pastes were investigated at water to binder (w/b) ratio of 0.5. The optimum blend composition to give maximum strength was 50% WSA-50% GGBS, and after 90 days, pastes manufactured from this blend exhibit compressive strengths close to 50% of those from an equivalent Portland cement paste.

Naik *et al.*, (2003) incorporated the fibrous residuals from mills into ready-mixed concrete with view to improve the strength, durability, and life span of concrete structures exposed to weather. A large amount of ash is produced from wood burning with additional fuels such as coal , oil , natural gas and coke produced by pulp and paper mills and by manufacturers of wood products. In this investigation, such ash is referred to as combined-fuel ash (CFA). This investigation was conducted to produce controlled low-strength (CLSM) mixtures using various sources of CFAs. Three separate CLSM mixtures were developed using five CFA sources. Five sources of CFAs were used to generate three different series of CLSM mixtures. Each series of CLSM mixtures was engineered to have a different long-term compressive strength: < 0.7 MPa (< 100 psi), 0.7 to 3.4 MPa (100 to 500 psi) and 3.4 to 8.3 MPa (500 to 1200 psi). All CLSM mixtures were tested for flow, bleed water, sedimentation, shrinkage and cracking, setting characteristics, density, compressive strength and permeability. Results have shown that CLSM, meeting the specifications of ACI 229R, can be used.

Ritzawaty binti Mohamad Shukeri *et al.*, (2008) reported on the results of an investigation of utilization of waste paper as additional material in concrete mixes. 5%, 10%, 15% waste paper as an additional material to concrete were prepared with ratios of 1:2:3 by weight of cement, sand and aggregate respectively. With the addition of 25% waste paper in proportion to the amount of cement, the mechanical strength decreased significantly: Overall, a high correlation was observed between density and strength of concrete containing paper. In general, for the concrete mixes containing wastepaper, there is a decrease in compressive strength, tensile strength, and flexural strength was observed with the increase of wastepaper content. Concrete mix with 5% wastepaper had a greater tensile and flexural strength of all the samples studied in the present research work. Good agreement has been observed with density and compressive, tensile, and flexural strength of concrete mixes.

Balwaik *et al.*, (2010) worked the use of paper-mill pulp in concrete formulations in view of making them as an alternative to landfill disposal which will concern in solid waste management. Use of waste paper pulp in concrete could relieve the pulp and paper industries from disposal costs and also produce a ‘greener’ concrete for construction. The cement was replaced by waste paper sludge in various concentrations ranging from of 5% to 20% by weight for M_{20} and M_{30} mix. The slump increased upto 5% replacement of cement. The increase in compressive, splitting tensile and flexural strength were observed upto 10% addition of waste paper pulp. The water absorption of the concrete mixes is increased with increase of paper pulp content. This phenomenon is quite general since more amount of paper pulp is tending to contribute in the cement hydration process. However, higher water content decreased the strength of concrete.

R. Srinivasan *et al.*, (2010) carried out experimental investigation on strength of concrete by replacing cement via 10%, 20%, 30%, 40%, 50%, 60% and 70% of paper sludge. Compressive strength of the concrete increased when the percentage of replacement was increased upto 40%. Further replacement of cement reduced the compressive strength. Replacement of cement with paper sludge material gave maximum compressive strength at 30% replacement.

Gabriele Fava *et al.*, (2011) on the basis of the data collected, it was concluded that paper mill sludge ash (PA), if used to replace upto 10% of the Portland cement, shows a positive effect on the mechanical performance of mortars. In other words, because of its high fineness and subsequent high water absorption, it needs high amount of water. It was concluded that the use of PA should not be higher than 10% replacement by weight of the cement.

Bashar Mohammed *et al.*, (2011) found out that, higher residual and fly ash content in concrete mixtures would increase the water demand of concrete for a given slump, thereby, decreasing the workability of fresh concrete. The workability of concrete containing paper-mill residuals and fly ash content could be tuned and stabilized by using appropriate amount of super plasticizer. The Class F fly ash decreased the workability of concrete due to the high percentage of fly ash replacement in mixture proportion and high carbon content which increased the water demand.

Mikael Ottossona *et al*., (2013) based on a study of policy-induced changes in the Swedish pulp and paper industry, this paper followed a process of socio-technical regime destabilization. Results from the study showed that in industries where established firms have significant power, processes of endogenous renewal were more likely to destabilize established regimes than processes based on riche solutions. Further, the study showed how policy measures aimed to destabilize the current regime may result in different responses, owing to the different capabilities of individual firms. The analysis suggested that heterogeneous capabilities within established industries provide possibilities for policy makers to initiate change.

Sajad Ahmad *et al.*, (2013) reported on the results of partial replacement of cement by WPA at different percentage (5%, 10%, 15% and 20%) in M_{25} grade concrete and tested its workability. They concluded that, use of WPA in concrete will reduce the amount of cement used for construction. Waste paper sludge can be used in concrete for partial cement replacement and also the disposal problem for paper industries for this waste material is partially rectified.

The detailed perusal of review clearly states that, paper sludge could enhance the strength of concrete upto 30% replacement level.

2.6 SELF CURING CONCRETE

Dhir *et al.*, (1995) have tested and described the durability of self-cured concrete in detail. The significant long term tests such as initial surface absorption, chloride ingress, carbonation, corrosion potential and freeze/thaw resistance characteristics were carried out for air cured self-cure concrete and the results were compared with plain air cured concrete. The test results showed that the specimen under air cured self-cure concrete serves better than plain air cured concrete. Also the test results additionally proved that, the film controlled concrete gives superior behaviour than air cured self-cure concrete, but the enhancement of air cured self-cure specimen could be achieved by varying the dosage of self-cure chemical (or) by use of various self-cure agent only.

Dhir *et al.*, (1998) have presented self-cure concrete contains a chemical agent that reduces the evaporation of water from its surface, primarily by reducing the vapor pressure at the concrete pore solution surface. The self-curing agent developed at the concrete technology unit, University of Dundee, also produces an alteration in cement hydration product micro structure, and it was considered that this may also contribute to the improved water retention properties. To investigate this weight loss tests are conducted on both self-cure and ordinary pastes exposed to controlled ambient conditions, whilst thermo gravimetric analysis was carried out on identical specimens. It was found that, whilst the evolution of heat of hydration renders the early stages of drying very complex, it was possible to examine the diffusion dependent stage of drying. The diffusion coefficients observed for water vapor passing through the dry region of self-cure paste surface were much lower than those observed for the control. This has been attributed in two mechanisms: the lower vapor pressure above the pore solution leading to a smaller difference across the dried portion of the paste and lower relative humidity in the cement pores, and the change in microstructure which reduces permeability. When viewed through the scanning electron microscope, self-cure cement pastes display numerous, extremely thin crystals of calcium hydroxide. It is portable that the presence of these crystals refines the pore structure of the paste, since these modifications appear to strongly influence concrete permeability.

Roland & Robert (2002) have carried out experimental work on internal curing composition for concrete which includes a glycol and a wax. The work is reported for the first time an internal curing composition which, when added to concrete or other cementitious mixes meets the required standards of curing as per Australian Standard AS 3799.

El–Dieb (2006) has evaluated water retention capacity, hydration and moisture transport of self-curing concrete. Concrete weight loss and internal relative humidity measurements with time were carried out, in order to estimate the water retention of self-curing concrete. Non-evaporable water at various intervals were determined to evaluate the cement hydration. Water transport through concrete is evaluated through measuring absorption percentage, permeable voids percentage, sorptivity and water permeability. The water transport through self-curing concrete is calculated with age. The effect of the concrete mix proportions on the performance of self-curing concrete were examined. The calculated water transport is compared to conventional concrete continuously by moist-cured and air-cured. Here, it was found that the internal cured concrete showed better outcome related to water retention, hydration and moisture diffusivity.

Jagannadha Kumar and co-workers (2012) were investigated the use of shrinkage reducing admixture of molecular weight 400 as an internal curing agent has been reported by the application of such admixture in concrete enabled in self-curing and enhanced better hydration and strength. In this study, the effect of admixture on compressive strength, split tensile and modulus of rupture by varying the percentage of dosage by weight of cement from 0% to 2% were studied for M20 and M40 mixes. It was concluded that, the admixture could help in self-curing by giving strength on par with conventional curing.

Geetha *et al*., (2012) have utilized natural internal curing agent and made the self-curing concrete. The curing agent at following dosages 0.05%, 0.1%, 0.15% upto 0.45% with a constant interval of 0.05% based on weight of cement has been taken for the research. The workability, mechanical and durability properties of the concrete with curing agent for various dosages were measured and compared the results obtained with conventional concrete which involves full curing. Result showed that the better performance of concrete was achieved for 0.3% of self-curing agent which showed superior behavior than conventional cured concrete. The researcher has also taken the other natural curing agent, Calotropis gigantean at a dosage of 0.05%, 0.1% 0.15% upto 0.7% based on the weight of cement. Results concluded that, the optimized percentage for self-curing concrete of Calotropis gigantean was found to be 0.6%. But in comparison with both natural curing agents, Spinacia Oleracea showed better results than Calotropis gigantean.

Subramaniaii *et al*., (2015) have made an attempt to minimize the autogenous shrinkage in low w/c concrete with the use of various shrinkage reducing admixtures. Fly ash, Metakaolin, GGBS and micro silica were the four supplementary materials used as the partial replacement to the cement. Results concluded that, concrete with individual fly ash and metakaolin replacement to cement under ethyl propyl polyoxy ethylene ether at a dosage of 0.025% reduced the shrinkage by about 40%.

2.7 SUMMARY

From the literature review, it was understood that, sufficient research has been done to study the strength and durability aspects of concrete using GGBS and PS but not much work has been carried out to study the behavior of paper sludge as self-curing agent in GGBS added concrete.

CHAPTER 3

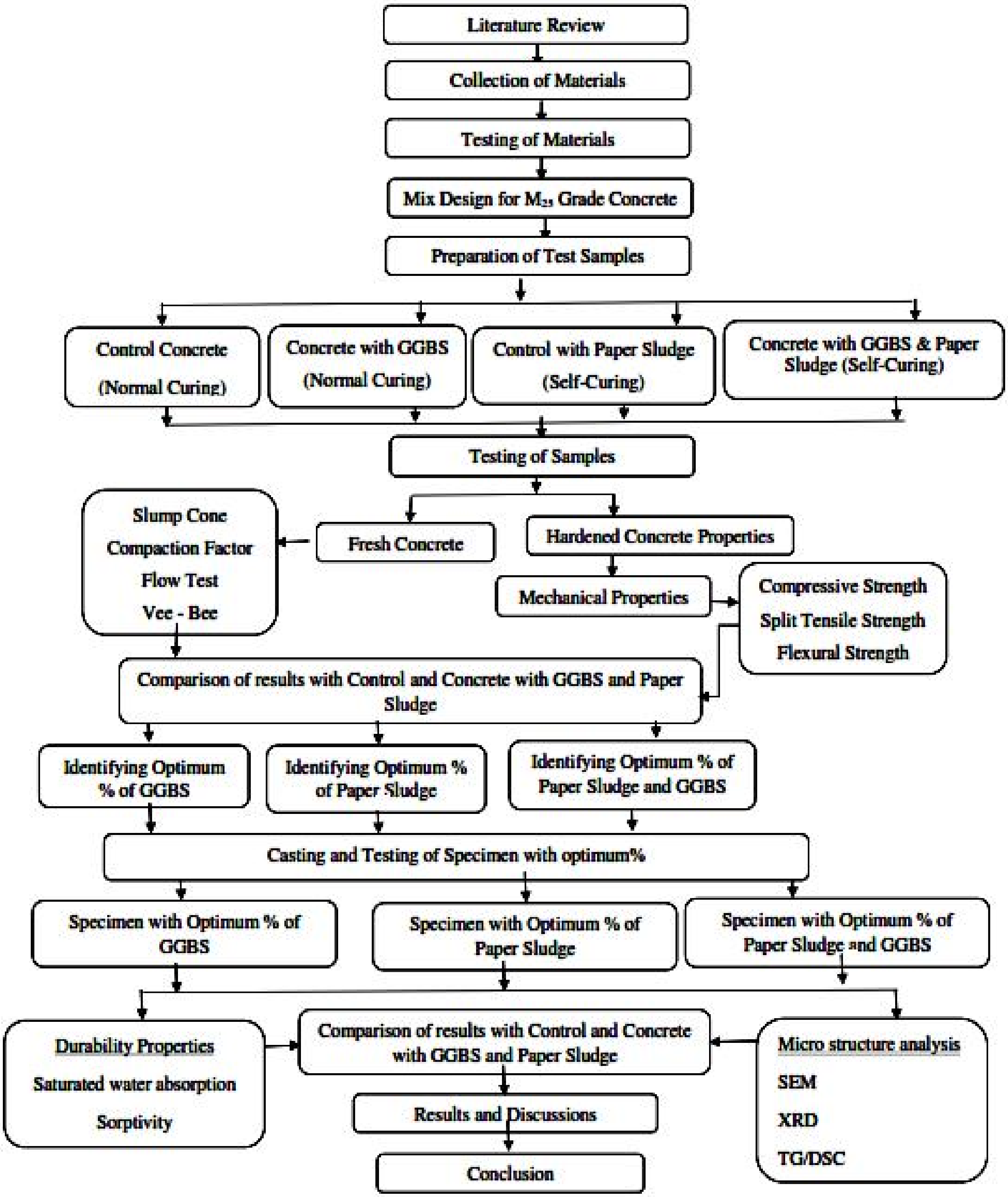
METHODOLOGY AND MATERIALS

3.1 INTRODUCTION

This chapter discusses about the methodology and properties of materials used in the present research work.

3.2 METHODOLOGY OF RESEARCH WORK

The review of literature has been studied and materials GGBS and PS have been selected for PRCM and PS as a self-curing agent. The physical and chemical properties were evaluated for GGBS and PS. M_{25} grade concrete mix design was designed as per IS 10262-1999. Fresh concrete properties, workability test (Slump cone test, Compacting factor test, Flow table test and Vee-Bee consistometer test) was evaluated. The hardened concrete properties, Mechanical properties (Compressive strength test, Split tensile strength test and Flexure strength test) for various curing days were evaluated for normal and self-curing conditions. From that the optimum percentage of PRCM by GGBS, PS and GGBS with PS was obtained. Durability properties (Saturated water absorption test, Rapid chloride penetration test, sorptivity test) were evaluated for the optimum percentage of PRCM and CC. The mathematical modeling was developed based on the results. Also this investigation was followed by micro structural analysis (SEM, XRD, EDX, TG, DSC and DTG) for the optimum percentage of PRCM and CC. The results and discussions were made in brief with concluding remarks of the research. The detailed methodology of the research work is given in Figure 3.1.



3.1 METHODOLOGY OF RESEARCH WORK

3.3 MATERIAL DESCRIPTION

The specifications of the materials used for the experimental study are discussed below.

3.3.1 Cement

Cement confirming to IS 12269:1987, Ordinary Portland Cement (Birla Super) with OPC 53 grade is considered for the concrete mix. The cement sample was tested as per the procedure given in IS 4031:1988 and IS 4032:1985. The physical properties and chemical composition of OPC are given in Table 3.1 and 3.2.

Table 3.1 Physical Properties of OPC 53 Grade Cement

Sl. No.	Test Particulars	Results Obtained	Requirements as per IS 12269-1987
1	Fineness (m^2/kg)	320	Minimum 225
2	Initial setting time (minutes)	35	Minimum 30
3	Final setting time (minutes)	190	Maximum 600
4	Normal consistency (%)	29	-
5	Soundness (mm)	1.00	Maximum 10
6	Compressive strength (MPa) 3-days	40.5	Minimum 27
7	Compressive strength (MPa) 7-days	50.0	Minimum 37
8	Compressive strength (MPa) 28-days	68.0	Minimum 53
9	Specific gravity	3.15	-

Table 3.2 Chemical Composition of OPC 53 Grade Cement

Sl. No.	Compound	Chemical content (%)	Requirements as per IS 12269-1987
1	SiO_2	21.8	-
2	Al_2O_3	4.8	-
3	Fe_2O_3	3.8	-
4	CaO	63.3	-
5	SO_3	2.2	-
6	MgO_3	0.9	Maximum 6
7	Na_2O	0.21	-
8	K_2O	0.46	-
9	CI	0.04	Maximum 0.1
10	P_2O_5	0.04	-
11	Loss of Ignition	2.0	Maximum 4
12	Insoluble residue	0.4	Maximum 2

3.3.2 Ground Granulated Blast Furnace Slag

Ground Granulated Blast Furnace Slag (GGBS) shown in Figure 3.2 (a byproduct of the steel industry) has been purchased from JSW Steel Ltd at Salem (IS 12089). Blast furnace slag is defined as “the non-metallic product consisting essentially of calcium silicates and other bases that is developed in a molten condition simultaneously with iron in a blast furnace”. About 10% by mass of binders was replaced with GGBS. It is white in colour and has fineness in the range of 400 to 600 m^2/kg. Most of the chemical constituents are same as Ordinary Portland cement, but in different proportions as shown in Table 3.3 and 3.4.

Figure 3.2 Ground Granulated Blast Furnace Slag (GGBS)

Table 3.3 Physical Properties of GGBS

Sl. No.	**Physical properties**	
	Property	**GGBS**
1	Physical form	Powder
2	Bulk density (kg/m^3)	1200
3	Specific gravity	2.9
4	Specific surface (m^2/kg)	425-470

Table 3.4 Chemical Composition of GGBS

Sl. No.	Chemical composition	
	Compound	%
1	SiO_2	33.45
2	Al_2O_3	13.46
3	Fe_2O_3	0.31
4	CaO	41.70
5	SO_3	2.74
6	MgO	5.99
7	Na_2O	0.16
8	K_2O	0.29
9	TiO_2	0.84
10	Mn_2O_3	0.40

3.3.3 Paper Sludge

The chemical composition and physical properties of Paper Sludge (collected from J.K. Papers mill Pvt. Ltd, Namakkal District) are given in Table 3.5 and Table 3.6.

Table 3.5 Physical properties of PS

Sl. No.	Physical properties	
	Property	PS
1	Physical form	Powder
2	Bulk density (kg/m^3)	1169
3	Specific gravity	2.65
4	Specific surface (m^2/kg)	77.26

Table 3.6 Chemical composition of PS

Sl. No.	Chemical composition	
	Compound	%
1	SiO_2	5.28
2	Al_2O_3	0.09
3	Fe_2O_3	0.73
4	CaO	47.84
5	SO_3	0.19
6	MgO	6.41
7	Loss on Ignition	38.26

3.3.4 Fine Aggregate

Fine aggregate used in the present study is properly graded to give minimum void ratio and free from deleterious materials like clay, silt content and chloride contamination, etc. For the present investigation, locally available river sand (coarse sand) confirming to Grading Zone II of IS 383:1970 was used as fine aggregate. The sand was washed and screened at site to remove deleterious materials and tested as per the procedure given in IS 2386:1968 (Part-3). The details of physical properties of fine aggregates are tabulated in Table 3.7 and 3.8.

Table 3.7 Physical Properties of Fine Aggregate

Sl. No.	Test Particulars	Results Obtained
1	Specific gravity	2.60
2	Fineness modulus	2.96
3	Bulk density (kg/m^3)	1800
4	Void ratio	0.55

Table 3.8 Sieve Analysis of Fine Aggregate

Sl. No.	IS sieve designation	% passing	IS recommended range
1	4.75 mm	100.00	90-100
2	2.36 mm	90.91	75-100
3	1.18 mm	67.74	55-90
4	600 µm	45.15	35-59
5	300 µm	15.30	8-30
6	150 µm	0.00	0-10

Note: The fine aggregate confirms to grading zone II of Table 3.8 of IS: 383-1970 which has been used throughout the research work.

3.3.5 Coarse Aggregate

Crushed blue granite coarse aggregates of particle shape “angular and cubic” were used for the present study. The coarse aggregates were tested as per the procedure given in IS: 2386 -1963 and the results are given in Table 3.9 and 3.10. Coarse aggregates of size of 20 mm as per IS: 383 -1970 with specific gravity 2.80 were used in this research work.

Table 3.9 Physical Properties of Coarse Aggregate

Sl. No.	Test Particulars	Results Obtained
1.	Specific gravity	2.80
2.	Bulk density (kg/m^3)	1600
3.	Void ratio	0.68
4.	Porosity	0.34
5.	Fineness Modulus	6.69
6.	Crushing Value (%)	33.1

Table 3.10 Sieve Analysis of Coarse Aggregate

Sl. No.	IS sieve Designation (mm)	Percentage of Passing	IS Recommended range
1	20.00	92.48	85-100
2	16.00	44.82	N/A
3	12.50	19.30	N/A
4	10.00	7.66	0-20
5	4.75	0.14	0-5

Note: The coarse aggregate confirm to graded aggregate of nominal size 20 mm as per Table 3.10 of IS: 383-1970 has been used throughout the research work.

3.3.6 Water

Fresh and clean tap water has been used to cast specimens in the present research work. This water was free from organic matter, oil, sludge, sugar, chloride and acidic material as per BIS: 456-2000.

3.4 MIX PROPORTIONS AND TEST DETAILS

The mix design of M_{25} concrete has been designed by following IS 10262:2009 and their proportions are presented in Table 3.11. Various test specimens to evaluate the mechanical and durability properties of Paper Sludge and GGBS based mixtures are shown in Table 3.12. Quantity of materials per meter cube of GGBS and PS based M_{25} grade concrete mixtures are presented in Table 3.13.

Table 3.11 Mix Proportions of M_{25} grade concrete

Cement	Fine Aggregate	Coarse Aggregate	Water
1	2.33	4.1	0.45

Table 3.12 Specimens and Test Details

Sl. No.	Tests	Shape of Specimens	Size	No. of Specimens
STRENGTH PARAMETER TESTS				
1	Compressive strength based on IS: 516-1959			
	3 Days	Cube	150X150X150 mm	216
	7 Days	Cube	150X150X150 mm	216
	28 Days	Cube	150X150X150 mm	216
	60 Days	Cube	150X150X150 mm	216
	90 Days	Cube	150X150X150 mm	216
	120 Days	Cube	150X150X150 mm	216
	180 Days	Cube	150X150X150 mm	216
	365 Days	Cube	150X150X150 mm	216
2	Split Tensile Strength based on IS: 5816-1970	Cylinder	150 mm dia and 300 mm high	1728
3	Flexural Strength based on IS: 516-1959	Prism	100X100X500 mm	864
DURABILITY PARAMETER TESTS				
4	Saturated Water Absorption based on ASTM C - 6420 – 81	Cube	150X150X150 mm	135
5	Sorptivity based on ASTM C1585	Cube	150X150X150 mm	135
Total number of specimens				3726

Table 3.13 Mix Proportions of M_{25} grade concrete with GGBS and PS

Sl. No.	Mix ID	Cement	Fine Agg.	Coarse Agg.	Water	GGBS	PS
		(kg)	(kg)	(kg)	(kg)	(kg)	(kg)
1	CC	320	745	1309	144	0	0
2	G1	304	745	1309	144	16	0
3	G2	288	745	1309	144	32	0
4	G3	272	745	1309	144	48	0
5	G4	256	745	1309	144	64	0
6	G5	240	745	1309	144	80	0
7	G6	224	745	1309	144	96	0
8	G7	192	745	1309	144	128	0
9	P1	304	745	1309	144	0	16
10	P2	288	745	1309	144	0	32
11	P3	272	745	1309	144	0	48
12	P4	256	745	1309	144	0	64
13	P5	240	745	1309	144	0	80
14	P6	224	745	1309	144	0	96
15	P7	192	745	1309	144	0	128
16	PG1	288	745	1309	144	16	16
17	PG2	272	745	1309	144	16	32
18	PG3	256	745	1309	144	16	48
19	PG4	240	745	1309	144	16	64
20	PG5	224	745	1309	144	16	80
21	PG6	208	745	1309	144	16	96
22	PG7	176	745	1309	144	16	128
23	PG8	272	745	1309	144	32	16
24	PG9	256	745	1309	144	32	32

Sl. No.	Mix ID	Cement	Fine Agg.	Coarse Agg.	Water	GGBS	PS
		(kg)	(kg)	(kg)	(kg)	(kg)	(kg)
25	PG10	240	745	1309	144	32	48
26	PG11	224	745	1309	144	32	64
27	PG12	208	745	1309	144	32	80
28	PG13	192	745	1309	144	32	96
29	PG14	160	745	1309	144	32	128
30	PG15	256	745	1309	144	48	16
31	PG16	240	745	1309	144	48	32
32	PG17	224	745	1309	144	48	48
33	PG18	208	745	1309	144	48	64
34	PG19	192	745	1309	144	48	80
35	PG20	176	745	1309	144	48	96
36	PG21	144	745	1309	144	48	128
37	PG22	240	745	1309	144	64	16
38	PG23	224	745	1309	144	64	32
39	PG24	208	745	1309	144	64	48
40	PG25	192	745	1309	144	64	64
41	PG26	176	745	1309	144	64	80
42	PG27	160	745	1309	144	64	96
43	PG28	128	745	1309	144	64	128
44	PG29	224	745	1309	144	80	16
45	PG30	208	745	1309	144	80	32
46	PG31	192	745	1309	144	80	48
47	PG32	176	745	1309	144	80	64
48	PG33	160	745	1309	144	80	80
49	PG34	144	745	1309	144	80	96
50	PG35	112	745	1309	144	80	128

Sl. No.	Mix ID	Cement	Fine Agg.	Coarse Agg.	Water	GGBS	PS
		(kg)	(kg)	(kg)	(kg)	(kg)	(kg)
51	PG36	208	745	1309	144	96	16
52	PG37	192	745	1309	144	96	32
53	PG38	176	745	1309	144	96	48
54	PG39	160	745	1309	144	96	64
55	PG40	144	745	1309	144	96	80
56	PG41	128	745	1309	144	96	96
57	PG42	96	745	1309	144	96	128
58	PG43	176	745	1309	144	128	16
59	PG44	160	745	1309	144	128	32
60	PG45	144	745	1309	144	128	48
61	PG46	128	745	1309	144	128	64
62	PG47	112	745	1309	144	128	80
63	PG48	96	745	1309	144	128	96
64	PG49	64	745	1309	144	128	128
65	PG50	144	745	1309	144	160	16
66	PG51	128	745	1309	144	160	32
67	PG52	112	745	1309	144	160	48
68	PG53	96	745	1309	144	160	64
69	PG54	80	745	1309	144	160	80
70	PG55	64	745	1309	144	160	96
71	PG56	32	745	1309	144	160	128

CHAPTER 4

EXPERIMENTAL INVESTIGATION

4.1 GENERAL

Various tests such as workability, setting time, water absorption, compressive strength, split tensile strength and flexural strength have been performed in view of determining the mechanical properties of control concrete and concrete with GGBS and PS. Cubical, cylindrical and prism shaped specimens were subjected to the above tests for 3, 7, 28, 60, 90, 120, 180 and 365 days of curing. The theoretical prediction of the mechanical properties of concrete using mathematical model has also been developed and validated with experimental results.

4.2 WORKABILITY TEST

For control concrete and PRCM concrete (GGBS and PS), the values of slump, compacting factor, flow test and Vee-Bee consistometer test (Figure 4.1) were performed to assess the workability of fresh concrete.

Slump cone test

Compacting Factor test

Flow table test

VEE-BEE Consistometer test

Figure 4.1 **Slump Cone Test, Compacting Factor test, Flow Table Test and Vee-Bee Consistometer Test**

4.3 MECHANICAL PROPERTIES

4.3.1 Compressive Strength

For cube compression tests on concrete, cube specimens of size 150X150X150 mm were casted. All the cubes were tested in saturated surface dry condition after wiping out the surface moisture from the specimen. For each trial mix combination, three identical specimen cubes were tested at the age of 3, 7, 28, 60, 90, 120, 180 and 365 days of curing using 400 Ton capacity compression testing machine (CTM) as per BIS: 516-1959. The tests were carried out at a uniform stress after the specimen has been centered in the testing machine (Figure 4.2). Loading was continued until the dial gauge needle just reverses its direction of motion. The reversal in the directions of motion of the needle indicates that the specimen has failed. The dial reading at the instance was noted, which is the ultimate load. The ultimate load divided by the cross-sectional area of the specimen is equal to the ultimate cube compressive strength. Figure 4.2 shows the cube specimens during compressive strength test in CTM.

$$f_c = \frac{P}{A} \tag{4.1}$$

where, f_c = Compressive Strength of the Specimen (N/mm^2)

P = Maximum load applied to the specimen (N)

A = Area of the specimen (mm^2)

Figure 4.2 Compressive Strength Test Setup

4.3.2 Split Tensile Strength

This is an indirect test to determine the tensile strength of a specimen. Splitting tensile tests were carried out on 150 mm diameter X 300 mm height cylindrical specimens at the age of 7, 28, 60 and 90 days using 40 Ton capacity compression testing machine (Figure 4.3) as per IS: 5816 – 1970.

The load was applied until the specimen split and readings were noted. The splitting tensile strength is calculated using the following formula.

$$f_{ct} = \frac{2P}{\pi l d} \qquad (4.2)$$

where, f_{ct} = Splitting Tensile Strength of the Specimen (N/mm^2)

P = Max. Load applied on the specimen (N)

l = Specimens length (mm)

d = Diameter of the specimen (mm)

Figure 4.3 Split tensile strength test

4.3.3 Flexural Strength

Flexural strength tests were carried out on 100 mm x 100 mm x 500 mm beams at the age of 7, 28, 60 and 90 days curing, using 100 kN capacity UTM apparatus by subjecting the specimen to four points loading to determine the flexural strength as per BIS: 516-1959. The test setup for the flexural strength with the specimen is shown in the Figure 4.4. The flexural strength or modulus of rupture has been calculated using the following formula.

$$f_b = \frac{Pl}{bd^2} \tag{4.3}$$

where,

f_b = Flexural Strength (N/mm^2)

P = Max. Load (N) applied to the Specimen

l = Length of the Span (mm)

b = Measured Width (mm)

d = Measured Depth (mm)

Figure 4.4 Flexural Strength Test setup

4.4 DURABILITY PROPERTIES

4.4.1 Saturated Water Absorption Test

Saturated water absorption was determined on 100×100×100 mm cube specimen as per ASTM C-642 at the age of 28 days curing. Samples are weighed before drying. Drying was carried out in hot air oven at a temperature of 105°C (Figure 4.5). Drying process was continued until the difference in masses between two successive measurements at 24 hours interval is obtained.

Figure 4.5 Saturated water absorption Test

Specimens were cooled to room temperature and then immersed in water. Specimens were taken out at regular interval of time, surface dried using a clean cloth and weighed. The process was continued until the weight becomes constant. The percentages of the saturated water absorption were calculated using the formula given below.

$$\text{Percentage of saturated water absorption (\%)} = \frac{W_2 - W_1}{W_1} \times 100 \qquad (4.4)$$

where, W_1 - Weight of specimen in dry condition (at the oven temperature of 105°C).

W_2 - Weight of specimen at saturated condition

4.4.2 Acid Attack Test

Acid attack test was carried out on 150X150X150 mm concrete cubes after 28 days of curing (ACI 201.2R-08). Cube specimens were weighed and immersed in water diluted with 3% H_2SO_4 (by weight) for 45 days continuously.

Then, the specimens were taken out from the acid solutions and surfaces of the cubes were cleaned. Again, the weight loss of the specimens was found out and the percentage changes in weight were also calculated.

4.4.3 Chloride Attack Test

Chloride attack test was carried out on 150X150X150 mm concrete cubes after 28 days of curing. Cube specimens were weighed and immersed in 3% NaCl solution (by weight) for 45 days continuously. Then the specimens were taken out from the salt water and surfaces of the cubes were cleaned. Again the weight and compressive strengths of specimens were found out and the percentage change in weight and compressive strength were calculated.

4.4.4 Rapid Chloride Ion Penetration Test

According to ASTM C1202, the test method involves obtaining a 100 mm diameter core or cylinder sample from the concrete being tested (Figure 4.6). A 50 mm height specimen was cut from the sample. The side of the cylindrical specimen was coated with epoxy, and after the epoxy was dried, it was put in a vacuum chamber for three hours. The specimen was vacuum saturated for one hour and allowed to soak in solution for 18 hours. It was then placed in the test device. The left-hand side (–) of the test cell was filled with 3% NaCl solution. The right-hand side (+) of the test cell was filled with 0.3 N NaOH solution. The system was then connected and a 60-volt potential was applied for 6 hours. Readings were taken at every 30 minutes intervals. At the end of six hours the sample was removed from the cell and the amount of charge passed through the specimen was calculated. Table 4.1 presents the ASTMC 1202 rating of RCPT values.

Table 4.1 Rapid Chloride ion permeability (According to ASTM C-1202)

Charge passed (Coulombs)	Rapid Chloride ion permeability
>4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very low
<100	Negligible

$$\mathbf{Q = 900[I_0+2(I_{30}+I_{60}+\ldots\ldots\ldots\ldots I_{300}) +I_{360}]} \qquad (4.5)$$

Where Q = Charge Passed (Coulombs)

I_0 = Current (amperes) instantly behind voltage is applied,

I_t = Current (amperes) at t Min. following voltage is applied.

If the specimen diameter is other than 3.75 inches (95mm), net charge passed should be adjusted. The charge measured is made by multiplying the value obtained from the ratio of the cross sectional area of the literal and experimental specimens.

That is,

$$\mathbf{Q_S = Q^*(3.75/x)^2} \tag{4.6}$$

Where, Q_S = Charge passed (Coulombs) via 3.75 inch (95mm) diameter specimen

Q = Charge passed (Coulombs) via (Y) inch diameter specimen

x = Diameter of the regular specimen.

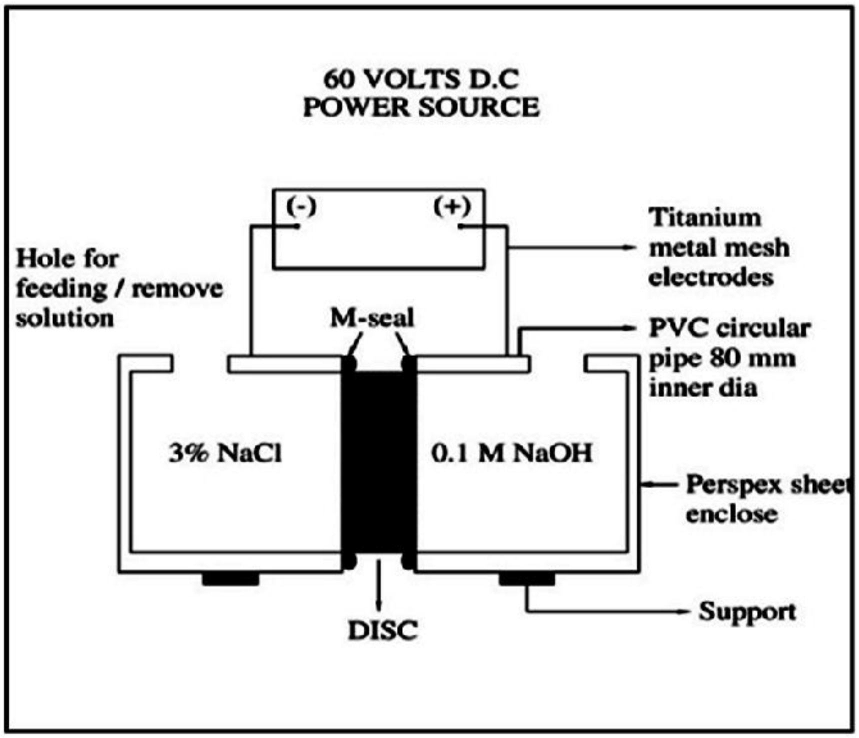


Figure 4.6 Chloride ion penetration tests

4.4.5 Sorptivity Test

The sorptivity measures the penetration rate of water into the pores of concrete through capillary suction. The cumulative quantity of water that has penetrated for each unit surface area of exposure (q) is plotted against the square root of time (√t). The sorptivity was determined on 60 mm dia X 120 mm height cylinder as per ASTM C1585. The resulting graph could be characterized by a straight line transient through the origin.

The slope obtained in that straight line is taken as rate of movement of water by the capillary pores and is known as sorptivity. The water level amount should be maintained at lower than 5 mm from the base of specimens and the flow with the peripheral surface has been retarded by sealing it with protective coating film. The amount of water absorbed at the time of 60 minutes was calculated by weighing the specimen using top pan balance weighing upto 0.1 mg. A dampened figure has been used to wipe off the surface water lying on the concrete specimen surface and all the weighing process has been carried out in less than a minute.

4.4.6 DSC, TGA and SEM Analysis

The thermal characteristic of PRCM has been determined by Differential Scanning Calorimetry and Thermo-Gravimetric analyses. It is the technique meant to evaluate the mass loss behavior with respect to the temperature of the cement paste sample in-built without and with PRCM of PS and GGBS. Scanning Electron Microscopy (SEM) is used to characterize the surface morphology of the tested concrete mixes that was performed using the EVO 18 research microscope, the LaB6 filament electron source. The images were taken with an acceleration voltages of 8 kV. The samples were tested using system vacuum technique.

CHAPTER 5

TEST RESULTS AND DISCUSSIONS

5.1 INTRODUCTION

The interpretation of the results were carried out for each phase of the experimental work. Based on the details available in the literatures. The results are compared and verified with reference to the standards specified by ACI, ASTM and IS. A detailed discussion on the test results are presented in this chapter.

5.2 WORKABILITY TEST

The workability is the physical property of the fresh concrete mix to determine its ability, to transported, place, compact and finish without any segregation. Slump test is one of the best tests which estimate the workability. It is a method for measuring the consistency of concrete which can be carried out in lab. The test is done on a truncated cone having dimension of 300 mm height and 100 mm diameter on the top and 200 mm diameter on the bottom. The slump tests were carried out by following IS: 1199-1959.

The slump values of mixtures GGBS and PS based mix are given in Table 5.1 and 5.2, respectively. The slump value obtained for the control mix is 80 mm (From the Figure 5.1, 5.2 and 5.3). The slump values obtained for control concrete mix is compared with the concrete mixes prepared using control concrete with GGBS and PS. The workability of the mixes prepared using various dosages of GGBS is found to be slightly higher with replacement level upto 50% when compared to control concrete, Optimum workability is obtained at 40% of GGBS. Similarly, as compared to control concrete, the workability of the mixes prepared using different dosages of PS is found to be marginally higher with replacement percentage upto 50 %. And optimum workability is obtained at 25% of PS.

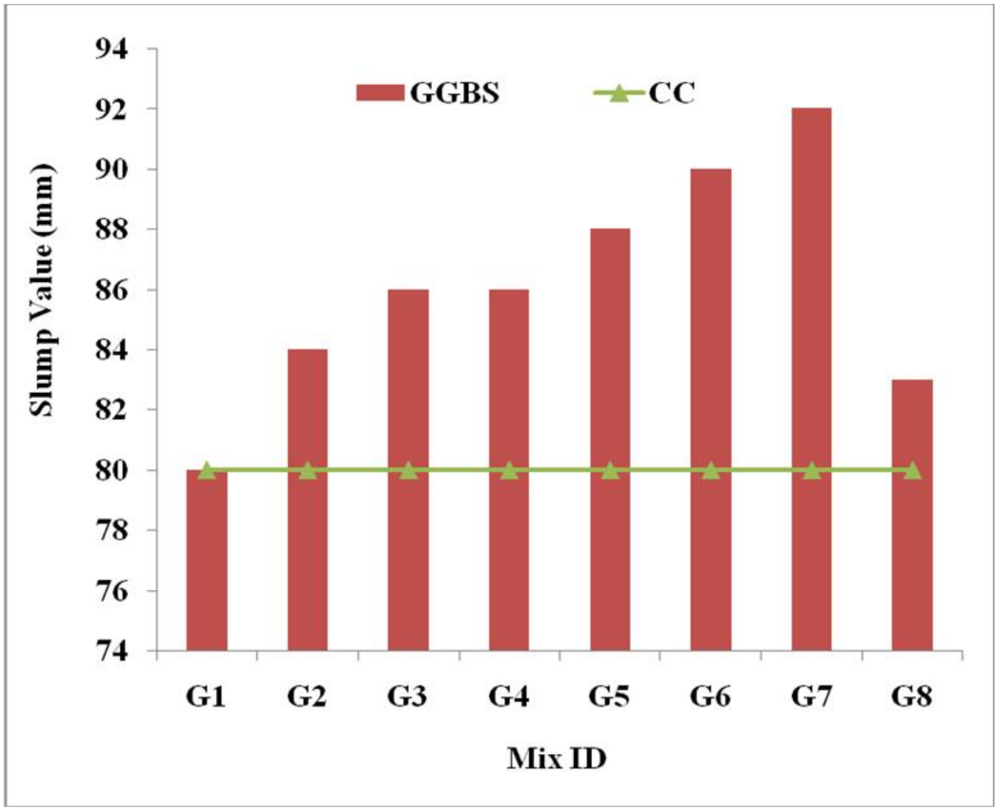


Figure 5.1 **Comparison of slump values with control concrete and Optimum Percentage of PRCM by GGBS added concrete**

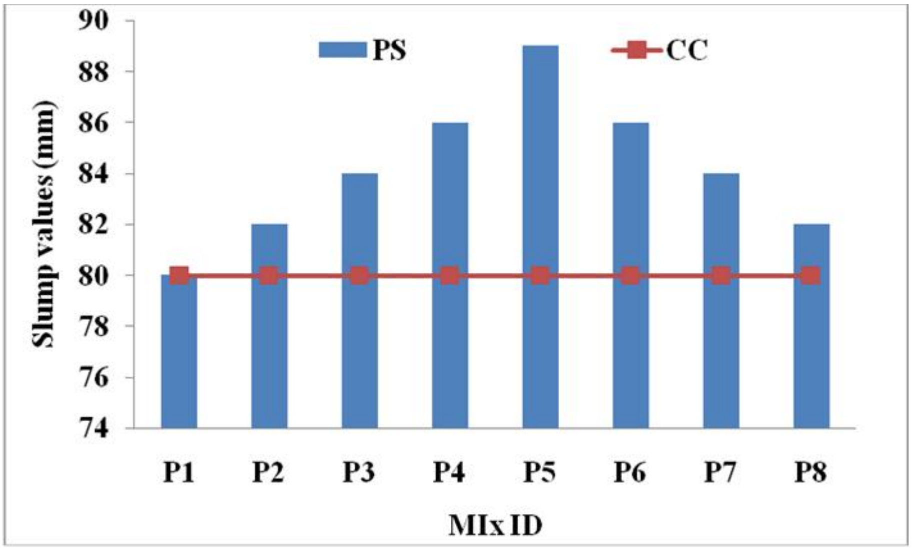


Figure 5.2 **Comparison of slump values with control concrete and PRCM by PS added concrete**

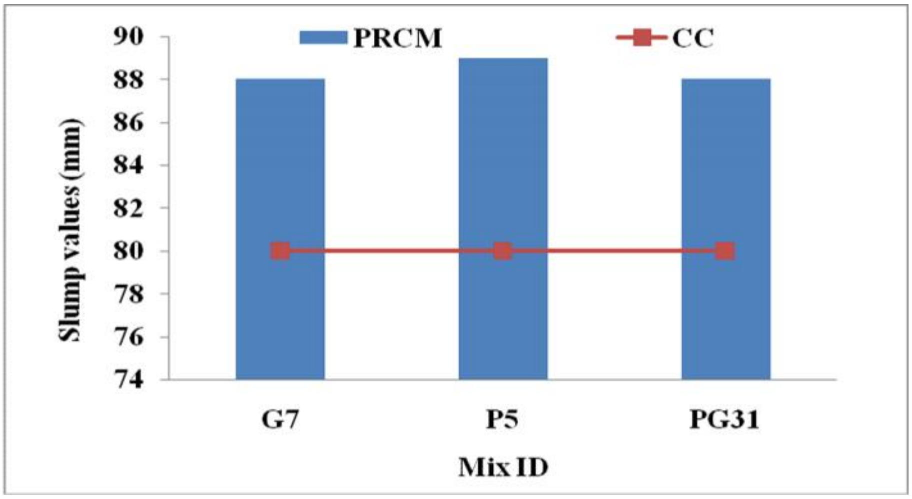


Figure 5.3 **Comparison of slump values with control concrete and optimum Percentage of PRCM added concrete**

The workability and Vee Bee values of Mix ID PG31 (25% GGBS with 15% PS) has been obtained as 88 mm and 11 sec, respectively, and the flow table test percentage was found to be 88 percentage, which indicated that GGBS, PS and GGBS combined with PS can be used as an alternatives for cement material which reduces the consumption of cement and possibility of reduction in pollution. Table 5.1 and 5.2 presents workability results using slump, compacting factor, flow table test and Vee-Bee test values for GGBS and PS mixtures, respectively.

Table 5.1 Workability test on M25 Grade concrete Mix with GGBS

Sl. No.	Mix ID	% of PRCM by GGBS	Slump (mm)	Compacting factor	Flow Table test (%)	Vee-Bee (sec)
1	CC	0	80	0.82	84	12
2	G1	5	80	0.81	79	12
3	G2	10	82	0.82	76	12
4	G3	15	84	0.82	83	12
5	G4	20	86	0.85	86	11
6	G5	25	88	0.87	88	11
7	G6	30	88	0.88	87	11
8	G7	40	88	0.89	88	11
9	G8	50	82	0.82	82	12

Table 5.2 Workability test on M25 Grade concrete Mix with PS

Sl. No.	Mix ID	% of PRCM by PS	Slump (mm)	Compacting factor	Flow Table test (%)	Vee-Bee (sec)
1	CC	0	80	0.82	84	12
2	P1	5	80	0.82	82	12
3	P2	10	82	0.82	84	11
4	P3	15	84	0.84	85	11
5	P4	20	86	0.85	86	10
6	P5	25	89	0.87	88	10
7	P6	30	86	0.88	90	9
8	P7	40	84	0.88	92	8
9	P8	50	82	0.90	92	7

5.3 MECHANICAL AND DURABILITY PROPERTIES OF PRCM BY GGBS AND PS ADDED CONCRETE

5.3.1 Compressive Strength of PRCM by GGBS added concrete

Compressive strength of concrete mixes prepared with and without GGBS, obtained at the ages of 3, 7, 28, 60, 90, 120, 180 and 365 days of water curing are given in Table 5.3. It shows decrease/increase in compressive strength compared to control concrete for various replacement percentages of GGBS added concrete specimens G1 to G8 (5%, 10%, 15%, 20%, 25%, 30%, 40% and 50%). It is observed that at the early age, strength of GGBS concrete are lower than the control concrete. As the curing period is extended, the strength values of the GGBS added concrete increased more than the control concrete. The test results of the mixes G1 to G8, revealed that, the compressive strength are found to be -7.8%, 2.3%, 7.0%, 7.8%, 11.0%, 15.5%, 23.8% and 2.9% respectively higher at the age of 28 days compared to the control concrete (Refer Annexure-II).

After 365 days, the GGBS concrete mixtures exhibit higher strength values compared to the control concrete mix (except for 5% of GGBS). The compared test results of the mixes G1 to G8, revealed that the compressive strengths are found to be -1.8%, 7.0%, 12.4%, 14.6%, 17.9%, 20.1%, 31.0% and 8.1% respectively higher the curing age of 365 days. This is because of pozzolanic reaction is slow and it depends on the calcium hydroxide availability, the strength gain takes prolonged time for the GGBS added concrete. The chemical reaction of the portland cement is expressed as follows:

$$\text{Cement } (C_3S, C_2S) + H_2O\ (H) \longrightarrow CSH\text{–}gel + Ca(OH)_2\ (CH) \qquad (5.1)$$

The pozzolanic reaction is

$$Ca(OH)_2\,(CH) + SiO_2(S) + H_2O\,(H) \longrightarrow CSH\text{–}gel \qquad (5.2)$$

From the above reaction, it is very clear that calcium hydroxide is produced by the hydration of portland cement and is consumed by the pozzolanic reaction. The pozzolanic reaction can only takes place after the commencement of portland cement hydration. It can be seen that, the mixture with the maximum 40% of GGBS (Mix ID G7) addition presents the highest compressive strength from the seventh day to 365 days. This results show that the strength enhanced with increase in GGBS percentages. The compressive strength improvement of the GGBS added concrete mixtures are presented in Figure 5.4.

Table 5.3 Percentage in compressive strength of PRCM by GGBS concrete compared to control concrete

Sl. No.	Mix ID	PRCM by GGBS	3 days	7 days	28 days	60 days	90 days	120 days	180 days	365 days
1	CC	0%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	G1	5%	-10.0	-10.0	-7.8	-6.2	-6.0	-4.0	-3.2	-1.8
3	G2	10%	-2.0	-1.0	2.3	2.2	3.3	4.5	5.3	7.0
4	G3	15%	3.0	3.4	7.0	7.4	7.5	9.8	10.6	12.4
5	G4	20%	5.0	6.7	7.8	9.5	9.6	12.0	12.7	14.6
6	G5	25%	8.1	7.8	11.0	12.6	12.8	15.2	15.9	17.9
7	G6	30%	10.0	12.2	15.5	14.7	14.8	17.3	18.0	20.1
8	G7	40%	20.0	21.1	23.8	25.1	25.3	28.0	28.6	31.0
9	G8	50%	-0.3	1.7	2.9	3.2	3.4	5.6	6.3	8.1

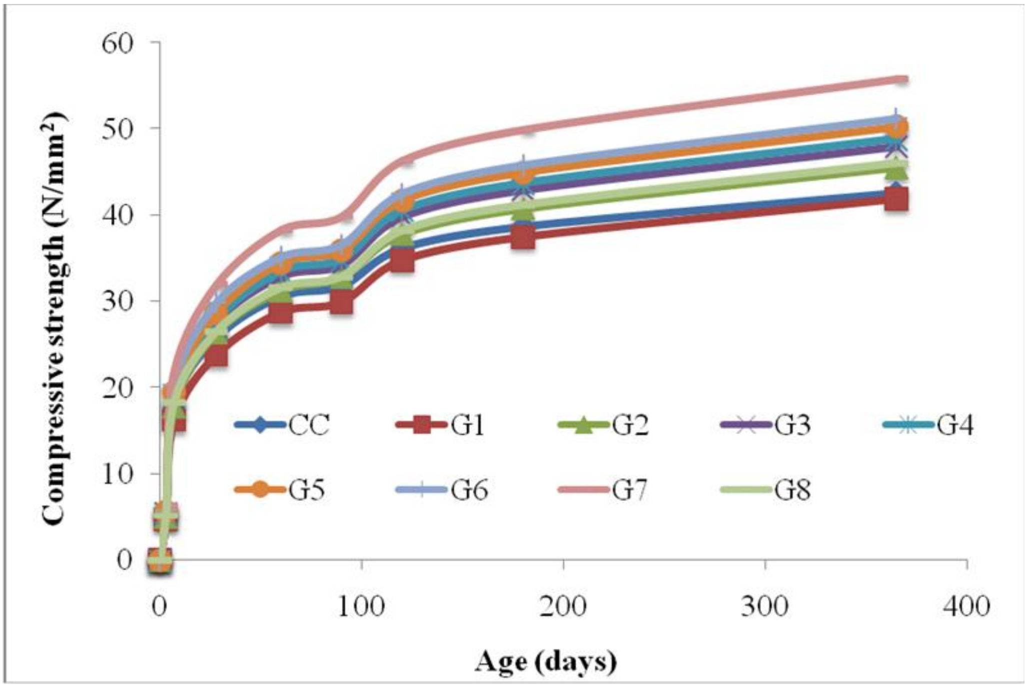


Figure 5.4 **Compressive strength development of PRCM by GGBS concrete in different curing days**

5.3.2 Compressive Strength of PRCM by PS added concrete

Self curing is an advanced technique that has been developed to extend cement hydration process by providing internal water in a concrete mixture that do not influence the concrete mixture's fresh or hardened physical properties. In the present study, PS is selected as self curing agent based on its water retention ability. PS (5% to 40% as partial replacement for cement) has been used to prepare various concrete mixes, which was cured in self curing method. The compressive strength of all the mixes prepared has been determined at the ages of 3, 7, 28, 60, 90, 120, 180 and 365 days and are listed in Table 5.4. These obtained values are plotted and compared with the values obtained for control concrete. Table 5.4 and Figure 5.5 clearly indicates that, for 3 days curing the compressive strength of PS added concrete specimens decreased than that of control concrete whereas after 7 days the compressive strength was found to be increased. When compared to control concrete, the test results of the mixes P1 to P7 obtained the compressive strength as -3.1%, 1.6%, 4.7%, 9.7%, 17.4%, 8.4% and -4.7% at the age of 28 days, respectively. For the same set of samples the compressive strength values were obtained as 16.4%, 24.2%, 27.9%, 31.2%, 39.7%, 15.3% and -5.6% at the age of 365 days, respectively (Refer Appendix-II). From the above observations, it is clearly known that, 25% PS replacement for cement had the maximum compressive strength (39.7%) compared to control concrete. PS can absorb and retain a high amount of water to its own mass, it forms as hydrogels when mixed and create bonding with cement slurry which improves the hydration which strengthen the concrete and PS also act as self-curing agent for a prolong period.

Table 5.4 Percentage in compressive strength of PS added concrete (self curing) compared to control concrete.

Sl. No.	**Mix Id**	**% of PRCM by PS**	**Change in compressive strength of PS concrete-self curing (%)**							
			3 days	**7 days**	**28 days**	**60 days**	**90 days**	**120 days**	**180 days**	**365 days**
1	CC	0%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	P1	5%	-17.3	4.4	-3.1	1.3	8.8	14.4	13.8	16.4
3	P2	10%	-13.5	15.0	1.6	3.6	15.1	18.2	19.6	24.2
4	P3	15%	-9.6	23.3	4.7	5.6	16.4	20.7	21.7	27.9
5	P4	20%	-5.8	31.1	9.7	8.2	22.6	26.5	27.3	31.2
6	P5	25%	-1.9	44.4	17.4	11.1	29.9	34.8	34.9	39.7
7	P6	30%	-3.8	28.9	8.5	-1.0	19.5	31.5	23.7	15.3
8	P7	40%	-9.6	15.6	-4.7	-12.4	-7.9	-3.9	-0.3	-5.6

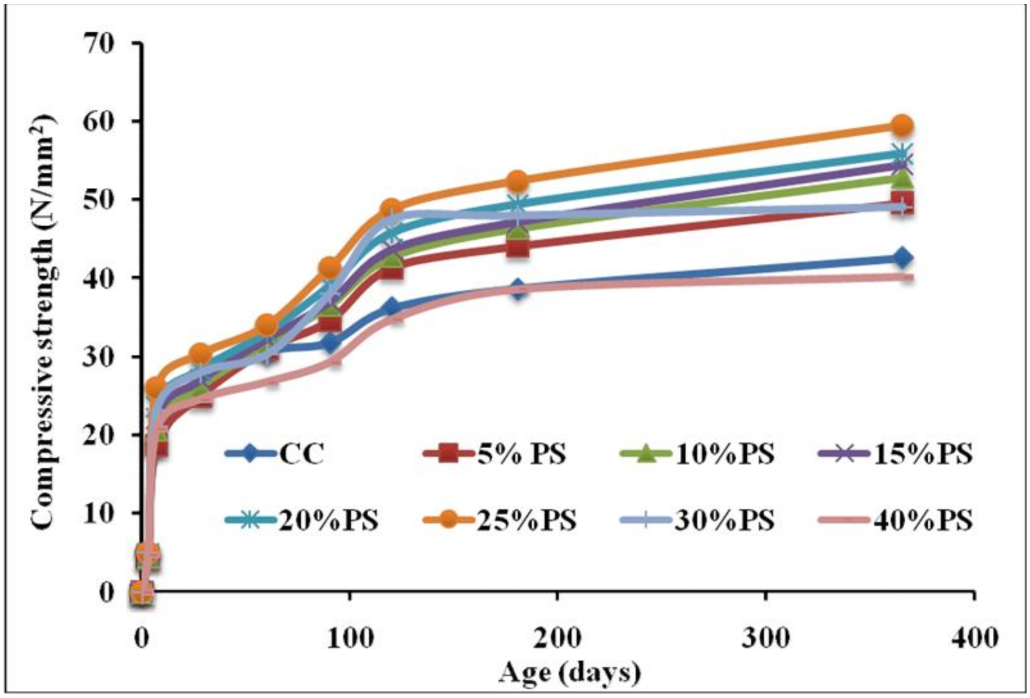


Figure 5.5 **Compressive strength development of PRCM by PS added concrete in different curing days**

5.3.3 Compressive Strength of PRCM by GGBS and PS added concrete

Test specimens PG1 to PG56 were prepared by partially replacing cement with various combined dosages of GGBS and PS simultaneously. All the test specimens were allowed to cure by self curing methods. After the self curing, concrete mixes PG1-PG56 were tested as per IS 516-1959 to get that compressive strength. The test results are illustrated in Figure 5.6-5.13 and Tables 5.5-5.12. From the observations, compressive strength is decreased excluding PG31 (after 7 days of self-curing) whereas PG17, PG22, PG23, PG24, PG25, PG26 and PG27 were improved after 90 days of curing. The partial replacement of 15% of PS and 25% of GGBS concrete Mix ID PG31 were found to get maximum compressive strengths 6.2%, 9.5%, 12.2%, 34.6%, 39.3%, 40.9% and 59.7 after 7 days of curing compared to control concrete.

It is observed from the table 5.5-5.12 that, the compressive strength is increased with the addition of 25% of GGBS with 15% of PS in self curing mode. All the specimens incorporating GGBS with PS exhibited greater compressive strength and particularly achieved greatest strength at 25% of GGBS with 15% of PS replacement by cement. Thereafter, the strength decreased with further addition of GGBS with PS, but still the strengths are higher than that of control concrete. The increased compressive strengths may be attributed to the following reasons. The behaviour of PS may modified its physio-chemical properties of concrete. The physical phase of this action is in the refinement of the void system of cement paste and particularly in the transition zone.

Table 5.5 Percentage in compressive strength development of PRCM by 5% of GGBS added concrete with different dosage of PS compared to control concrete

Sl. No.	Mix ID	% of PRCM by PS	Change in compressive strength of PS concrete-self curing (%)							
			3 days	7 days	28 days	60 days	90 days	120 days	180 days	365 days
1	CC	0%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	PG1	5%	-56.2	-44.2	-48.2	-45.8	-41.9	-37.0	-38.6	-37.8
3	PG2	10%	-54.0	-38.4	-45.7	-44.6	-38.5	-34.0	-35.5	-33.7
4	PG3	15%	-50.8	-30.5	-44.0	-41.4	-29.7	-26.7	-27.2	-27.9
5	PG4	20%	-50.8	-30.8	-48.6	-52.1	-36.9	-34.9	-34.9	-33.9
6	PG5	25%	-49.8	-30.0	-45.9	-49.8	-34.4	-32.5	-31.4	-29.9
7	PG6	30%	-48.8	-31.2	-49.9	-53.4	-36.1	-29.8	-33.3	-38.4
8	PG7	40%	-52.9	-36.7	-50.8	-54.7	-41.2	-35.4	-38.5	-43.3

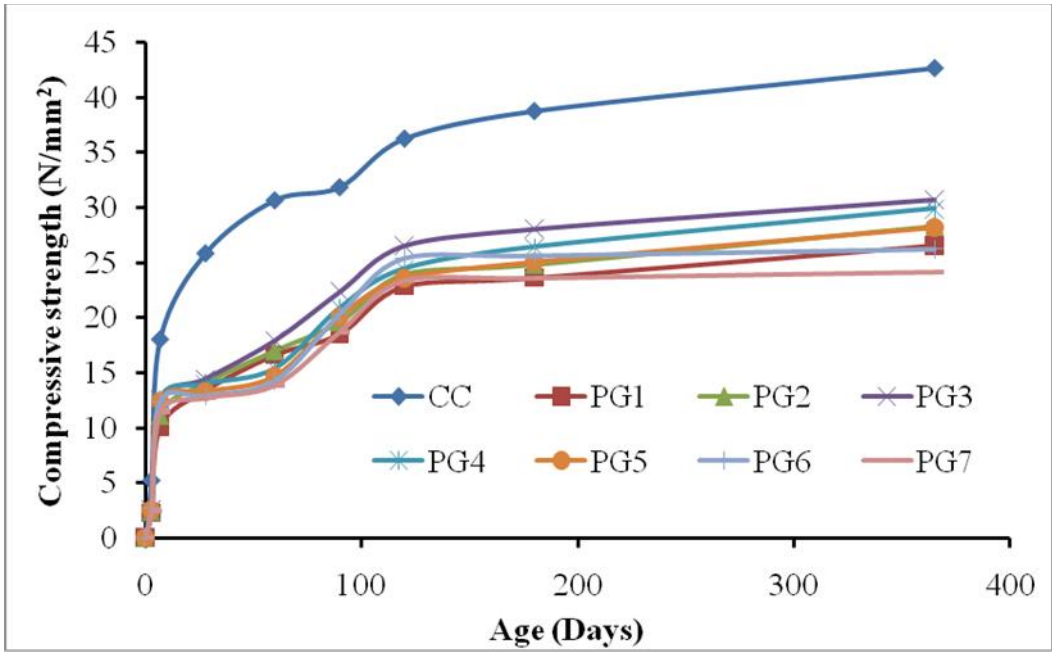


Figure 5.6 Compressive strength development of PRCM by 5% GGBS added concrete with different dosage of PS compared to control concrete

Table 5.6 Percentage in compressive strength development of PRCM by 10% GGBS added concrete with different dosage of PS compared to control concrete

Sl. No.	Mix ID	% of PRCM by PS	Change in compressive strength of PS concrete-self curing (%)							
			3 days	7 days	28 days	60 days	90 days	120 days	180 days	365 days
1	CC	0%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	PG8	5%	-42.5	-26.8	-32.1	-29.0	-23.8	-17.3	-19.9	-16.9
3	PG9	10%	-39.8	-19.3	-28.8	-27.4	-19.4	-13.4	-15.9	-11.4
4	PG10	15%	-35.4	-8.8	-26.6	-23.2	-7.8	-3.9	-4.9	-3.6
5	PG11	20%	-35.0	-14.4	-29.0	-34.2	-14.0	-11.5	-10.4	-6.3
6	PG12	25%	-37.7	-16.8	-32.6	-37.2	-17.2	-14.6	-15.0	-11.6
7	PG13	30%	-41.9	-22.4	-34.3	-38.9	-16.2	-7.9	-13.0	-17.7
8	PG14	40%	-38.3	-26.4	-35.5	-40.7	-22.9	-15.3	-19.8	-24.3

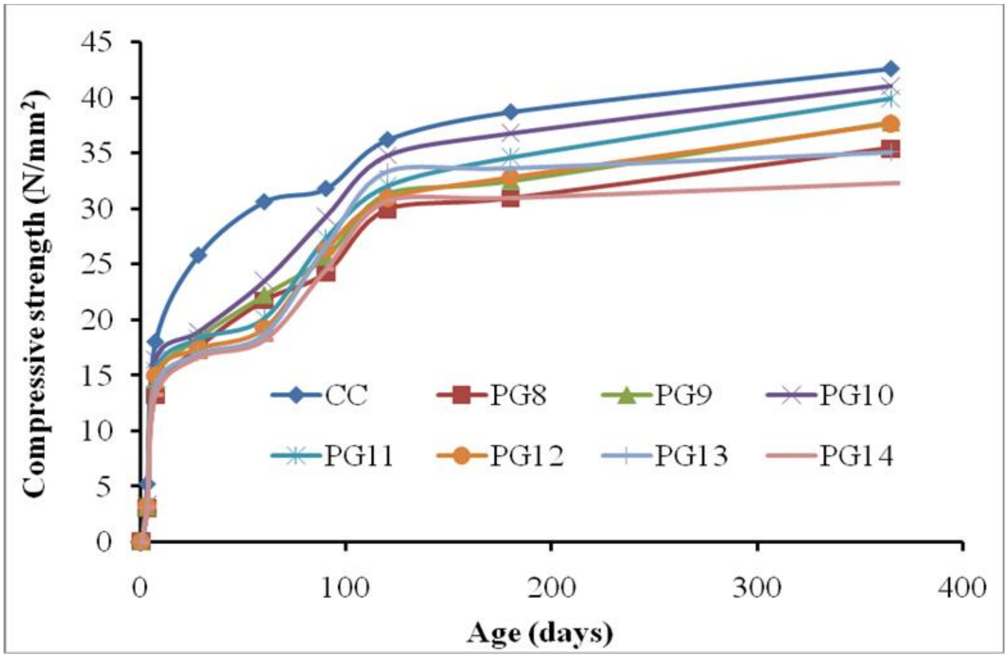


Figure 5.7 Compressive strength development of PRCM by 10% GGBS added concrete with different dosage of PS compared to control concrete

Table 5.7 Percentage in compressive strength development of PRCM by 15% GGBS added concrete with different dosage of PS compared to control concrete

Sl. No.	Mix ID	% of PRCM by PS	Change in compressive strength of PS concrete-self curing (%)							
			3 days	7 days	28 days	60 days	90 days	120 days	180 days	365 days
1	CC	0%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	PG15	5%	-32.3	-13.8	-20.0	-16.4	-10.3	-2.7	-5.8	1.6
3	PG16	10%	-29.0	-4.9	-16.1	-14.4	-5.0	2.0	-1.1	8.3
4	PG17	15%	-22.1	10.1	-11.4	-7.3	11.3	16.0	14.6	20.8
5	PG18	20%	-29.0	-6.7	-22.6	-28.3	-6.3	-3.5	-2.5	5.9
6	PG19	25%	-32.1	-9.3	-26.5	-31.5	-9.8	-7.0	-7.5	-0.1
7	PG20	30%	-36.7	-15.4	-28.4	-33.4	-8.7	0.3	-5.3	-7.0
8	PG21	40%	-32.7	-19.8	-29.7	-35.3	-16.0	-7.7	-12.8	-14.4

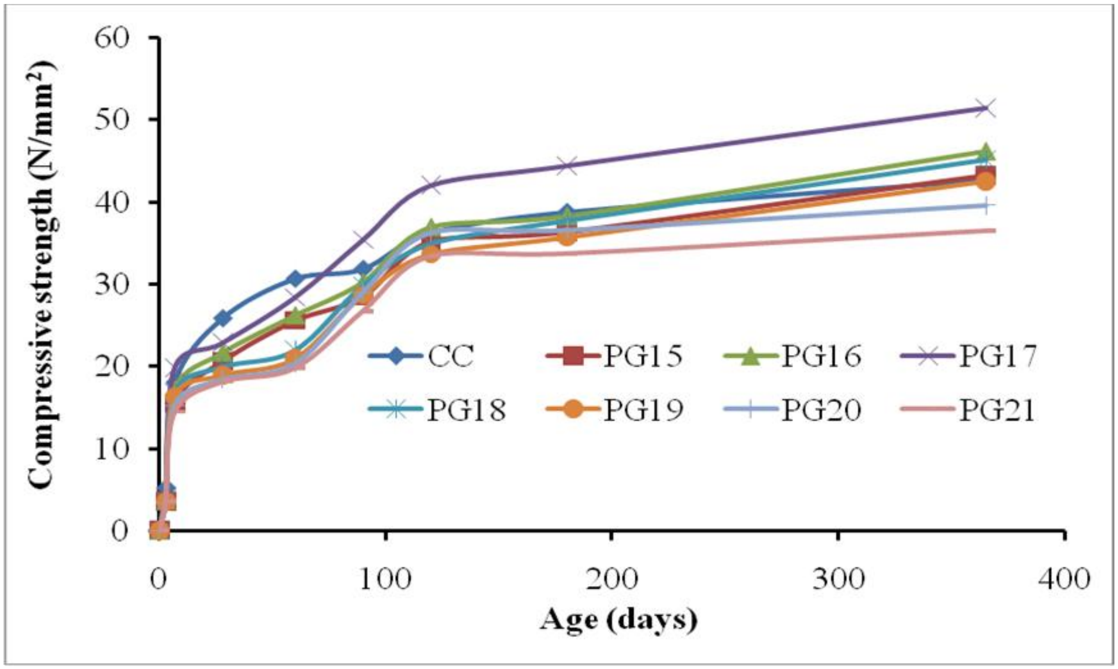


Figure 5.8 Compressive strength development of PRCM by 15% GGBS added concrete with different dosage of PS compared to control concrete

Table 5.8 Percentage in compressive strength development of PRCM by 20% GGBS added concrete with different dosage of PS compared to control concrete

Sl. No.	Mix ID	% of PRCM by PS	Change in compressive strength of PS concrete-self curing (%)							
			3 days	7 days	28 days	60 days	90 days	120 days	180 days	365 days
1	CC	0%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	PG22	5%	-28.1	-8.6	-15.2	-11.4	-4.9	3.2	-0.3	13.8
3	PG23	10%	-24.8	0.8	-11.1	-9.3	0.7	8.1	4.7	21.3
4	PG24	15%	-14.2	21.1	-2.5	2.0	22.4	27.7	25.9	38.8
5	PG25	20%	-24.8	-1.2	-18.0	-24.0	-0.7	2.3	3.3	18.6
6	PG26	25%	-28.1	-3.9	-22.1	-27.4	-4.4	-1.4	-2.0	11.9
7	PG27	30%	-32.9	-10.4	-24.1	-29.4	-3.2	6.4	0.3	4.2
8	PG28	40%	-28.7	-15.0	-25.5	-31.4	-11.0	-2.2	-7.6	-4.1

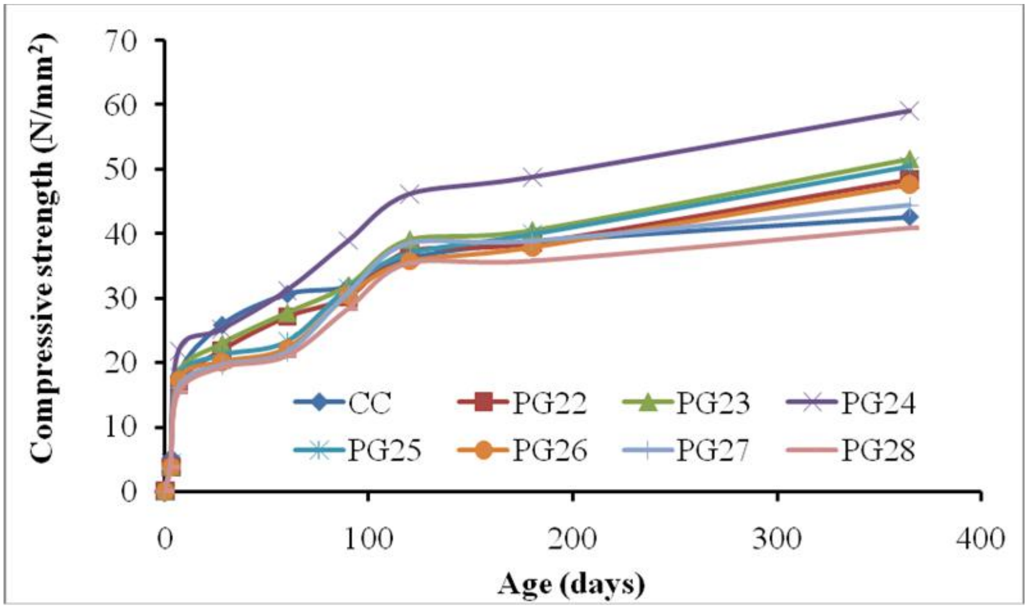


Figure 5.9 Compressive strength development of PRCM by 20% GGBS added concrete with different dosage of PS compared to control concrete

Table 5.9 Percentage in compressive strength development of PRCM by 25% GGBS added concrete with different dosage of PS compared to control concrete

Sl. No.	Mix ID	% of PRCM by PS	Change in compressive strength of PS concrete-self curing (%)							
			3 days	7 days	28 days	60 days	90 days	120 days	180 days	365 days
1	CC	0%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	PG29	5%	-23.8	-3.1	-10.1	-2.5	0.8	15.6	5.6	30.9
3	PG30	10%	-20.2	1.3	-5.7	-0.3	6.7	21.0	10.9	39.5
4	PG31	15%	-5.6	6.2	9.5	12.2	34.6	39.3	40.9	59.7
5	PG32	20%	-18.3	7.6	-10.7	-14.1	8.1	17.6	12.3	40.1
6	PG33	25%	-21.7	4.6	-15.2	-18.0	4.1	13.4	6.5	32.1
7	PG34	30%	-26.9	-2.4	-17.4	-20.3	5.3	22.3	9.1	23.1
8	PG35	40%	-22.3	-7.4	-18.9	-22.5	-3.1	12.5	0.5	13.2

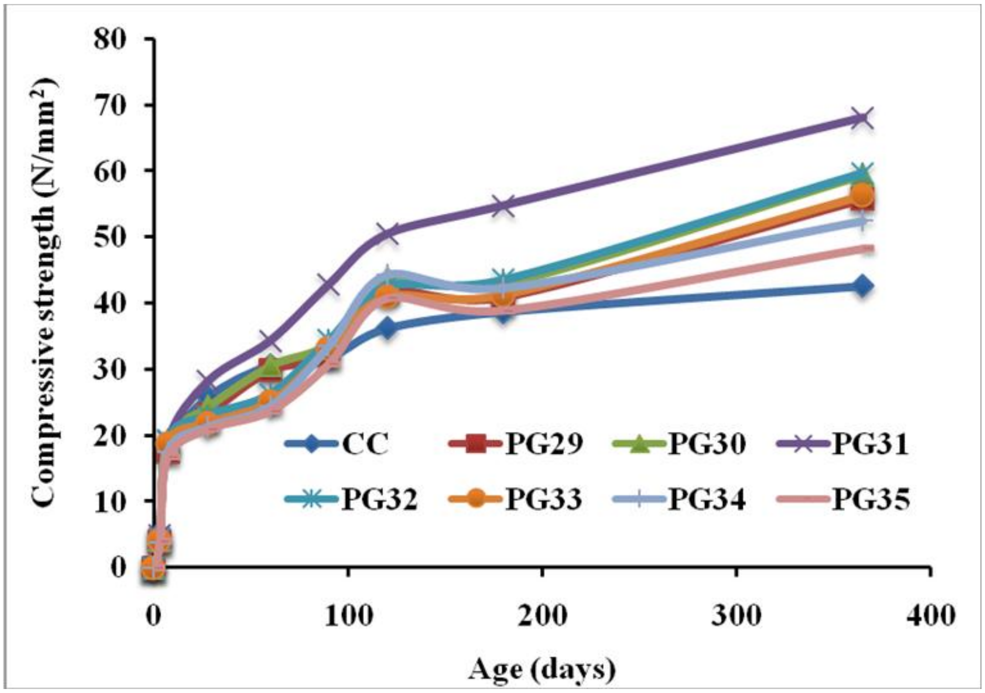


Figure 5.10 Compressive strength development of PRCM by 25% GGBS added concrete with different dosage of PS compared to control concrete

Table 5.10 Percentage in compressive strength development of PRCM by 30% GGBS added concrete with different dosage of PS compared to control concrete

Sl. No.	Mix ID	% of PRCM by PS	Change in compressive strength of PS concrete -self curing (%)							
			3 days	7 days	28 days	60 days	90 days	120 days	180 days	365 days
1	CC	0%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	PG36	5%	-38.3	-21.4	-27.1	-23.8	-18.2	-11.3	-14.1	-2.1
3	PG37	10%	-35.2	-13.3	-23.5	-22.0	-13.4	-7.0	-9.8	4.3
4	PG38	15%	-28.1	1.6	-18.2	-14.4	2.7	7.1	5.8	16.5
5	PG39	20%	-30.2	-8.1	-25.0	-29.3	-7.6	-4.9	-3.9	10.3
6	PG40	25%	-33.1	-10.7	-27.6	-32.5	-11.1	-8.3	-8.8	4.0
7	PG41	30%	-37.5	-16.7	-29.5	-34.4	-10.1	-1.1	-6.6	-3.1
8	PG42	40%	-33.7	-21.0	-30.8	-36.3	-17.3	-9.0	-14.0	-10.9

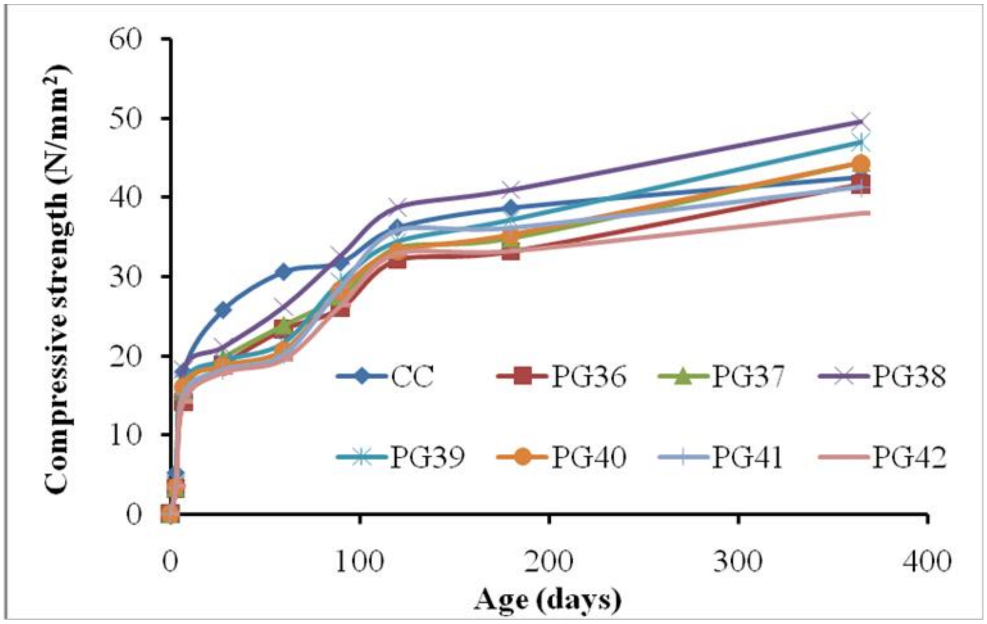


Figure 5.11 Compressive strength development of PRCM by 30% GGBS added concrete with different dosage of PS compared to control concrete

Table 5.11 Percentage in compressive strength development of PRCM by 40% GGBS added concrete with different dosage of PS compared to control concrete

Sl. No.	Mix ID	% of PRCM by PS	Change in compressive strength of PS added concrete- self curing (%)							
			3 days	7 days	28 days	60 days	90 days	120 days	180 days	365 days
1	CC	0%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	PG43	5%	-44.4	-29.3	-34.4	-31.4	-26.4	-20.1	-22.5	-11.9
3	PG44	10%	-41.7	-22.0	-31.2	-29.8	-22.1	-16.3	-18.6	-6.1
4	PG45	15%	-35.2	-8.6	-26.4	-23.0	-7.6	-3.6	-4.6	4.9
5	PG46	20%	-37.1	-17.3	-32.5	-36.4	-16.9	-14.4	-13.4	-0.7
6	PG47	25%	-39.8	-19.6	-34.8	-39.3	-20.0	-17.5	-17.8	-6.4
7	PG48	30%	-43.8	-25.0	-36.6	-40.9	-19.1	-11.0	-15.8	-12.8
8	PG49	40%	-40.4	-28.9	-37.7	-42.6	-25.5	-18.1	-22.5	-19.8

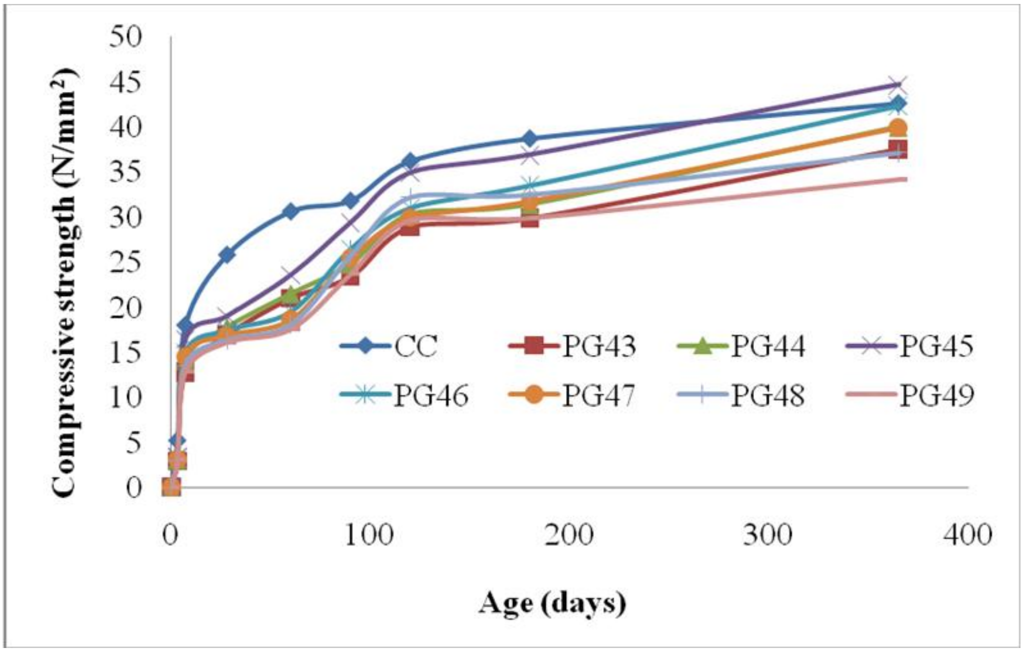


Figure 5.12 Compressive strength development of PRCM by 40% GGBS added concrete with different dosage of PS compared to control concrete

Table 5.12 Percentage in compressive strength development of PRCM by 50% GGBS added concrete with different dosage of PS compared to control concrete

Sl. No.	Mix ID	PRCM by PS	Change in compressive strength of PS added Concrete-Self curing (%)							
			3 days	7 days	28 days	60 days	90 days	120 days	180 days	365 days
1	CC	0%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	PG50	5%	-52.7	-39.8	-44.1	-41.6	-37.4	-32.0	-33.9	-25.0
3	PG51	10%	-50.4	-33.6	-41.4	-40.3	-33.7	-28.8	-30.6	-20.1
4	PG52	15%	-44.8	-22.2	-37.3	-34.4	-21.4	-18.0	-18.6	-10.8
5	PG53	20%	-46.5	-29.6	-42.5	-45.8	-29.3	-27.2	-26.1	-15.5
6	PG54	25%	-48.8	-31.6	-44.5	-48.3	-31.9	-29.8	-29.9	-20.4
7	PG55	30%	-52.1	-36.2	-46.0	-49.7	-31.1	-24.3	-28.2	-25.8
8	PG56	40%	-49.2	-39.5	-47.0	-51.2	-36.6	-30.3	-33.8	-31.7

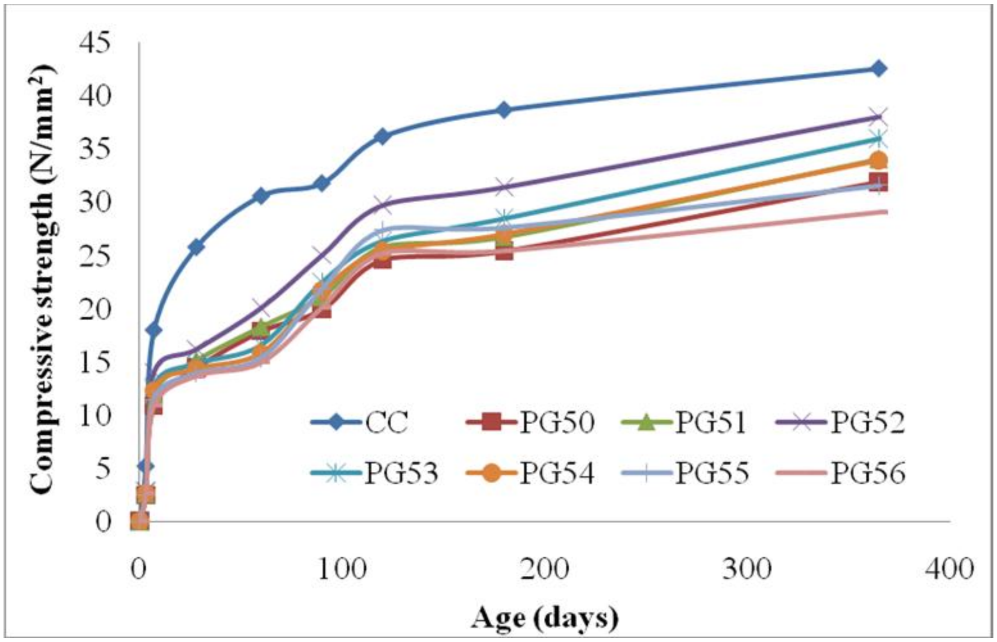


Figure 5.13 Compressive strength development of PRCM by 50% GGBS added concrete with different dosage of PS compared to control concrete

Table 5.13 Percentage change in compressive strength development of PRCM added concrete compared with control concrete

Sl. No.	Mix ID	% of PRCM	3 days	7 days	28 days	60 days	90 days	120 days	180 days	365 days
1	CC	0%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	G7	40% GGBS	20.0	20.0	11.2	8.8	12.7	14.1	21.0	21.6
3	P5	25% PS	-1.9	44.4	17.4	11.1	29.9	34.8	34.9	39.7
4	PG31	25% GGBS & 15% PS	-5.6	6.2	9.5	12.2	34.6	39.3	40.9	59.7

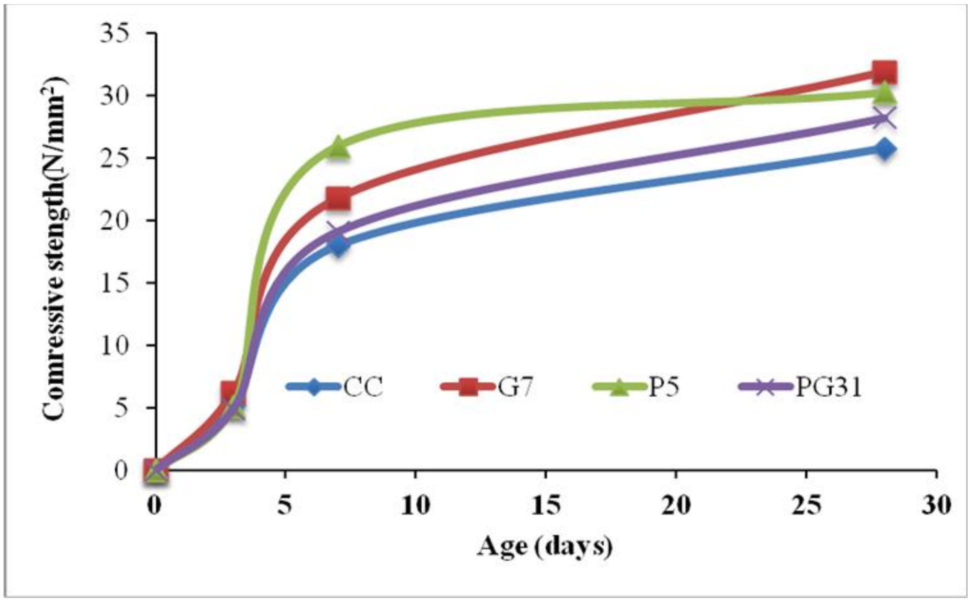


Figure 5.14 Compressive strength development of PRCM by 40% GGBS, 25% PS and 25% GGBS with 15% PS added concrete in 28 days

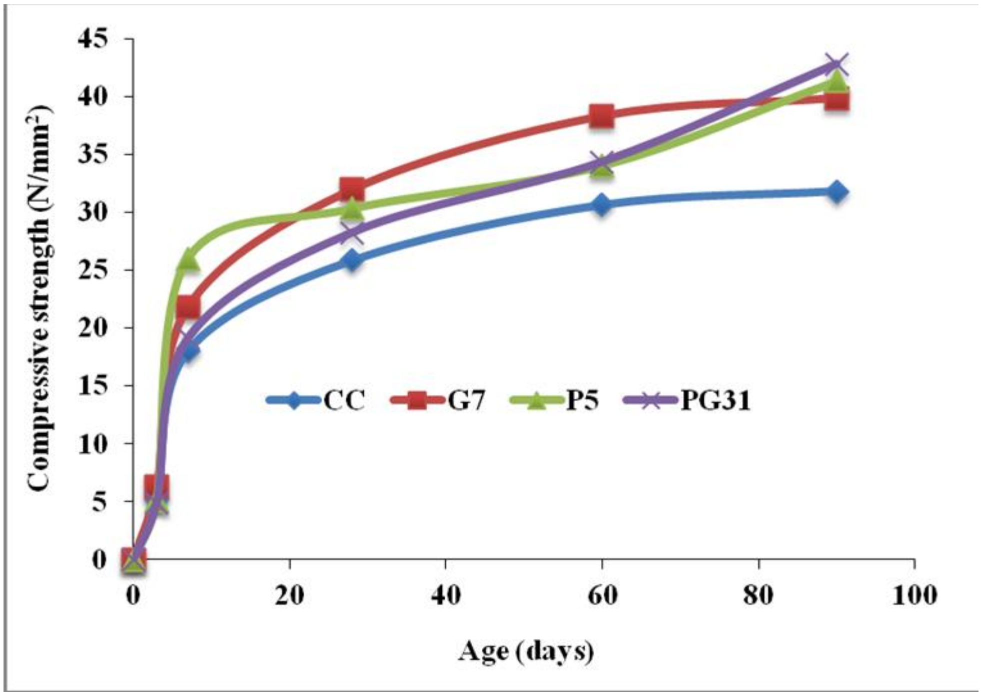


Figure 5.15 Compressive strength development of PRCM by 40% GGBS, 25% PS and 25% GGBS with 15% PS added concrete in 90 days

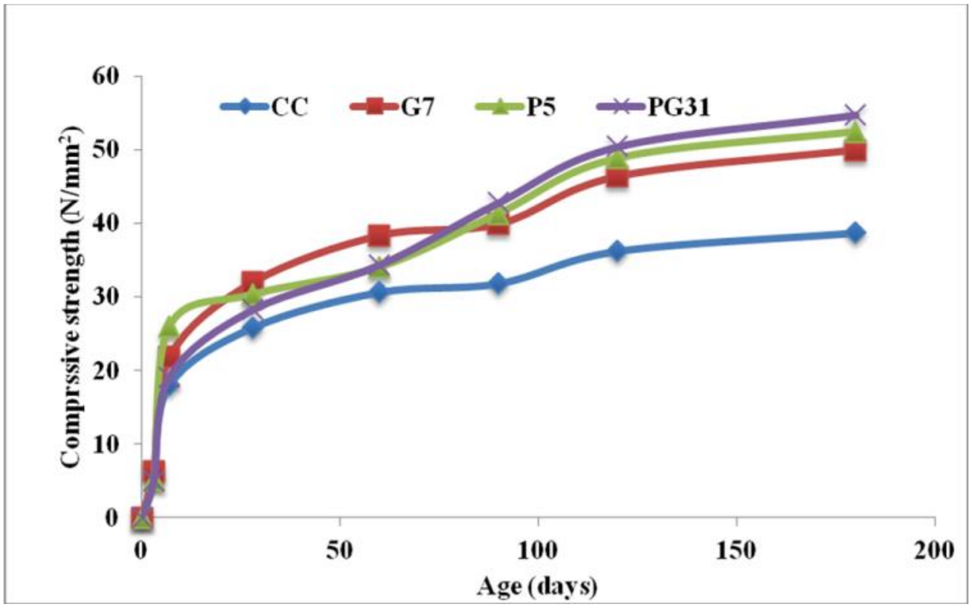


Figure 5.16 Compressive strength development of PRCM by 40% GGBS, 25% PS and 25% GGBS with 15% PS added concrete in 180 days

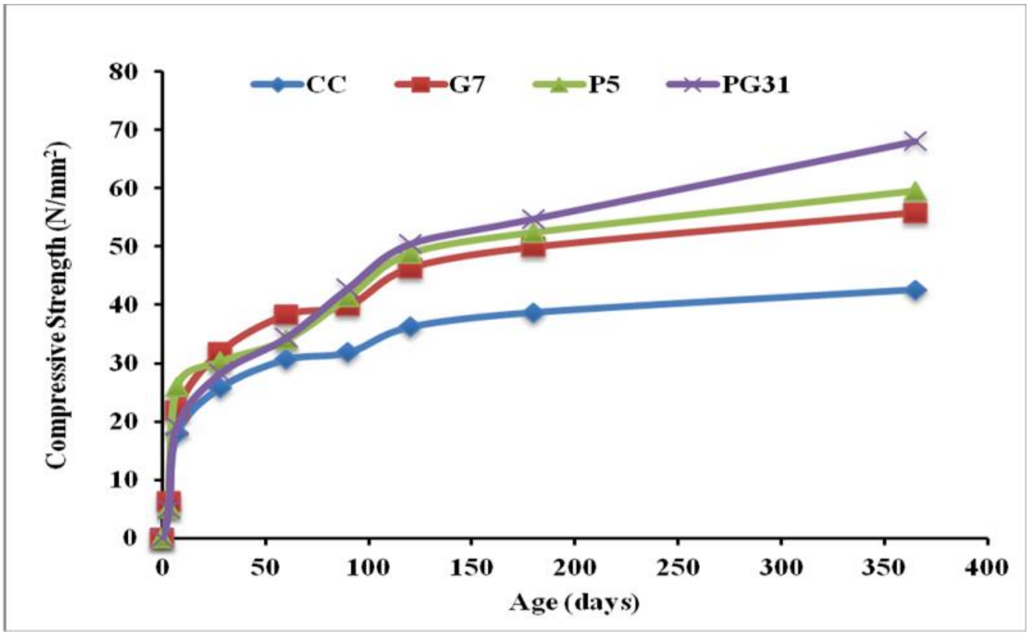


Figure 5.17 Compressive strength development of PRCM by 40% GGBS, 25% PS and 25% GGBS with 15% PS added concrete in 365 days

The compressive strength is increased compared to the control concrete as the replacement percentages of 40% of GGBS, 25% of PS and 15% of PS with 25% of GGBS for cement which is shown in Table 5.13. However, the compressive strength is slightly increased over the curing age compared to control concrete, which is shown in Figures 5.14-5.17. Except mixes P5 and PG31 shows marginal reduction in compressive strength at the age of 3 days. From the observations, the initially reduced compressive strength due to a decrease in carbonation and hydration and a higher percentage of PS has higher silica content than cement. However, the degree of improvement in strength appeared to be highly dependent on the level of cement replacement. It was noted that concretes with more than 25% PS had shown a reduction in compressive strength.

5.3.4 Split Tensile Strength of GGBS added concrete

The split tensile strength tests are carried out using cylindrical specimens prepared by PRCM by GGBS added concrete of size 150 mm diameter and 300 mm height. The test has been conducted after 7, 28, 60 and 90 days of curing and compared with the results obtained for control concrete and are shown in Figure 5.18 and 5.19. From the results, it can be seen that, there is an increased split tensile strength except for 5%, 10% and 50% of GGBS concrete mixes over to control concrete. In addition, 40% of the partial replacement of GGBS concrete achieved maximum split tensile strength over to control concrete.

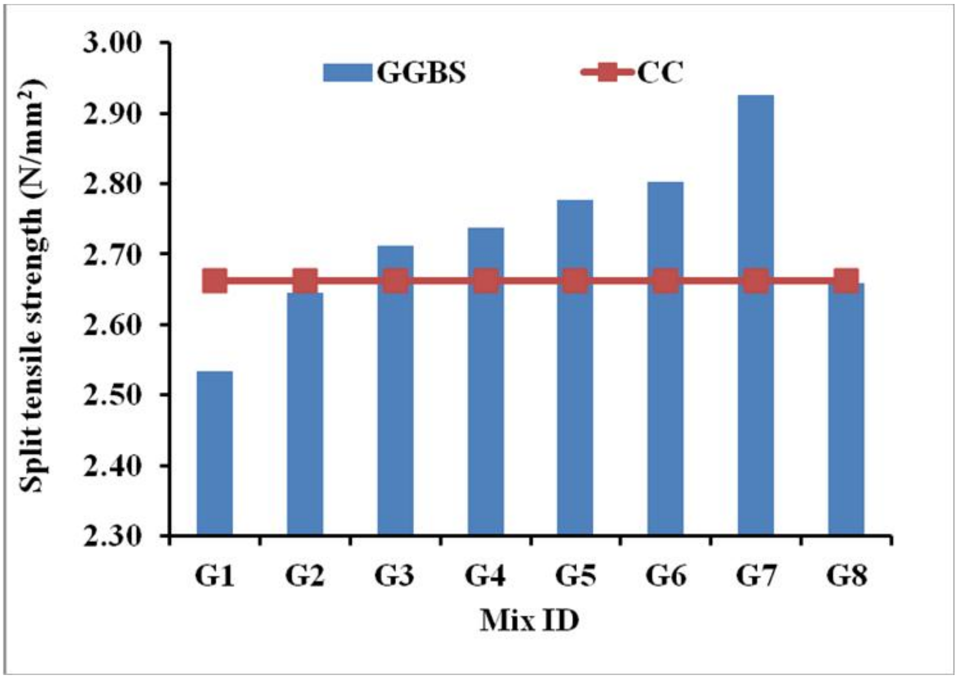


Figure 5.18 Split tensile strength of control concrete and PRCM by GGBS added concrete at 28 days of curing

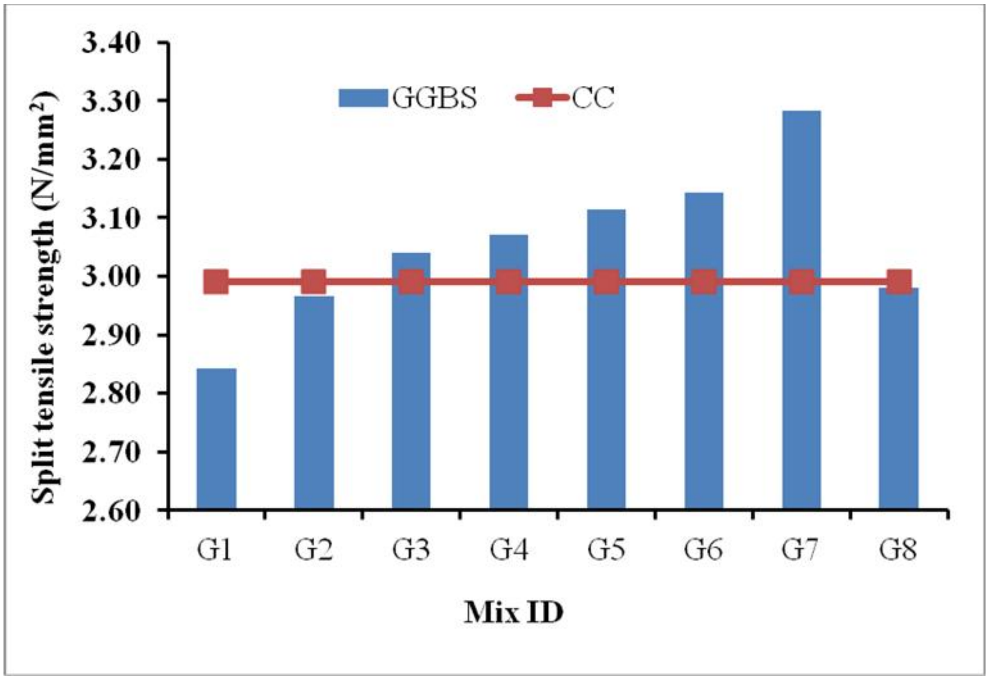


Figure 5.19 Split tensile strength of control concrete and PRCM by GGBS added concrete at 90 days of curing

5.3.5 Split Tensile Strength of PS added concrete

The splitting tensile strength of PS added concrete mixes were determined at the ages of 7, 28, 60 and 90 days for the various replacement levels of PS using a compression testing machine of 1000 KN capacity as per IS 516-1959. The split tensile test has been carried out and the results were compared with the control concrete (Figure.5.20 and 5.21). The results show an increased split tensile strength except for 5%, 30% and 40% of PS concrete mixes over to control concrete in 28 days of self curing. Also 25% of PS added concrete showed an improved split tensile strength than control concrete at the age of 28 and 90 days of self-curing.

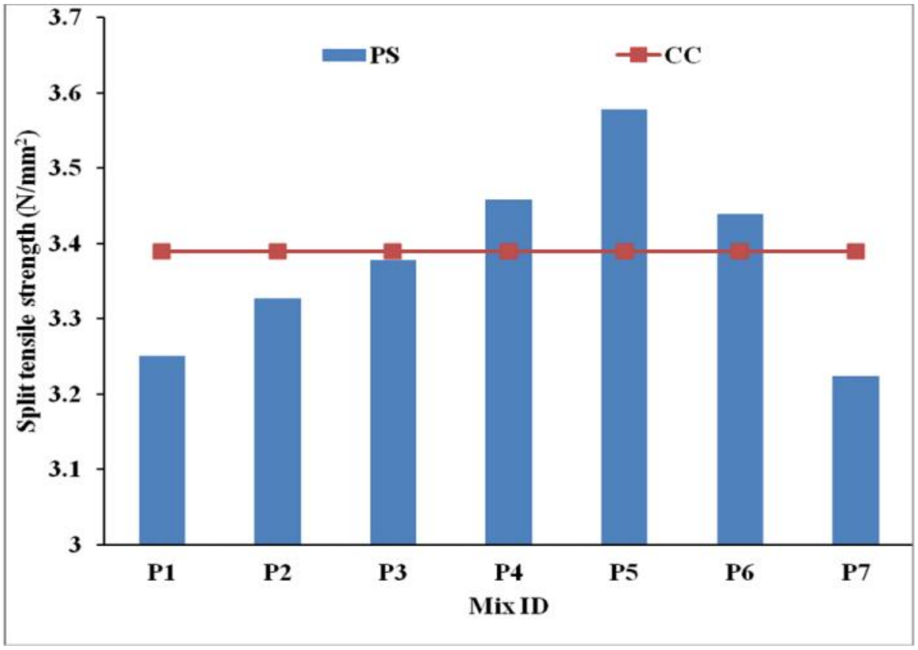


Figure 5.20 Split tensile strength of PRCM by PS and control concrete at 28 days curing

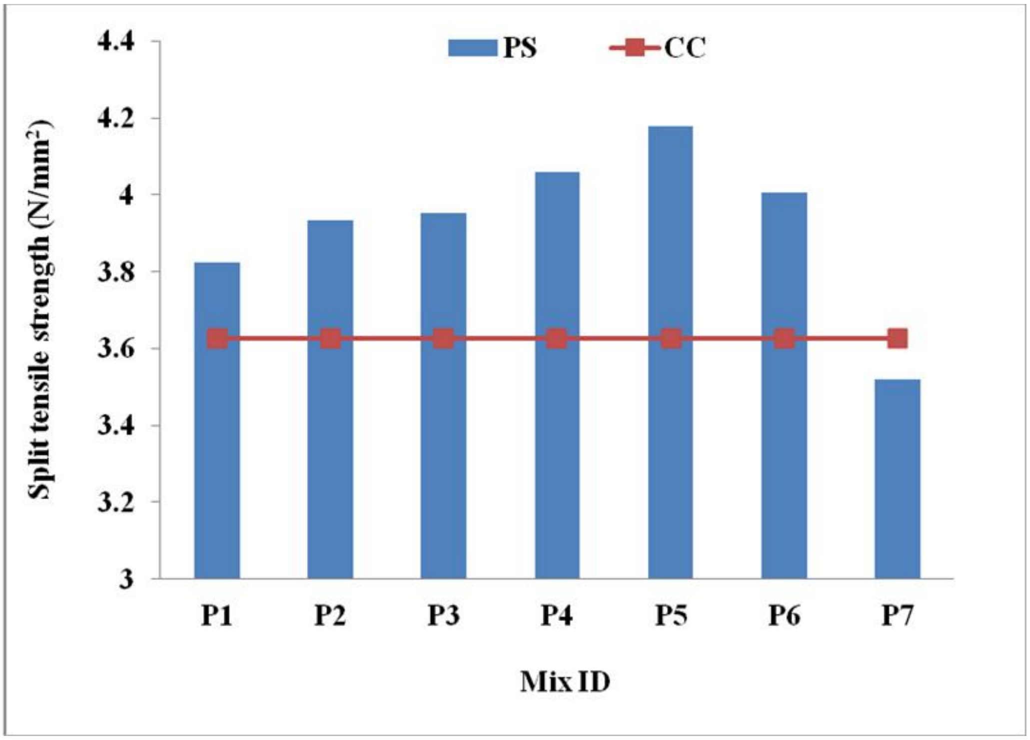


Figure 5.21 Split tensile strength of PRCM by PS and control concrete at 90 days of curing

5.3.6 Split Tensile Strength of PRCM by GGBS and PS Added concrete

The split tensile strength tests of PRCM by GGBS and PS added concrete was performed at different ages of 7, 28, 60 and 90 days for the various replacement levels using a compression testing machine with a capacity of 1000 KN as per IS: 516-1959. The test results are illustrated in Figure 5.22. The split tensile strength of PRCM by GGBS and PS added concrete when compared with control concrete and was found to be higher than control concrete.

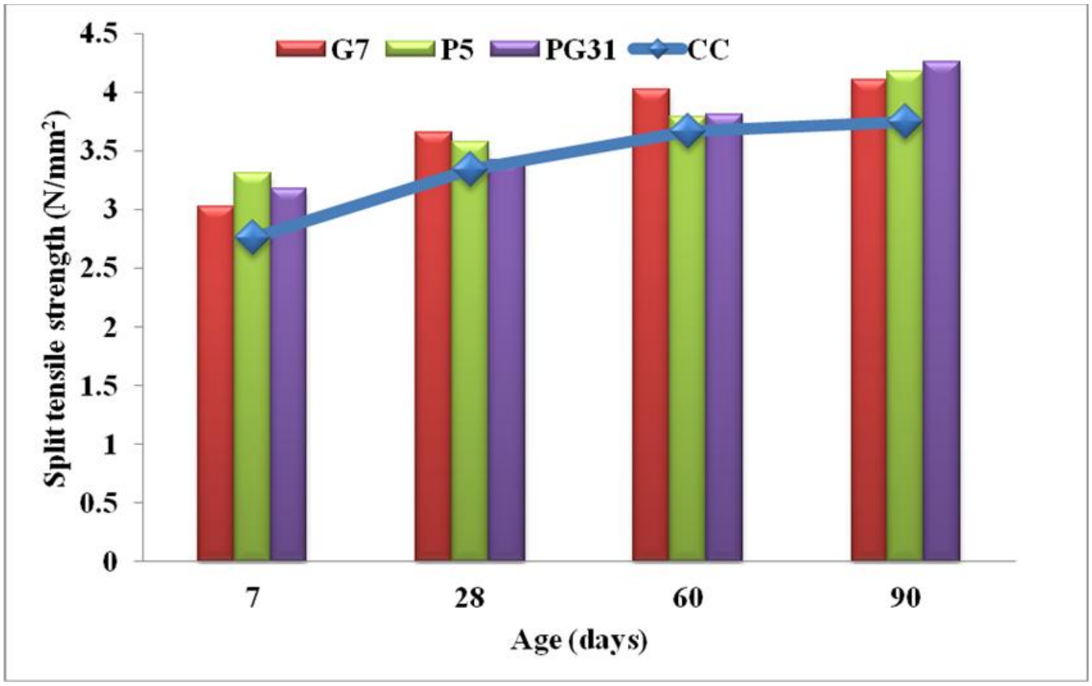


Figure 5.22 **Split tensile strength of optimum Percentage of PRCM by GGBS, PS GGBS with PS and control concrete at different curing days**

The splitting tensile strength for all the test specimens cast using various replacements levels of GGBS and PS with cement has been tested at ages of 7, 28, 60 and 90 days of curing, decreased after addition of the PRCM split tensile strength compared with the control concrete. The addition of the PRCM (PS) maintains moisture and reduces the split tensile strength (Table 5.14). The split tensile strength of PRCM by GGBS,PS and GGBS with PS in various replacement dosages are compared with control concrete which are listed in Table 5.14. The results showed that the Mix ID G7, P5 and PG31 (40% of GGBS, 25% PS and 25% of GGBS with 15% PS) split tensile strength was increased when compared with the control concrete.

Table 5.14 Split tensile strength of control concrete, PRCM by GGBS, PS and GGBS with PS at different curing days

Mix ID	**PRCM (weight of cement)**		**Split tensile strength (N/mm^2)**			
			7 days	**28 days**	**60 days**	**90 days**
CC	0%		2.20	2.67	2.93	3.01
G1	5% GGBS		2.09	2.53	2.79	2.84
G2	10% GGBS		2.18	2.64	2.91	2.97
G3	15% GGBS		2.24	2.71	2.98	3.04
G4	20% GGBS		2.26	2.74	3.01	3.07
G5	25% GGBS		2.29	2.78	3.05	3.11
G6	30% GGBS		2.31	2.80	3.08	3.14
G7	**40%** GGBS		**2.42**	**2.93**	**3.22**	**3.28**
G8	50% GGBS		2.20	2.66	2.92	2.98
P1	5% PS		2.25	2.60	2.90	3.06
P2	10% PS		2.37	2.66	2.93	3.15
P3	15% PS		2.45	2.70	2.96	3.16
P4	20% PS		2.53	2.77	2.99	3.25
P5	**25% PS**		**2.65**	**2.86**	**3.03**	**3.34**
P6	30% PS		2.50	2.75	2.86	3.21
P7	40% PS		2.37	2.58	2.69	2.81
PG1	5% PS	5% GGBS	1.65	1.90	2.12	2.23
PG2	10% PS	5% GGBS	1.73	1.95	2.14	2.30
PG3	15% PS	5% GGBS	1.84	1.98	2.20	2.46
PG4	20% PS	5% GGBS	1.85	1.94	2.04	2.37
PG5	25% PS	5% GGBS	1.83	1.89	1.99	2.33
PG6	30% PS	5% GGBS	1.83	1.87	1.96	2.34
PG7	40% PS	5% GGBS	1.75	1.85	1.94	2.25
PG8	5% PS	10% GGBS	1.89	2.18	2.42	2.56
PG9	10% PS	10% GGBS	1.98	2.23	2.45	2.63

Table 5.14 (Continued)

Mix ID	PRCM (weight of cement)		Split tensile strength (N/mm^2)			
			7 days	28 days	60 days	90 days
PG10	15% PS	10% GGBS	2.11	2.26	2.52	2.82
PG11	20% PS	10% GGBS	2.04	2.23	2.33	2.72
PG12	25% PS	10% GGBS	2.01	2.17	2.28	2.67
PG13	30% PS	10% GGBS	1.94	2.14	2.25	2.68
PG14	40% PS	10% GGBS	1.89	2.12	2.22	2.57
PG15	5% PS	15% GGBS	2.05	2.36	2.63	2.78
PG16	10% PS	15% GGBS	2.15	2.42	2.66	2.86
PG17	15% PS	15% GGBS	2.31	2.49	2.77	3.09
PG18	20% PS	15% GGBS	2.13	2.32	2.44	2.84
PG19	25% PS	15% GGBS	2.10	2.26	2.38	2.79
PG20	30% PS	15% GGBS	2.03	2.23	2.35	2.80
PG21	40% PS	15% GGBS	1.98	2.21	2.31	2.69
PG22	5% PS	20% GGBS	2.11	2.43	2.71	2.86
PG23	10% PS	20% GGBS	2.21	2.49	2.74	2.94
PG24	15% PS	20% GGBS	2.43	2.61	2.91	3.24
PG25	20% PS	20% GGBS	2.19	2.39	2.51	2.92
PG26	25% PS	20% GGBS	2.16	2.33	2.45	2.87
PG27	30% PS	20% GGBS	2.09	2.30	2.42	2.88
PG28	40% PS	25% GGBS	2.03	2.28	2.38	2.77
PG29	5% PS	25% GGBS	2.17	2.50	2.84	2.94
PG30	10% PS	25% GGBS	2.28	2.56	2.87	3.03
PG31	**15% PS**	**25% GGBS**	**2.55**	**2.74**	**3.05**	**3.40**
PG32	20% PS	25% GGBS	2.29	2.50	2.67	3.05
PG33	25% PS	25% GGBS	2.26	2.43	2.60	2.99

Table 5.14 (Continued)

Mix ID	PRCM (weight of cement)		Split tensile strength (N/mm^2)			
			7 days	28 days	60 days	90 days
PG34	30% PS	25% GGBS	2.18	2.40	2.57	3.01
PG35	40% PS	25% GGBS	2.12	2.38	2.53	2.89
PG36	5% PS	30% GGBS	1.96	2.26	2.51	2.65
PG37	10% PS	30% GGBS	2.05	2.31	2.54	2.73
PG38	15% PS	30% GGBS	2.22	2.39	2.66	2.97
PG39	20% PS	30% GGBS	2.11	2.29	2.42	2.82
PG40	25% PS	30% GGBS	2.09	2.25	2.36	2.76
PG41	30% PS	30% GGBS	2.01	2.22	2.33	2.78
PG42	40% PS	30% GGBS	1.96	2.20	2.30	2.67
PG43	5% PS	40% GGBS	1.86	2.14	2.38	2.52
PG44	10% PS	40% GGBS	1.95	2.19	2.41	2.59
PG45	15% PS	40% GGBS	2.11	2.27	2.52	2.82
PG46	20% PS	40% GGBS	2.01	2.17	2.29	2.67
PG47	25% PS	40% GGBS	1.98	2.13	2.24	2.62
PG48	30% PS	40% GGBS	1.91	2.10	2.21	2.64
PG49	40% PS	50% GGBS	1.86	2.09	2.18	2.53
PG50	5% PS	50% GGBS	1.71	1.97	2.20	2.32
PG51	10% PS	50% GGBS	1.80	2.02	2.22	2.39
PG52	15% PS	50% GGBS	1.95	2.09	2.33	2.60
PG53	20% PS	50% GGBS	1.85	2.00	2.12	2.47
PG54	25% PS	50% GGBS	1.83	1.97	2.07	2.42
PG55	30% PS	50% GGBS	1.76	1.94	2.04	2.43
PG56	40% PS	50% GGBS	1.72	1.92	2.01	2.33

5.3.7 Flexural Strength of PRCM by GGBS added concrete

The flexural strength test has been carried out and the results were compared with the control concrete (Fig.5.23 and 5.24). The flexural strength of GGBS added concrete for the Mix ID G3 to G8 are increased by 1.8%, 2.8%, 4.3%, 5.2%, 9.9% and 0.2% at 28 days of curing. Further, the optimum percentage of 40% GGBS replacement for cement provides better results when compared with all other test mixtures, including control concrete at 7, 28, 60 and 90 days of curing.

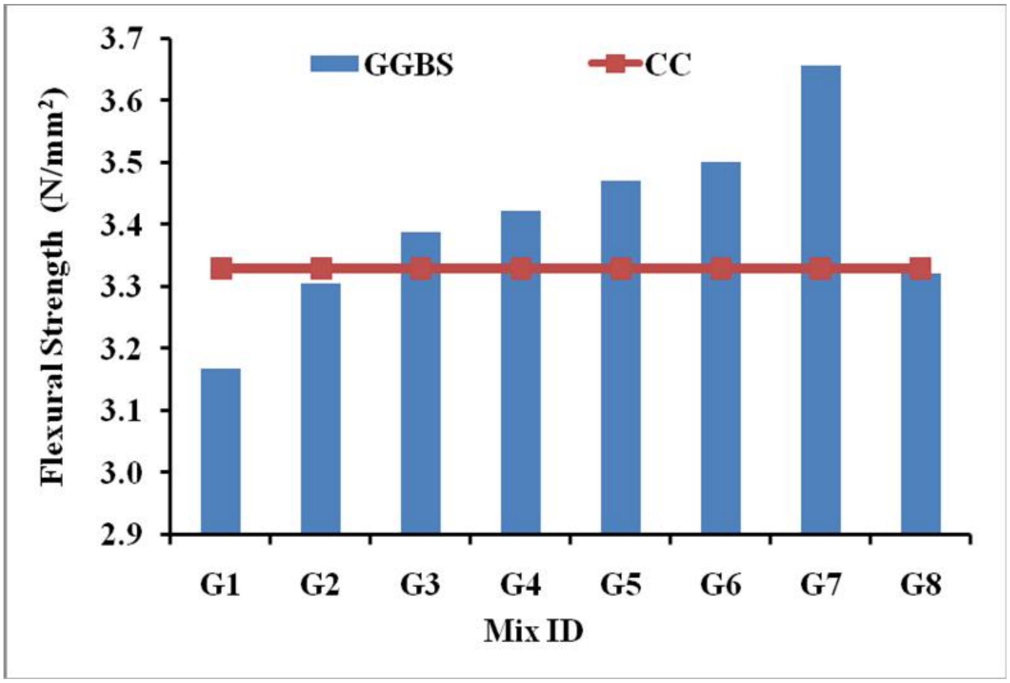


Figure 5.23 Flexural strength of control concrete and PRCM by GGBS added concrete at 28 days of curing

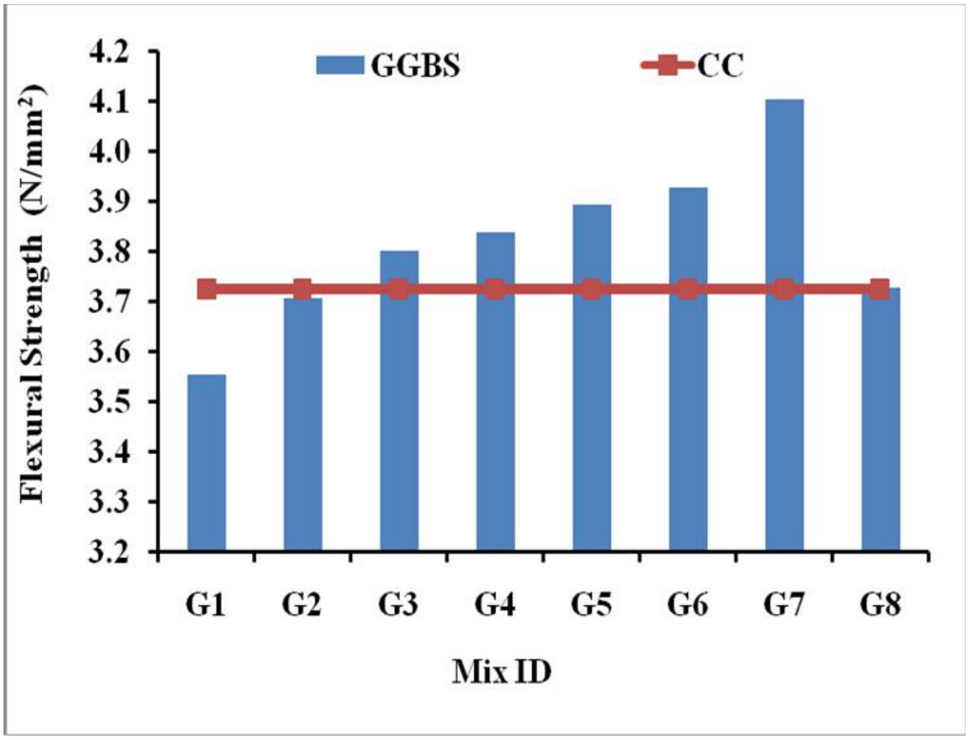


Figure 5.24 Flexural strength of control concrete and PRCM by GGBS added concrete at 90 days of curing

The presence of GGBS in concrete results in a denser microstructure that improves the flexural strength. GGBS has a high percentage of calcium silicate hydrates relative to Portland cement concrete. Figure 5.23 and 5.24 shows the flexural strength test results of GGBS added concrete tested at the age of 28 days and 90 days curing period, respectively.

5.3.8 Flexural Strength of PRCM by PS added concrete

Flexural strength of the PRCM by PS is performed at various self curing days and are shown in Table 5.15 and Figure 5.25, 5.26. The variations of flexural strength noted for the Mix ID's P1 to P7 are -1.3%, 1.1%, 2.6%, 5.0%, 8.7%, 4.5% and -1.2%, respectively, at the age of 28 days (self-curing). In addition, the improved flexural strength is observed for Mix ID, P1 to P7 are 5.5%, 8.5%, 9.1%, 12.0%, 15.2%, 10.5% and 2.9%, respectively, at the age of 90 days (self-curing) when compared with control concrete. Based on the compressive strength values optimum proportion was found to be 25% replacement level of PS. The results showed that, it was possible to obtain a flexural strength of 3.58 N/mm^2 after 28 days. PS added concrete performs better result in self curing due to the presents of moisture in the concrete pores decrease the flexural strength in the early age.

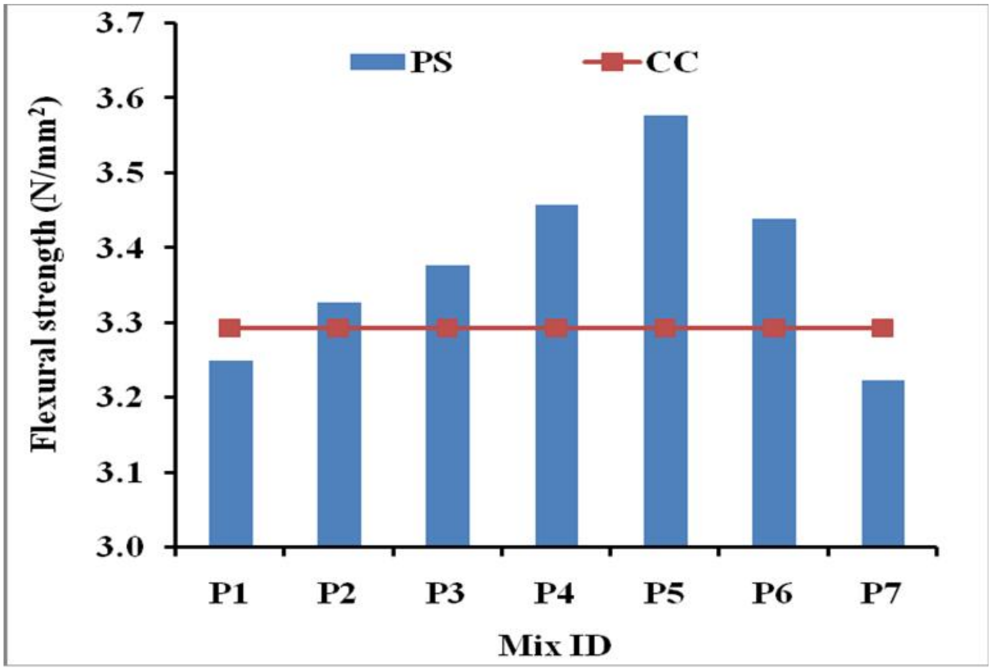


Figure 5.25 **Flexural strength of control concrete and PCRM by PS added concrete at 28 days of curing**

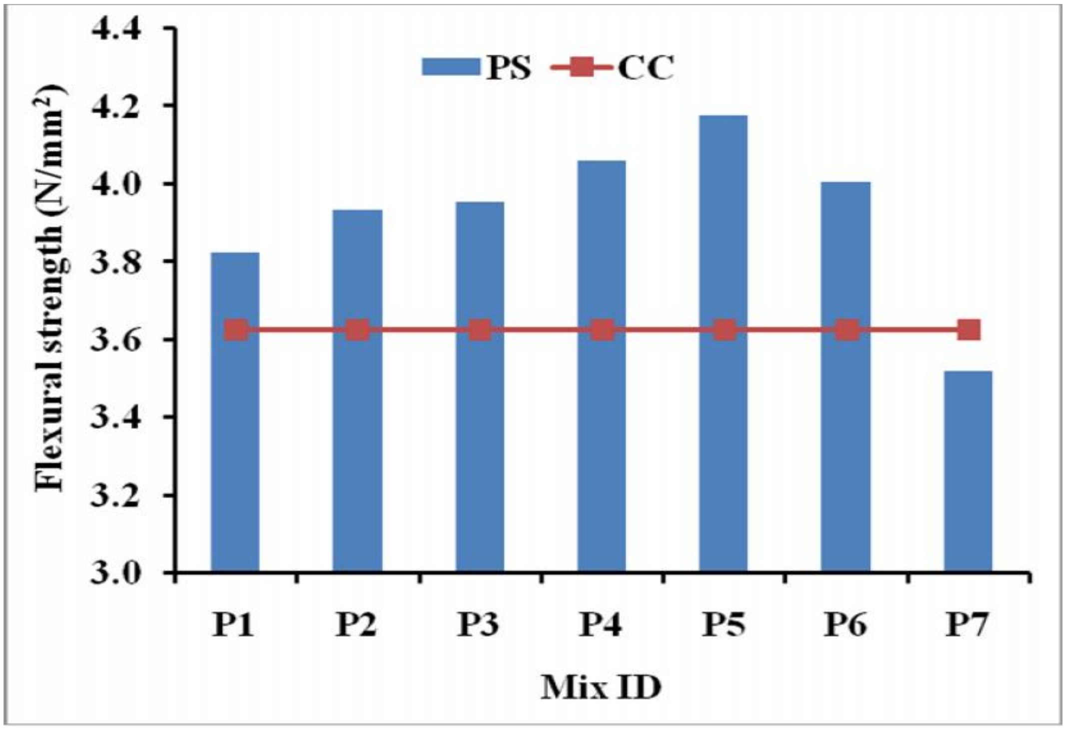


Figure 5.26 Flexural strength of control concrete and PRCM by PS added concrete at 90 days of curing

5.3.9 Flexural Strength of PRCM by PS with GGBS Added concrete

The flexural strength of PRCM of PS with GGBS for various dosages are carried out for different self-curing days (7, 28, 60 and 90). The flexural strength of Mix ID, PG1-PG56 and control concrete is shown in Table 5.15. The Mix ID, PG31 has achieved maximum flexural strength 3.7%, 7.2%, 8.7%, 13.6% (7, 28, 60 and 90 days) compared to control concrete. On the other hand, looking at results of 40% of GGBS, 25% of PS and 15% of PS with 25% of GGBS of PRCM concrete mixes, there is an increase in the flexural strength compared to control concrete is also noted. Additionally, for 40% PRCM of GGBS, flexural strength are increased to 9.61%, 9.84%, 9.94%, 10.14% and 25% of PS 7.92%, 8.69%, 9.60%, 13.60% and 15% PS with 25% of GGBS 3.74%, 7.21%, 8.66%, 13.56% over to control concrete. The results noted clearly revealed that, flexural strength of mixture of PS with GGBS gradually increased over to control concrete and is shown in Figure 5.27.

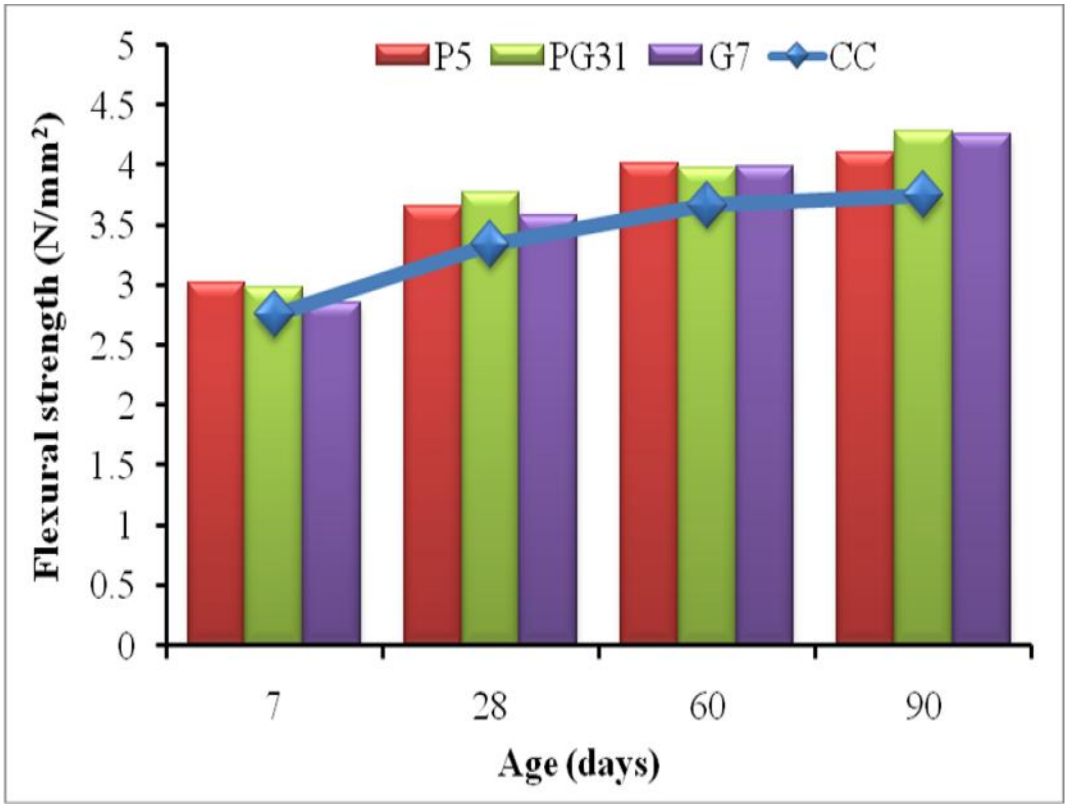


Figure 5.27 Flexural strength of PRCM by GGBS, PS and control concrete at different curing days

Table 5.15 Flexural strength of PRCM by GGBS, PS and control concrete at different curing days

Mix ID	PRCM (weight of cement)		Flexural strength (N/mm^2)			
			7 days	28 days	60 days	90 days
CC	0%		2.76	3.33	3.66	3.73
G1	5% GGBS		2.62	3.17	3.48	3.55
G2	10% GGBS		2.73	3.31	3.63	3.71
G3	15% GGBS		2.80	3.39	3.73	3.80
G4	20% GGBS		2.83	3.42	3.76	3.84
G5	25% GGBS		2.87	3.47	3.82	3.89
G6	30% GGBS		2.89	3.50	3.85	3.93
G7	**40% GGBS**		**3.02**	**3.66**	**4.02**	**4.10**
G8	50% GGBS		2.74	3.32	3.65	3.73
P1	5% PS		2.82	3.25	3.62	3.82
P2	10% PS		2.96	3.33	3.66	3.93
P3	15% PS		3.06	3.38	3.69	3.95
P4	20% PS		3.16	3.46	3.74	4.06
P5	**25% PS**		**3.31**	**3.58**	**3.79**	**4.18**
P6	30% PS		3.13	3.44	3.58	4.01
P7	40% PS		2.96	3.22	3.36	3.52
PG1	5% PS	5% GGBS	2.06	2.38	2.65	2.79
PG2	10% PS	5% GGBS	2.16	2.43	2.68	2.87
PG3	15% PS	5% GGBS	2.30	2.47	2.75	3.07
PG4	20% PS	5% GGBS	2.31	2.43	2.55	2.97
PG5	25% PS	5% GGBS	2.29	2.37	2.49	2.91
PG6	30% PS	5% GGBS	2.29	2.34	2.45	2.93
PG7	40% PS	5% GGBS	2.19	2.32	2.42	2.81
PG8	5% PS	10% GGBS	2.36	2.72	3.03	3.20
PG9	10% PS	10% GGBS	2.48	2.79	3.06	3.29

Table 5.15 (Continued)

Mix ID	PRCM (weight of cement)		Flexural strength (N/mm^2)			
			7 days	28 days	60 days	90 days
PG10	15% PS	10% GGBS	2.63	2.83	3.15	3.52
PG11	20% PS	10% GGBS	2.55	2.78	2.92	3.40
PG12	25% PS	10% GGBS	2.52	2.71	2.85	3.34
PG13	30% PS	10% GGBS	2.43	2.68	2.81	3.35
PG14	40% PS	10% GGBS	2.37	2.65	2.77	3.22
PG15	5% PS	15% GGBS	2.56	2.95	3.29	3.47
PG16	10% PS	15% GGBS	2.69	3.02	3.33	3.57
PG17	15% PS	15% GGBS	2.89	3.11	3.46	3.87
PG18	20% PS	15% GGBS	2.66	2.90	3.05	3.55
PG19	25% PS	15% GGBS	2.63	2.83	2.98	3.48
PG20	30% PS	15% GGBS	2.54	2.79	2.93	3.50
PG21	40% PS	15% GGBS	2.47	2.77	2.89	3.36
PG22	5% PS	20% GGBS	2.64	3.04	3.38	3.57
PG23	10% PS	20% GGBS	2.77	3.11	3.42	3.68
PG24	15% PS	20% GGBS	3.03	3.26	3.63	4.06
PG25	20% PS	20% GGBS	2.74	2.99	3.14	3.65
PG26	25% PS	20% GGBS	2.70	2.91	3.06	3.58
PG27	30% PS	20% GGBS	2.61	2.88	3.02	3.61
PG28	40% PS	25% GGBS	2.54	2.85	2.98	3.46
PG29	5% PS	25% GGBS	2.71	3.13	3.55	3.68
PG30	10% PS	25% GGBS	2.78	3.21	3.59	3.79
PG31	**15% PS**	**25% GGBS**	**2.86**	**3.58**	**3.99**	**4.25**
PG32	20% PS	25% GGBS	2.86	3.12	3.33	3.81
PG33	25% PS	25% GGBS	2.82	3.04	3.26	3.74
PG34	30% PS	25% GGBS	2.72	3.00	3.21	3.76

Table 5.15 (Continued)

Mix ID	PRCM (weight of cement)		Flexural strength (N/mm^2)			
			7 days	28 days	60 days	90 days
PG35	40% PS	25% GGBS	2.65	2.97	3.16	3.61
PG36	5% PS	30% GGBS	2.45	2.82	3.14	3.31
PG37	10% PS	30% GGBS	2.57	2.89	3.18	3.41
PG38	15% PS	30% GGBS	2.78	2.99	3.33	3.71
PG39	20% PS	30% GGBS	2.64	2.86	3.02	3.52
PG40	25% PS	30% GGBS	2.61	2.81	2.95	3.46
PG41	30% PS	30% GGBS	2.52	2.77	2.91	3.48
PG42	40% PS	30% GGBS	2.45	2.75	2.87	3.33
PG43	5% PS	40% GGBS	2.32	2.67	2.98	3.14
PG44	10% PS	40% GGBS	2.44	2.74	3.01	3.24
PG45	15% PS	40% GGBS	2.64	2.83	3.16	3.52
PG46	20% PS	40% GGBS	2.51	2.71	2.87	3.34
PG47	25% PS	40% GGBS	2.47	2.67	2.80	3.28
PG48	30% PS	40% GGBS	2.39	2.63	2.76	3.30
PG49	40% PS	50% GGBS	2.33	2.61	2.72	3.16
PG50	5% PS	50% GGBS	2.14	2.47	2.75	2.90
PG51	10% PS	50% GGBS	2.25	2.53	2.78	2.99
PG52	15% PS	50% GGBS	2.43	2.61	2.91	3.25
PG53	20% PS	50% GGBS	2.31	2.50	2.65	3.08
PG54	25% PS	50% GGBS	2.28	2.46	2.59	3.02
PG55	30% PS	50% GGBS	2.20	2.43	2.55	3.04
PG56	40% PS	50% GGBS	2.15	2.40	2.51	2.92

The relationship between split tensile strength and compressive strength for PRCM with GGBS concrete is obtained as y=0.0468x+1.4264 (R^2=0.9816) at 28 days and y= 0.0424x+1.5914 (R^2=0.9783), at 90 days and are closely related with each other (Figure 5.28 and 5.29). In addition, the obtained results of the present investigation were plotted to verify the relation between flexural strength and compressive strength at the age of 28 and 90 days and are shown in Figure 5.30 and 5.31. The regression coefficient of PRCM concrete mixes with 5%, 10%, 15%, 25%, 30%, 40% and 50% GGBS for flexural strength and compressive strength were closely related. From the Figure 5.30 and 5.31, it was noted that, the regression coefficient of the strength of concrete in terms of flexural strength and compressive strength are obtained as y= 0.0584x+1.7861 (R^2=0.9803) at 28 days and y= 0.0533x+1.9791 (R^2=0.9825) at 90 days. The obtained values are very close to each other.

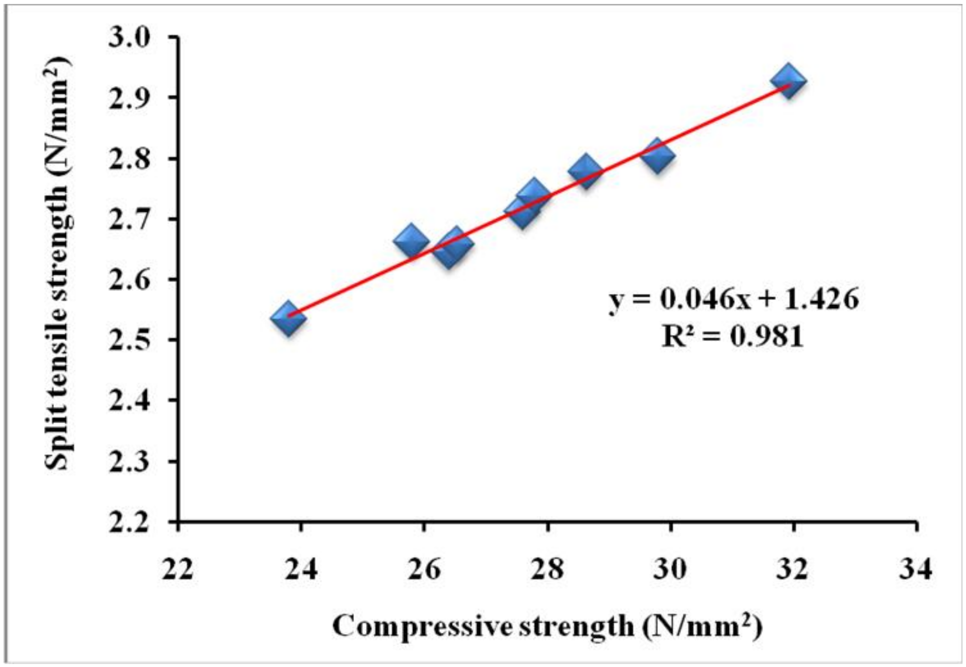


Figure 5.28 Relationship between compressive strength and split tensile strength of PRCM by GGBS added concrete at 28 days

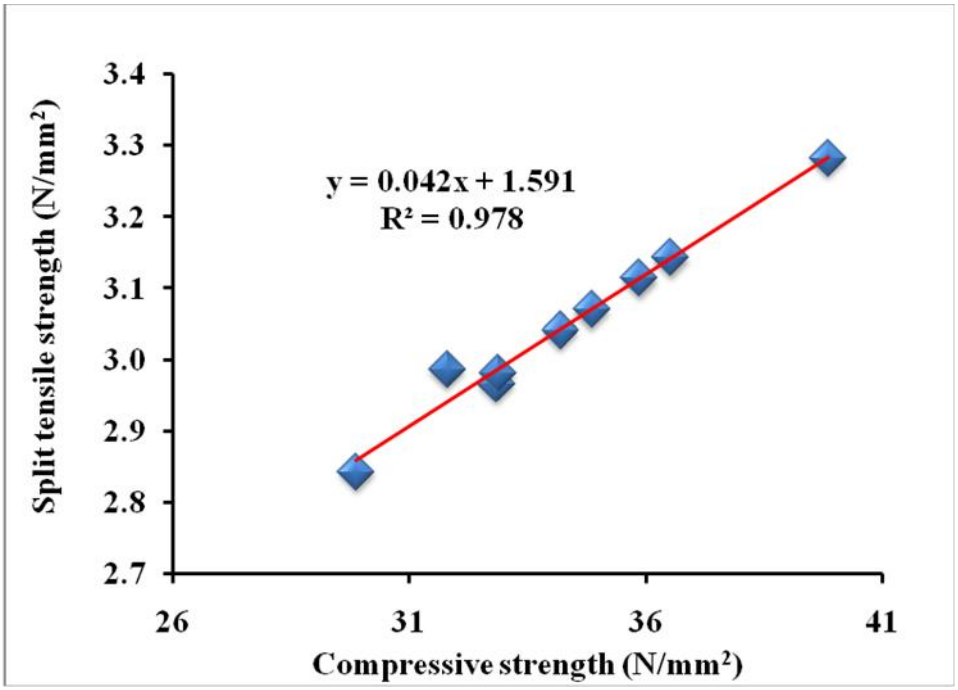


Figure 5.29 **Relationship between compressive strength and split tensile strength of PRCM by GGBS added concrete at 90 days**

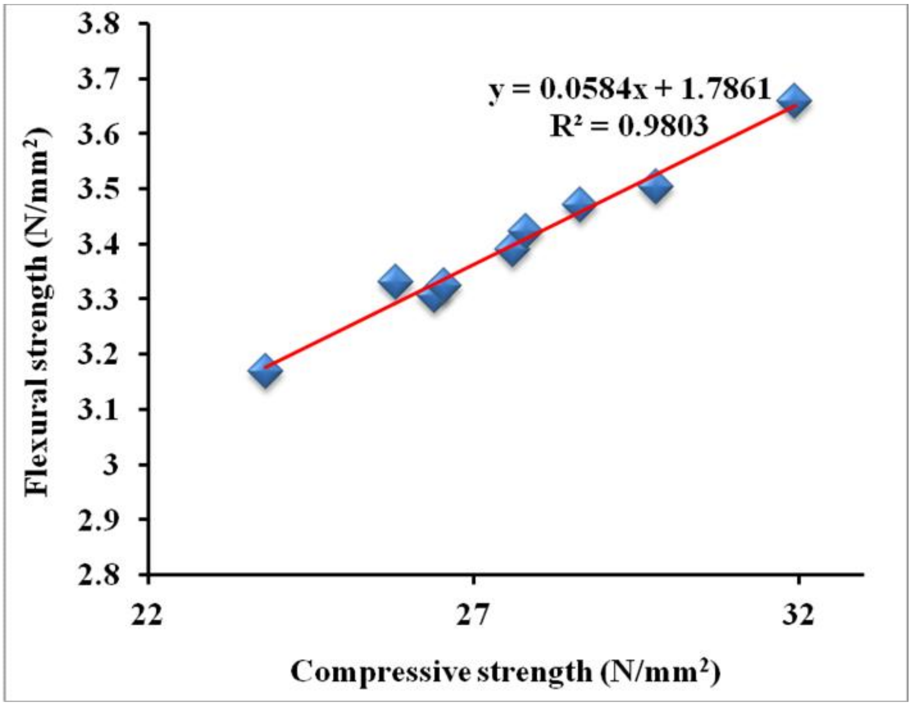


Figure 5.30 **Relationship between compressive strength and flexural strength of PRCM by GGBS added concrete at 28 days**

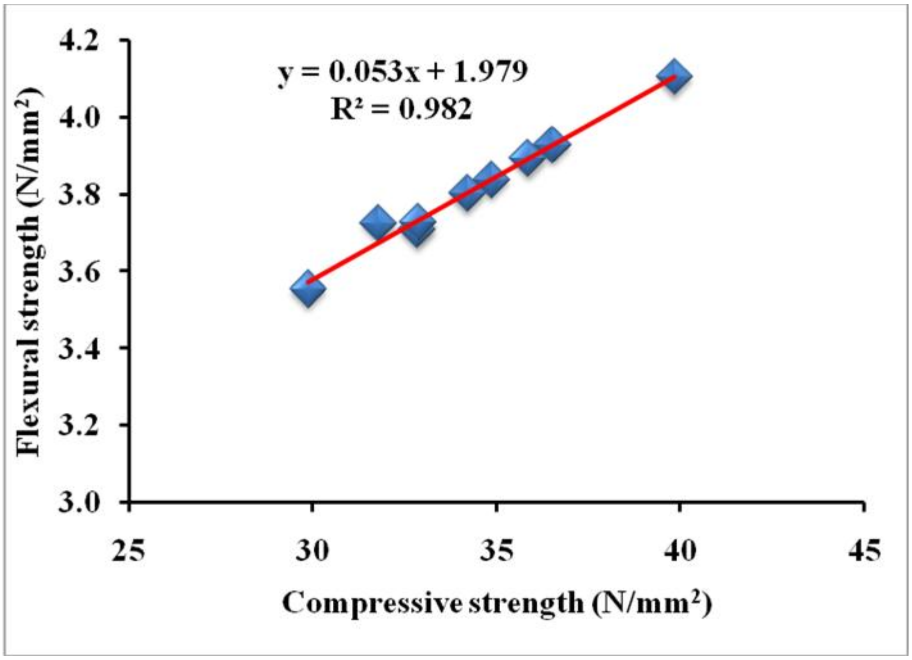


Figure 5.31 Relationship between compressive strength and flexural strength of GGBS added concrete at 90 days

Relationship between the strength properties of PRCM by 5%, 10%, 15%, 25%, 30% and 40% PS added concrete

The relationship between split tensile strength and compressive strength of PRCM by PS added concrete are obtained as y= 0.0484x+1.3961 (R^2=0.9864) at 28 days and y= 0.0415x+1.6292 (R^2=0.9829) at 90 days which were found to have very close relationship (Figure 5.32 and 5.33). Also, the results of the present study are plotted for flexural strength and compressive strength of concrete specimens for 28 and 90 days of curing and are shown in Figure 5.34 and 5.35. The regression coefficient of flexural strength and compressive strength were closely related to all the test specimens investigated in the present study and the equations are obtained as y= 0.0626x+1.6844 (R^2=0.9992) at 28 days and y= 0.0566x+1.854 (R^2=0.9964) at 90 days, respectively.

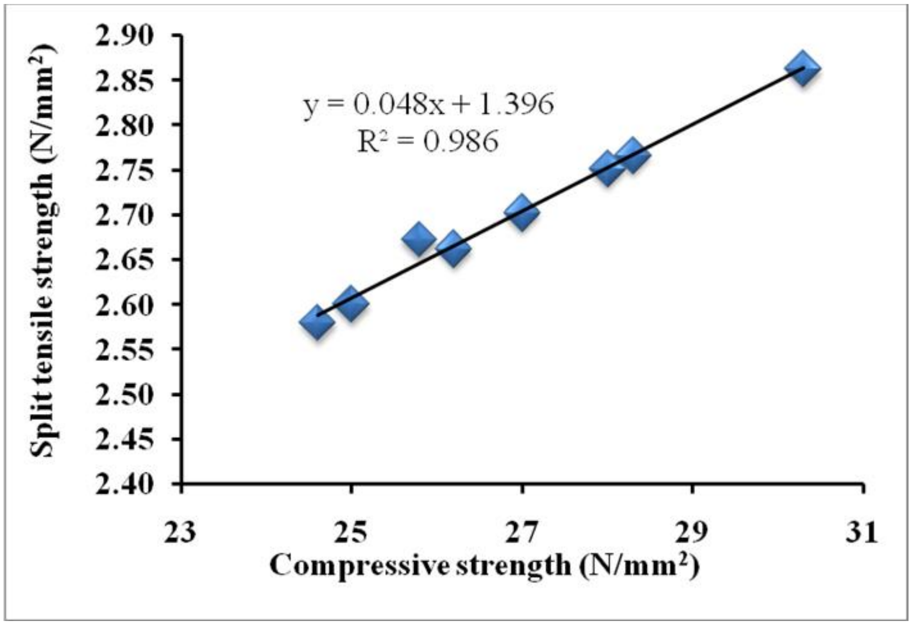


Figure 5.32 Relationship between compressive strength and Split tensile strength of PRCM by PS added concrete at 28 days

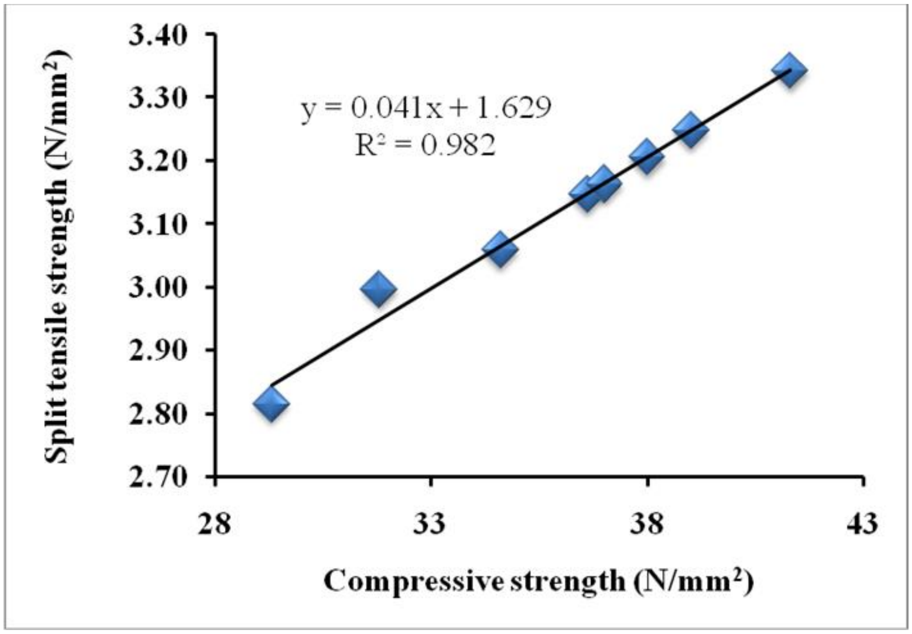


Figure 5.33 Relationship between compressive strength and Split tensile strength of PRCM by PS added concrete at 90 days

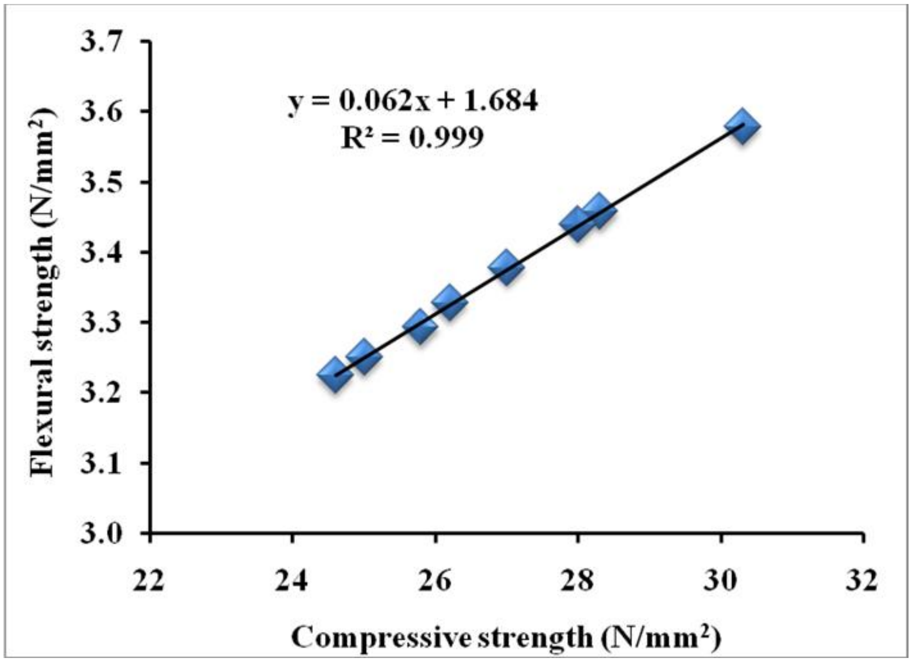


Figure 5.34 Relationship between compressive strength and Flexural strength of PRCM by PS added concrete at 28 days

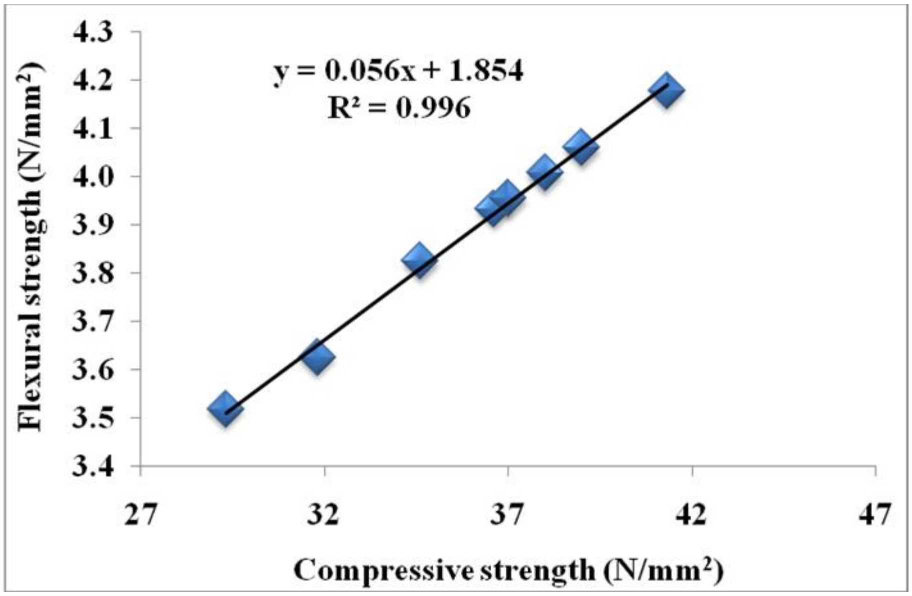


Figure 5.35 Relationship between compressive strength and Flexural strength of PS added concrete at 90 days

Relationship between the strength properties of PRCM by PS with GGBS (15% of PS with 25% of GGBS)

The PRCM by PS with GGBS added concrete of Mix ID PG31 have obtained maximum strength and the relationship between compressive strength, split tensile strength and flexural strength are shown in Figure 5.36, 5.37, 5.38 and 5.39. It is apparent from Figure 5.36 and 5.37 that, the regression coefficient values derived for establishing the relationships between split tensile strength and compressive strength are observed as $y= 0.0522x+1.3285$ (R^2=0.6727) for 28 days $y= 0.0337x+1.9729$ (R^2=0.8592) for 90 days. Further examination of the figure showed that both the split tensile strength and the compressive strength were closely related after a prolonged curing time, although they were not related to each other at an early stage.

Similarly, it is understandable from Figure 5.38 and 5.39 that the regression coefficient values derived for establishing the relationship between flexural and compressive strength are observed as y= 0.06041x 0.5263 (R2=0.6906) for 28 days and y= 0.0428x+2.4416 (R2=0.8566) for 90 days respectively. Further, assessment of figure revealed that, at a prolonged curing period, both the flexural strength and compressive strength are closely related whereas at early stage they were not related to one another.

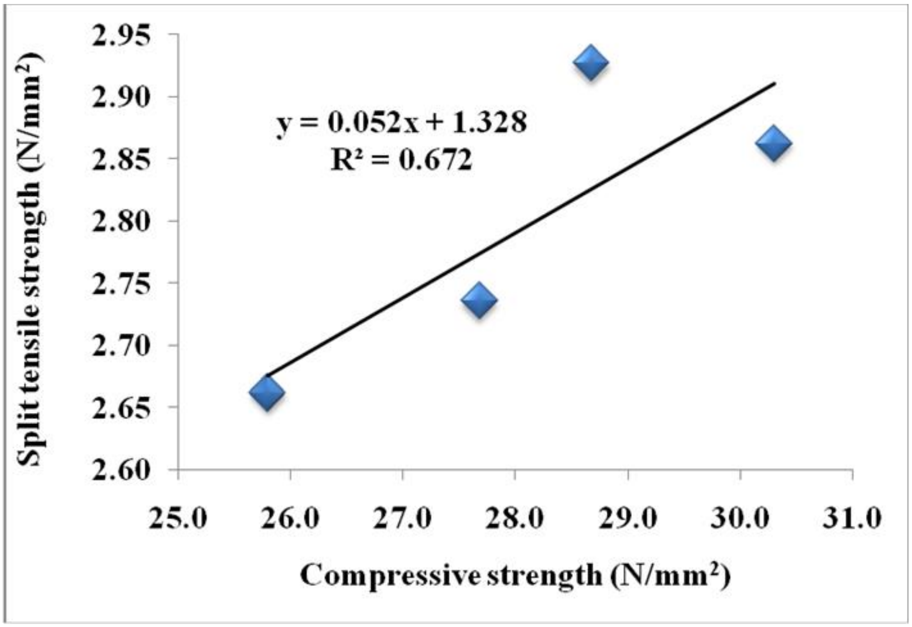


Figure 5.36 Relationship between compressive strength and split tensile strength of PRCM added concrete at 28 days

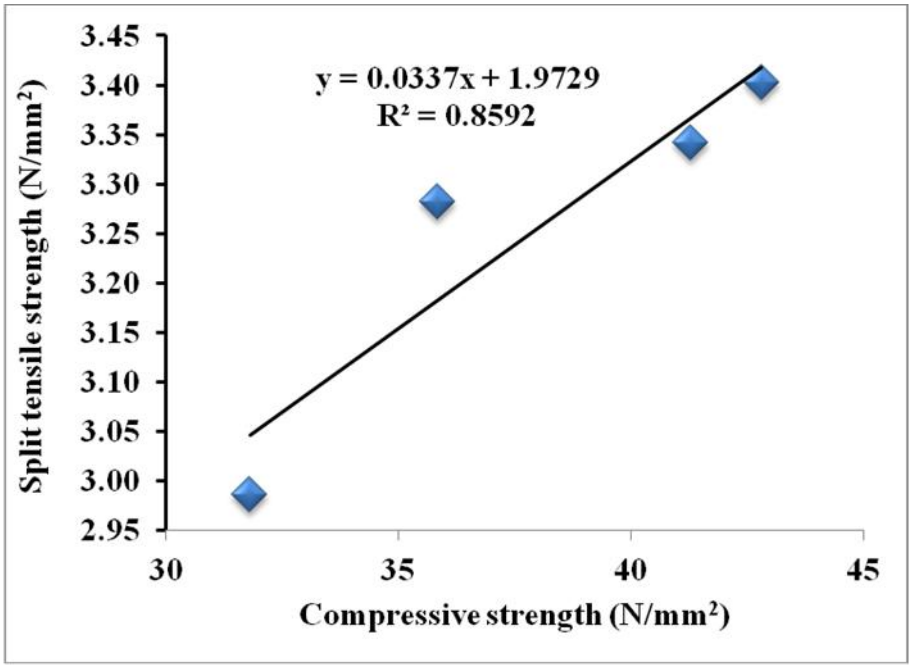


Figure 5.37 Relationship between compressive strength and split tensile strength of PRCM added concrete at 90 days

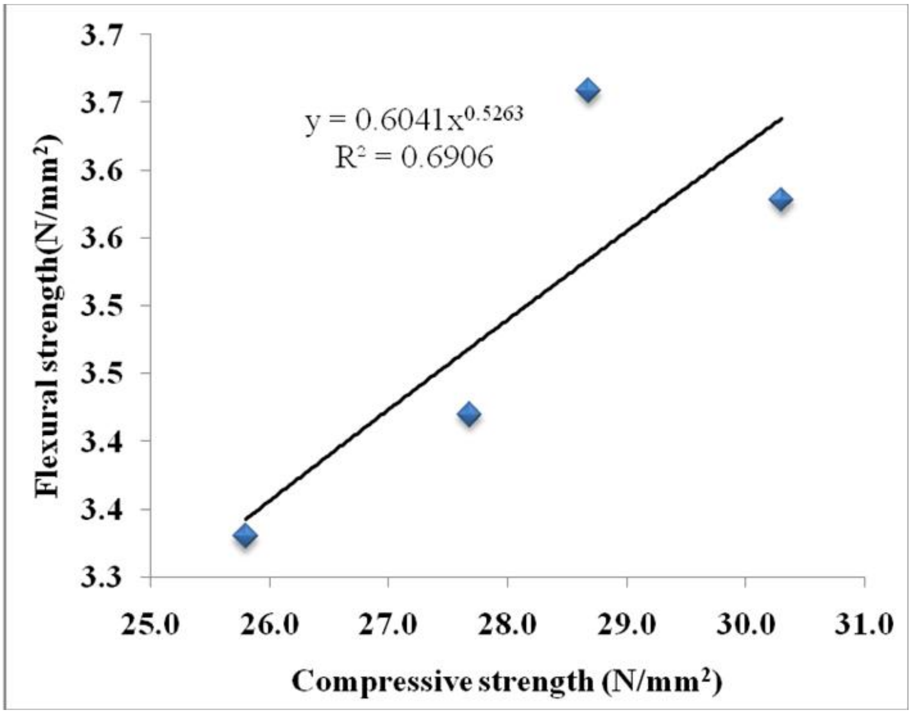


Figure 5.38 Relationship between compressive strength and Flexural strength of PRCM added concrete at 28 days

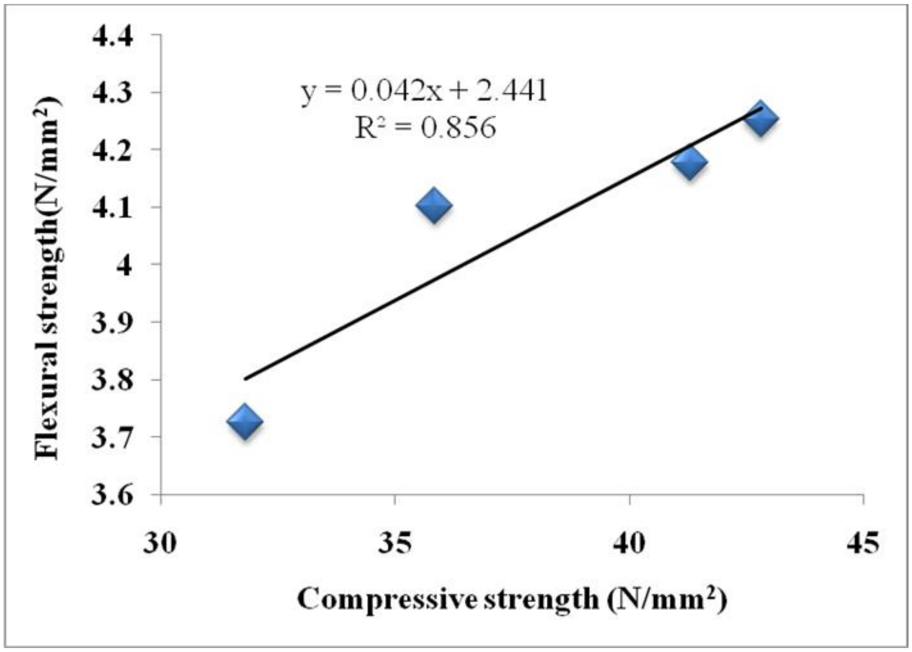


Figure 5.39 Relationship between compressive strength and Flexural strength of PRCM added concrete at 90 days

5.4 WATER ABSORPTION OF PRCM BY GGBS, PS and GGBS WITH PS ADDED CONCRETE

Water absorption was measured in order to determine whether there was a rise in the pore space of the mortar attributable to weathering result of exposure to silage waste. The water absorption of GGBS added concrete for cement replacement from 0 to 50% by weight of cement for 28 days has been carried out and listed in Table 5.16. The water absorption of the concrete Mix ID of G1, G2, G3, G4, G5, G6, G7 and G8 (5%, 10%, 15%, 20%, 25%, 30%, 40%, 50% of GGBS) has decreased by 6.92%, 16.26%, 19.90%, 24.76%, 34.47%, 36.89%, 42.96% and 49.08%, respectively when compared with control concrete. From the Table 5.16, it is clearly evident that the increase of GGBS percentage, decreased the water absorption and the same has been graphically represented in Figure 5.40.

Similarly, after 28 days water absorption of self curing PS mixes P1, P2, P3, P4, P5, P6 and P7 (5%, 10%, 15%, 20%, 25%, 30% and 40% of PS for cement replacement of the concrete) has been increased by 5.58%, 12.86%, 15.29%, 14.08%, 20.15%, 16.5% and 5.58% respectively, when compared to control concrete. The water absorption of the Mix ID, P1 to P7 is listed in Table 5.17 the same has been graphically represented in Figure 5.41. In addition, water absorption for various specimens casted using PRCM by PS with GGBS added concrete (Mix ID PG1 to PG56) for 28 days has also been obtained and given in Table 5.18. Of all the above mixes, specimen with Mix ID PG31 (15% of PS and 25% of GGBS) showed the maximum percentages of water absorption as 26.8%, compared with control concrete and are given in Table 5.18, the water absorption percentage of control concrete with optimum percentage of PRCM by GGBS and PS added concrete were compared and the same has been graphically represented in Figure 5.42.

Table 5.16 Average water absorption percentage at 28 days for PRCM by GGBS added concrete

Mix ID	% of PRCM by GGBS	Dry Weight (kg)	Wet Weight (kg)	% of Water absorption	% increase water absorption compared to control concrete
CC	0	927.4	935.6	0.89	0.00
G1	5	918.6	926.3	0.83	-6.92
G2	10	922.4	929.3	0.75	-16.26
G3	15	924.2	930.8	0.71	-19.90
G4	20	923.4	929.6	0.67	-24.76
G5	25	924.8	930.2	0.58	-34.47
G6	30	923.4	928.6	0.56	-36.89
G7	40	926.5	931.2	0.51	-42.96
G8	50	921.9	926.1	0.46	-49.03

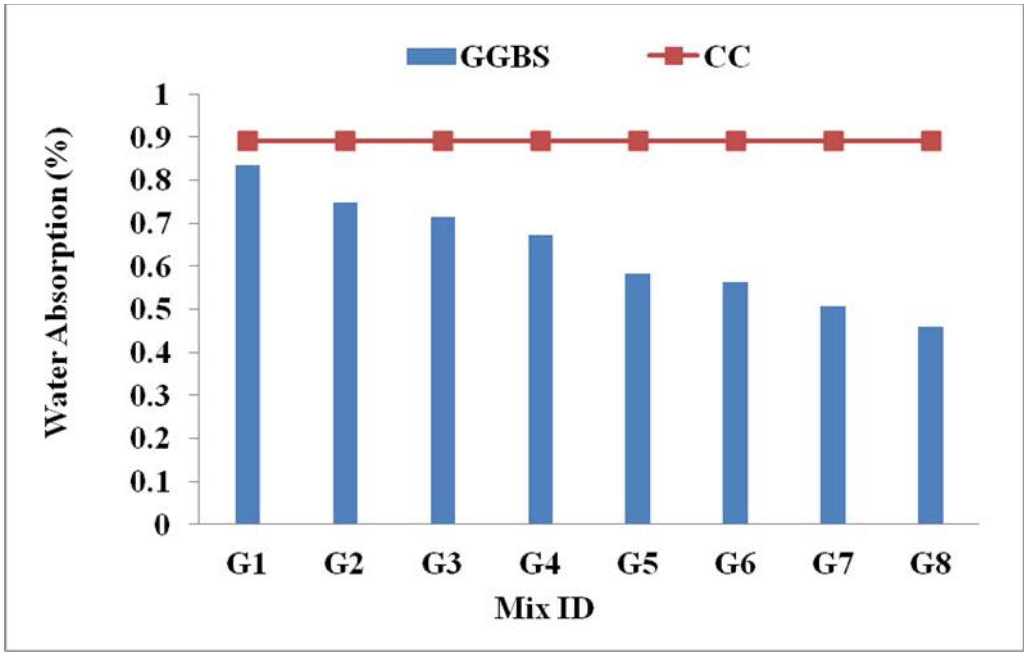


Figure 5.40 Water absorption of control concrete and GGBS added concrete at 28 days

Table 5.17 Average water absorption percentage at 28 days for PRCM by PS added concrete

Mix ID	% of PRCM by PS	Dry Weight (kg)	Wet Weight (kg)	% of Water absorption	% increase water absorption compared to control concrete
CC	**0**	**927.4**	**935.6**	**0.89**	**-**
P1	5	926.5	935.2	0.94	5.58
P2	10	924.2	933.5	1.01	12.86
P3	15	918.7	928.2	1.03	15.29
P4	20	916.8	926.2	1.03	14.08
P5	**25**	**915.5**	**925.4**	**1.08**	**20.15**
P6	30	908.6	918.2	1.06	16.5
P7	40	905.7	914.4	0.96	5.58

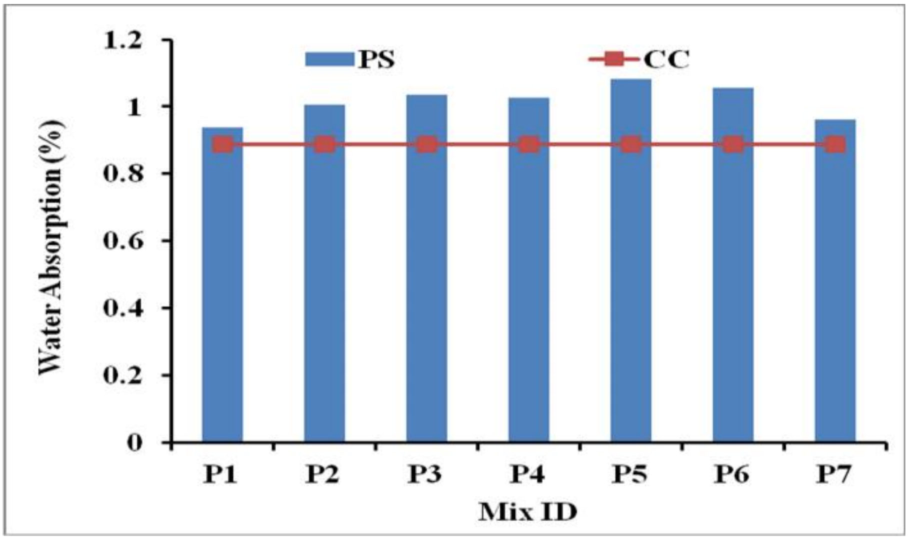


Figure 5.41 Water absorption of control concrete and PRCM by PS added concrete at 28 days

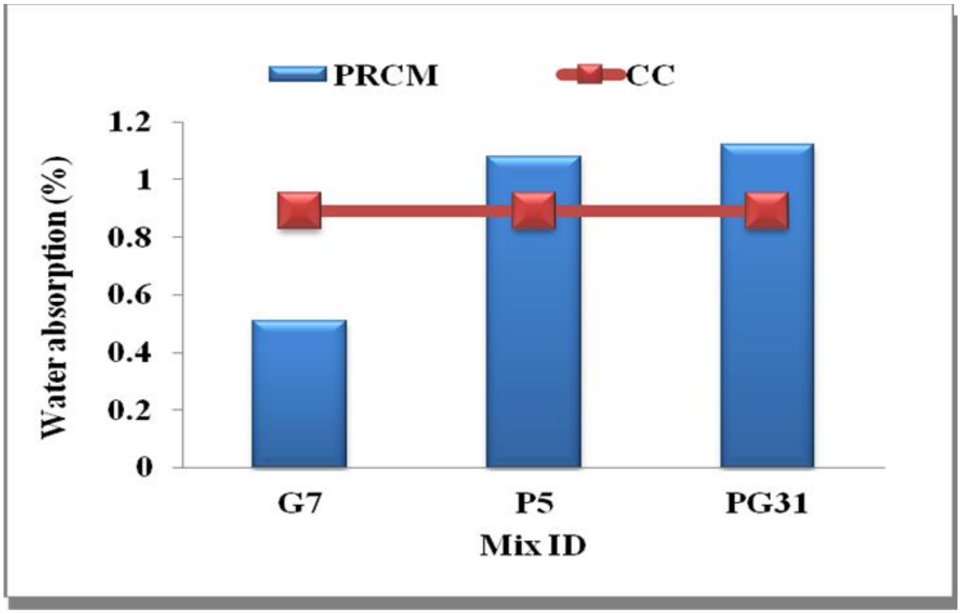


Figure 5.42 Water absorption of control concrete and optimum percentage of PRCM added concrete at 28 days

Table 5.18 Average water absorption percentage at 28 days for PPCM added concrete

Mix ID	% PRCM by PS	% PRCM by GGBS	Dry Weight (kg)	Wet Weight (kg)	% of Water absorption	% increase water absorption compared to control concrete
CC	**0**	**0**	**927.4**	**935.6**	**0.89**	**-**
PG1	5	5	926.5	935.2	0.94	6.1
PG2	10	5	925.6	934.8	0.99	12.2
PG3	15	5	924.8	934.6	1.06	19.5
PG4	20	5	925.2	934.7	1.03	15.9
PG5	25	5	926.5	935.6	0.98	11.0
PG6	30	5	925.6	935.1	1.03	15.9
PG7	40	5	924.5	934.2	1.05	18.3
PG8	5	10	925.6	934.2	0.93	4.9

Table 5.18 (Continued)

Mix ID	% PRCM by PS	% PRCM by GGBS	Dry Weight (kg)	Wet Weight (kg)	% of Water absorption	% increase water absorption compared to control concrete
PG9	10	10	926.7	935.4	0.94	6.1
PG10	15	10	924.8	934.6	1.06	19.5
PG11	20	10	926.2	935.2	0.97	9.8
PG12	25	10	926.5	935.9	1.01	14.6
PG13	30	10	925.6	935.1	1.03	15.9
PG14	40	10	922.5	932.2	1.05	18.3
PG15	5	15	926.2	935.2	0.97	9.8
PG16	10	15	927.4	936.2	0.95	7.3
PG17	15	15	924.8	933.7	0.96	8.5
PG18	20	15	926.2	935.2	0.97	9.8
PG19	25	15	926.4	935.2	0.95	7.3
PG20	30	15	925.6	934.6	0.97	9.8
PG21	40	15	922.8	931.3	0.92	3.7
PG22	5	20	925.2	934.2	0.97	9.8
PG23	10	20	926.4	935.3	0.96	8.5
PG24	15	20	924.8	934.2	1.02	14.6
PG25	20	20	925.2	934.4	0.99	12.2
PG26	25	20	926.4	935.8	1.01	14.6
PG27	30	20	926.2	935.6	1.01	14.6
PG28	40	20	922.4	931.6	1.00	12.2
PG29	5	25	925.2	934.3	0.98	11.0

Table 5.18 (Continued)

Mix ID	% PRCM by PS	% PRCM by GGBS	Dry Weight (kg)	Wet Weight (kg)	% of Water absorption	% increase water absorption compared to control concrete
PG30	10	25	926.4	935.8	1.01	14.6
PG31	**15**	**25**	**925.8**	**936.2**	**1.12**	**26.8**
PG32	20	25	925.2	935.5	1.11	25.6
PG33	25	25	926.4	935.8	1.01	14.6
PG34	30	25	927.2	936.5	1.00	13.4
PG35	40	25	922.6	931.2	0.93	4.9
PG36	5	30	926.2	935.1	0.96	8.5
PG37	10	30	926.4	935.6	0.99	12.2
PG38	15	30	926.9	935.9	0.97	9.8
PG39	20	30	925.4	934.6	0.99	12.2
PG40	25	30	927.4	936.4	0.97	9.8
PG41	30	30	926.5	935.6	0.98	11.0
PG42	40	30	924.6	933.8	1.00	12.2
PG43	5	40	927.2	936.3	0.98	11.0
PG44	10	40	926.6	935.8	0.99	12.2
PG45	15	40	927.9	936.8	0.96	8.5
PG46	20	40	925.4	934.4	0.97	9.8
PG47	25	40	926.4	935.3	0.96	8.5
PG48	30	40	927.6	936.6	0.97	9.8
PG49	40	40	925.6	935.2	1.04	17.1
PG50	5	50	928.2	937.1	0.96	8.5
PG51	10	50	928.4	937.4	0.97	9.8
PG52	15	50	928.9	937.8	0.96	8.5
PG53	20	50	928.4	937.6	0.99	12.2
PG54	25	50	928.8	937.8	0.97	9.8
PG55	30	50	928.6	937.6	0.97	9.8
PG56	40	50	927.6	936.5	0.96	8.5

5.5 SORPTIVITY OF PRCM BY GGBS AND PS ADDED CONCRETE

Sorptivity or capillary suction is the mobility of liquids in porous solids resulted by the surface tension acting in capillaries. It is a function of the viscosity, density in addition to the surface tension of the liquid and also the pore structure (radius) of the porous solid. The cylindrical specimens after casting were immersed in water for 28 days curing. The cylindrical specimens of size 60 mm diameter X 120 mm height cast completely after drying in oven at temperature of 100+10°C were drown with water level not exceeding 5 mm from the base of the specimen and the flow from the peripheral surface is retarded by sealing it properly using non-absorbent coating according to ASTM C1585.

The quantity of water absorbed in a time period of 60 minutes was measured by weighing the specimen on a top pan balance having 0.1 mg accuracy. Surface water on the specimen was wiped off using a dampened tissue and each weighting operation was completed within 30 seconds. Table 5.19 and Figure 5.43 show the obtained sorptivity of PRCM by GGBS concrete and control concrete.

Sorptivity of GGBS concrete exhibited higher sorptivity than that of control concrete. The sorptivity test indicated that, PRCM by GGBS concrete had significantly higher absorption rate, therefore more connected pores, when to compared with control concrete.

It was observed that, the water vapour can escape from the PRCM by GGBS concrete quicker than in control concrete, resulting in lower internal pore pressure. The sorptivity values can be improved by better curing of concrete, which contributes to the continued formation of hydration products for cement concrete. The gel products block the capillaries and pores inside the concrete, hence reducing the movement of fluids through the hardened concrete. At the curing age of 28 days, the sorptivity values of the concrete mix of G1, G2, G3, G4, G5, G6, G7 and G8 (5%, 10%, 15%, 20%, 25%, 30%, 40%, 50% of PRCM by GGBS) are 2.27, 2.28, 2.31, 2.34, 2.28, 2.36, 2.42, and 2.26 (mm/min$^{0.5}$). Figure 5.43 shows the comparison of sorptivity of GGBS and control concrete.

After 28 days of self curing by PS sorptivity values of the mixes P1, P2, P3, P4, P5, P6 and P7 (5%, 10%, 15%, 20%, 25%, 30% and 40% of PRCM by PS) of the concrete are 2.19, 2.35, 2.24, 2.34, 2.34, 2.48 and 2.42 (mm/min$^{0.5}$) than the to control concrete specimen. Figure 5.44 and Table 5.20 showed the comparison of sorptivity of PS and control concrete.

Further, sorpvitity test for various specimens cast using different dosage of PRCM by PS and GGBS (Mix ID PG1 to PG56) have also obtained by self curing method at 28 days and which is given Table 5.19. Of all the above mixes, specimen with Mix ID PG31 (PRCM by15% of PS with 25% of GGBS) shows the maximum sorpvitity value as 2.37 (mm/min$^{0.5}$) and is illustrated in Figure 5.45.

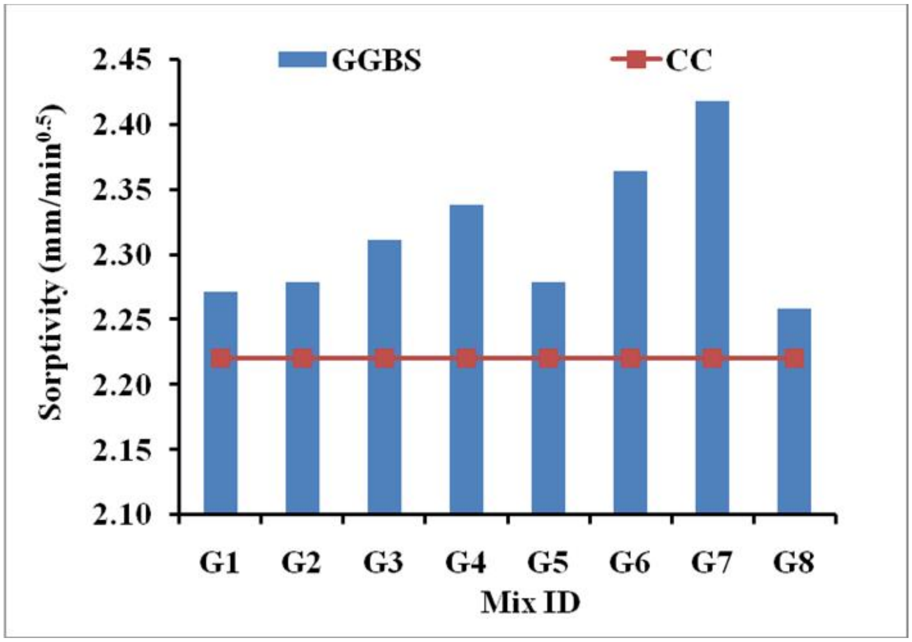


Figure 5.43 Comparison of sorptivity control concrete and PRCM by GGBS added concrete at 28 days

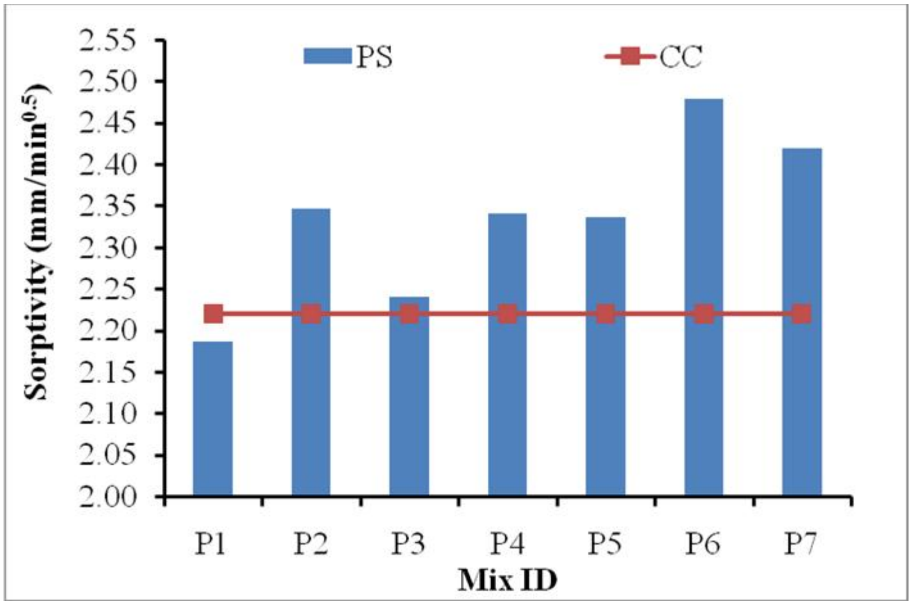


Figure 5.44 Comparison of sorptivity control concrete and PRCM by PS added concrete at 28 days (self curing)

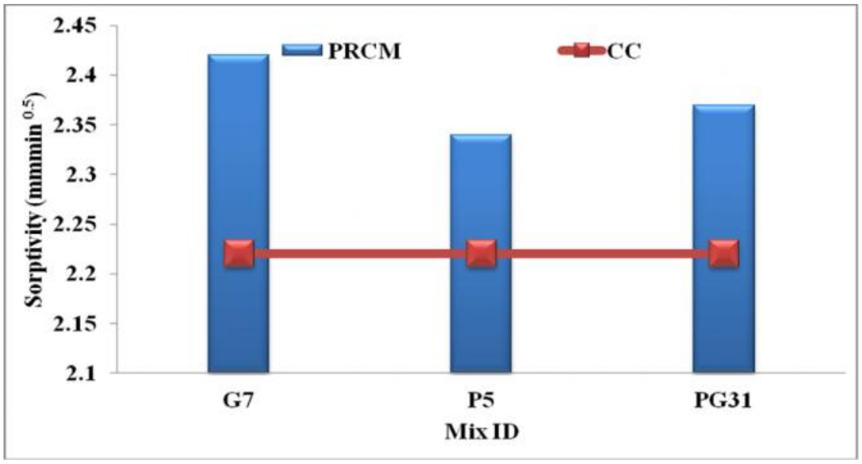


Figure 5.45 Comparison of sorptivity of control concrete and optimum percentage of PRCM by GGBS, PS added concrete at 28 days curing

Table 5.19 Average sorptivity at 28 days of PRCM by GGBS added concrete

Mix ID	**% of PRCM by GGBS**	**Dry Weight (kg)**	**Wet Weight (kg)**	**Sorptivity (mm/min$^{0.5}$)**
CC	**0**	**931.6**	**939.9**	**2.22**
G1	5	922.8	931.4	2.27
G2	10	926.6	935.2	2.28
G3	15	928.4	937.1	2.31
G4	20	927.6	936.4	2.34
G5	25	929.2	937.8	2.28
G6	30	927.6	936.5	2.36
G7	**40**	**928.7**	**937.8**	**2.42**
G8	50	926.1	934.6	2.26

Table 5.20 Average sorptivity at 28 days for PRCM by PS added concrete

Mix ID	**% of PRCM by PS**	**Dry Weight (kg)**	**Wet Weight (kg)**	**Sorptivity (mm/min$^{0.5}$)**
CC	0	927.4	935.6	2.22
P1	5	926.5	935.2	2.19
P2	10	924.2	933.5	2.35
P3	15	918.7	928.2	2.24
P4	20	916.8	926.2	2.34
P5	**25**	**915.5**	**925.4**	**2.34**
P6	30	908.6	918.2	2.48
P7	40	905.7	914.4	2.42

Table 5.21 Average sorptivity at 28 days for PRCM added concrete

Mix ID	**% of PRCM by PS**	**% of PRCM by GGBS**	**Dry Weight (kg)**	**Wet Weight (kg)**	**Sorptivity (mm/min$^{0.5}$)**
CC	0	0	927.4	935.6	2.22
PG1	5%	5%	930.7	939.0	2.19
PG2	10%	5%	929.8	938.4	2.27
PG3	15%	5%	929.6	938.3	2.30
PG4	20%	5%	929.4	938.1	2.29
PG5	25%	5%	930.3	938.9	2.28
PG6	30%	5%	929.8	938.7	2.35
PG7	40%	5%	928.7	937.3	2.27
PG8	5%	10%	929.8	938.2	2.21
PG9	10%	10%	930.9	939.4	2.24
PG10	15%	10%	929.0	937.8	2.34

Table 5.21 (Continued)

Mix ID	**% of PRCM by PS**	**% of PRCM by GGBS**	**Dry Weight (kg)**	**Wet Weight (kg)**	**Sorptivity (mm/min$^{0.5}$)**
PG11	20%	10%	930.4	939.0	2.27
PG12	25%	10%	930.7	939.5	2.32
PG13	30%	10%	929.8	938.6	2.32
PG14	40%	10%	926.7	935.4	2.29
PG15	5%	15%	930.4	938.8	2.21
PG16	10%	15%	931.6	940.4	2.32
PG17	15%	15%	929.3	938.2	2.35
PG18	20%	15%	930.4	939.6	2.43
PG19	25%	15%	930.6	939.8	2.43
PG20	30%	15%	929.8	939.4	2.53
PG21	40%	15%	927.0	935.9	2.35
PG22	5%	20%	929.1	937.8	2.29
PG23	10%	20%	929.4	938.4	2.37
PG24	15%	20%	930.6	939.5	2.36
PG25	20%	20%	930.4	939.2	2.32
PG26	25%	20%	928.6	937.5	2.35
PG27	30%	20%	929.4	938.0	2.27
PG28	40%	20%	930.6	939.4	2.32
PG29	5%	25%	929.6	938.8	2.43
PG30	10%	25%	929.4	938.4	2.37
PG31	**15%**	**25%**	**930.6**	**939.6**	**2.37**
PG32	20%	25%	931.2	939.8	2.28
PG33	25%	25%	926.8	935.5	2.29
PG34	30%	25%	929.4	937.7	2.21

Table 5.21 (Continued)

Mix ID	% of PRCM by PS	% of PRCM by GGBS	Dry Weight (kg)	Wet Weight (kg)	Sorptivity (mm/min$^{0.5}$)
PG35	40%	25%	930.6	939.2	2.27
PG36	5%	30%	931.4	940.2	2.32
PG37	10%	30%	929.6	938.3	2.31
PG38	15%	30%	931.4	939.9	2.26
PG39	20%	30%	931.2	939.9	2.31
PG40	25%	30%	928.8	937.4	2.28
PG41	30%	30%	931.6	939.9	2.19
PG42	40%	30%	930.4	939.2	2.32
PG43	5%	40%	932.1	940.7	2.27
PG44	10%	40%	929.6	938.5	2.35
PG45	15%	40%	930.3	939.0	2.29
PG46	20%	40%	931.8	940.5	2.31
PG47	25%	40%	929.8	938.5	2.29
PG48	30%	40%	931.4	939.7	2.19
PG49	40%	40%	931.4	939.9	2.24
PG50	5%	50%	932.1	941.0	2.35
PG51	10%	50%	931.6	940.2	2.27
PG52	15%	50%	932.6	941.4	2.32
PG53	20%	50%	932.8	941.5	2.31
PG54	25%	50%	931.8	940.4	2.28
PG55	30%	50%	930.7	939.0	2.19
PG56	40%	50%	929.8	938.4	2.27

5.6 RAPID CHLORIDE ION PENETRATION TEST (RCPT)

The rapid chloride ion penetration test for PRCM by GGBS, PS, GGBS with PS and control concrete were carried out on RCPT testing machine (ASTM C1202). For PRCM by GGBS concrete (Mix ID G1 to G8) the charge passed values varies from 1782 Coulombs to 1186 Coulombs which is given in Table 5.22 and Figure 5.46 and whereas PRCM by PS (Mix ID P1 to P7) the charge passed values varies from 1348 Coulombs to 923 Coulombs (Table 5.23 and Figure 5.47).

For Mix ID PG1 to PG7, the charge passed values varied from 1445 Coulombs to 976 Coulombs. For Mix ID PG8 to PG14, the charge passed values varies from 1315 Coulombs to 856 Coulombs. Similarly, For Mix ID PG15 to PG21, the charge passed values varies from 1362 Coulombs to 821 Coulombs.

For Mix ID PG22 to PG28 the charge passed values varied from 1289 Coulombs to 684 Coulombs and for Mix ID PG29 to PG35, the charge passed values varied from 1521 Coulombs to 984 Coulombs. For Mix ID PG36 to PG42 exhibited the variation of the charge passed values from 1562 Coulombs to 1104 Coulombs. For Mix ID PG43 to PG48 the charge passed values varied from 1762 Coulombs to 1143 Coulombs and For Mix ID PG49 to PG56, the charge passed values varied from 1819 Coulombs to 1128 Coulombs which are shown in Table 5.24 and Figure 5.48.

Among all the PRCM by GGBS and PS added concrete, as the replacement level increases, the chloride permeability value decreases which improves the chloride penetration resistance of the concrete and durability of concrete when compared to that of control concrete. PRCM by GGBS and PS added concrete has less chloride permeability than control concrete. The Table 5.24 clearly indicates that, 40% of GGBS, 25% of PS and 25% GGBS with 15% of PS concrete has less chloride permeability when compared to control concrete.

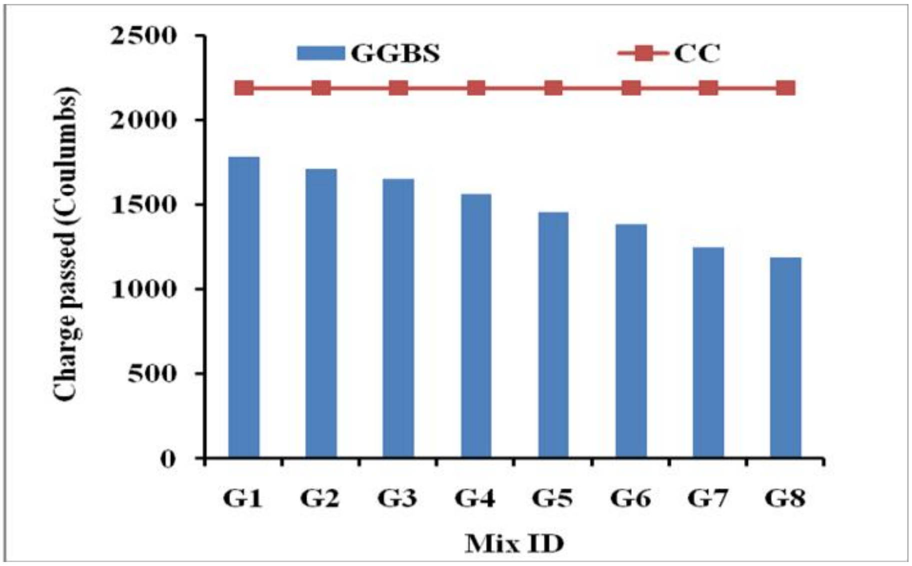


Figure 5.46 Rapid Chloride ion penetrations of control concrete and PRCM by GGBS added concrete at 28 days curing

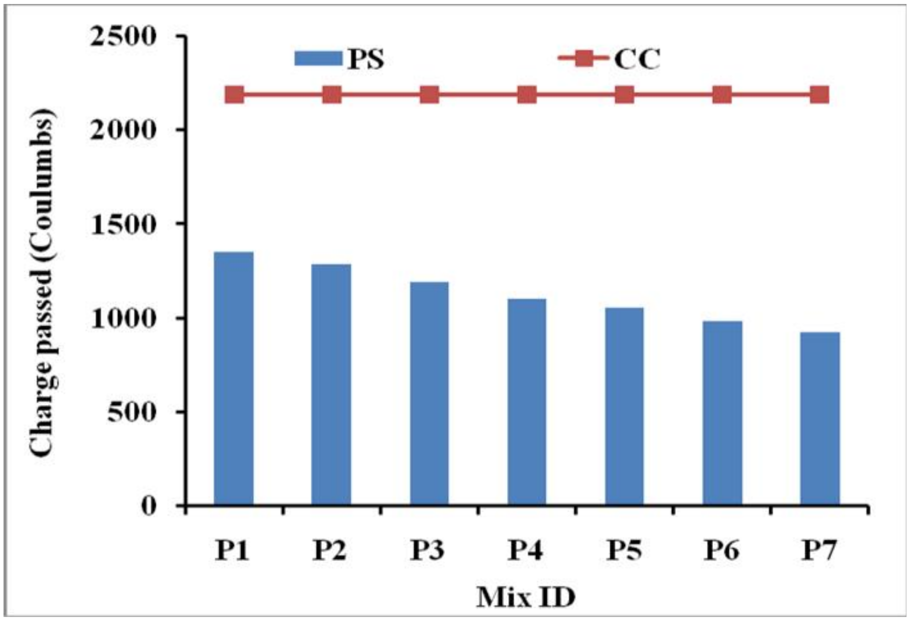


Figure 5.47 Rapid chloride ion penetrations of control concrete and PRCM by PS added concrete at 28 days (self-curing)

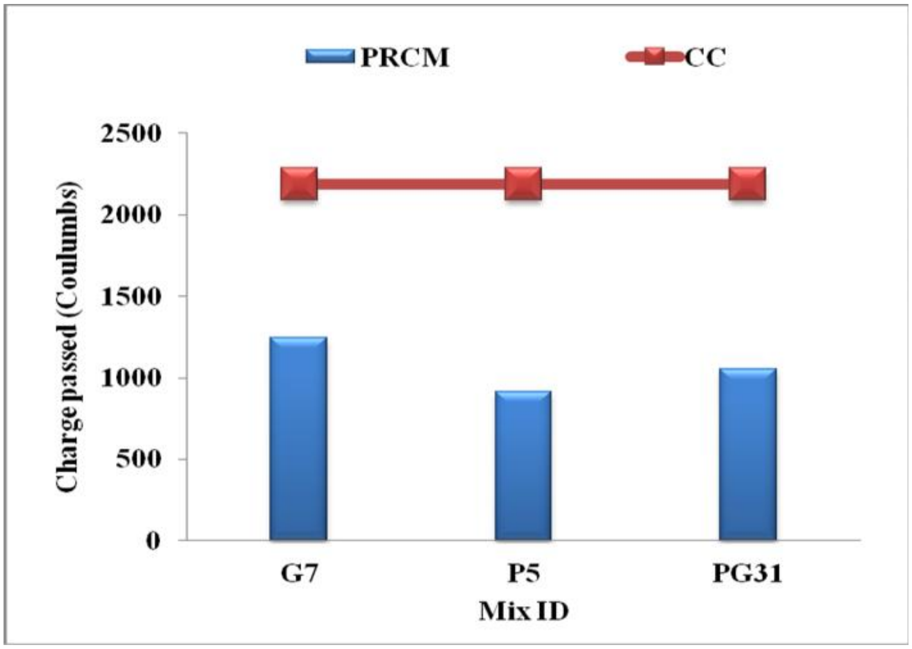


Figure 5.48 RCPT of control concrete and optimum percentage of PRCM by GGBS, PS added concrete at 28 days curing

Table 5.22 RCPT of control concrete and PRCM by GGBS concrete at 28 days of curing

Mix ID	% PRCM by GGBS	RCPT (coulombs)
CC	**0**	**2187.5**
G1	5	1782.8
G2	10	1712.8
G3	15	1652.4
G4	20	1563.8
G5	25	1456.4
G6	30	1382.9
G7	**40**	**1245.6**
G8	50	1386.2

Table 5.23 RCPT of control concrete and PS added concrete at 28 days of self curing

Mix ID	% PRCM by PS	RCPT (coulombs)
CC	0	**2187.5**
P1	5	926.5
P2	10	924.2
P3	15	918.7
P4	20	916.8
P5	**25**	**915.5**
P6	30	908.6
P7	40	905.7

Table 5.24 RCPT of control concrete, PRCM by PS with GGBS added concrete at 28 days of self curing

Mix ID	% PRCM by PS	% PRCM by GGBS	RCPT (coulombs)
CC	**0**	**0**	**2187.5**
PG1	5%	5%	1372.9
PG2	10%	5%	1283.3
PG3	15%	5%	1124.9
PG4	20%	5%	1088.6
PG5	25%	5%	1056.9
PG6	30%	5%	976.5
PG7	40%	5%	1315.8
PG8	5%	10%	1254.8
PG9	10%	10%	1165.9
PG10	15%	10%	1098.2
PG11	20%	10%	987.3
PG12	25%	10%	912.6
PG13	30%	10%	856.9
PG14	40%	10%	1362.6
PG15	5%	15%	1256.9
PG16	10%	15%	1176.3
PG17	15%	15%	1054.8
PG18	20%	15%	985.9
PG19	25%	15%	845.9
PG20	30%	15%	821.7
PG21	40%	15%	1289.6

Table 5.24 (Continued)

PG22	5%	20%	978.2
PG23	10%	20%	882.9
PG24	15%	20%	732.9
PG25	20%	20%	684.8
PG26	25%	20%	1521.7
PG27	30%	20%	1478.2
PG28	40%	20%	1398.4
PG29	5%	25%	1271.4
PG30	10%	25%	1134.9
PG31	**15%**	**25%**	**1052.6**
PG32	20%	25%	984.9
PG33	25%	25%	1652.8
PG34	30%	25%	1562.9
PG35	40%	25%	1452.7
PG36	5%	30%	1372.9
PG37	10%	30%	1285.1
PG38	15%	30%	1182.9
PG39	20%	30%	1104.6
PG40	25%	30%	1762.9
PG41	30%	30%	1678.2
PG42	40%	30%	1572.4
PG43	5%	40%	1452.3
PG44	10%	40%	1268.1
PG45	15%	40%	1182.6
PG46	20%	40%	1143.8
PG47	25%	40%	1819.2

Table 5.24 (Continued)

PG48	30%	40%	1678.3
PG49	40%	40%	1542.6
PG50	5%	50%	1356.9
PG51	10%	50%	1267.3
PG52	15%	50%	1193.5
PG53	20%	50%	1128.3
PG54	25%	50%	1445.6
PG55	30%	50%	1372.9
PG56	40%	50%	1283.3

Relationship between the durability properties of PRCM added concrete GGBS and PS in different dosages

Figures 5.49, 5.51 and 5.53 illustrated the relationship between durability properties viz., water absorption and sorptivity values of the optimum percentage of PRCM of GGBS, PS and GGBS with PS, respectively. From the test results, it is clear that, the water absorption increased with increase in sorptivity. The relationship between water absorption and sorptivity was found to be y=1.808x+0.524, for optimum percentage of PRCM by GGBS concrete y=2.6964x+1.8416, for optimum percentage of PRCM by PS concrete and y=4.062x+0.8945, for optimum percentage of PRCM by PS with GGBS added concrete with most reliable regression coefficient values (0.714, 0.8469 and 0.9021).

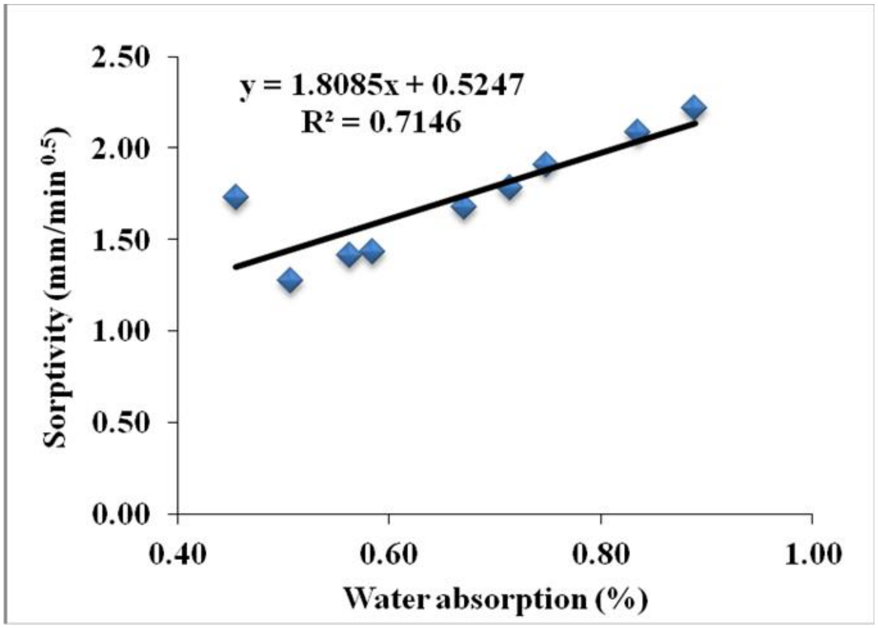


Figure 5.49 Relationship between sorptivity and water absorption of PRCM by GGBS added concrete at 28 days

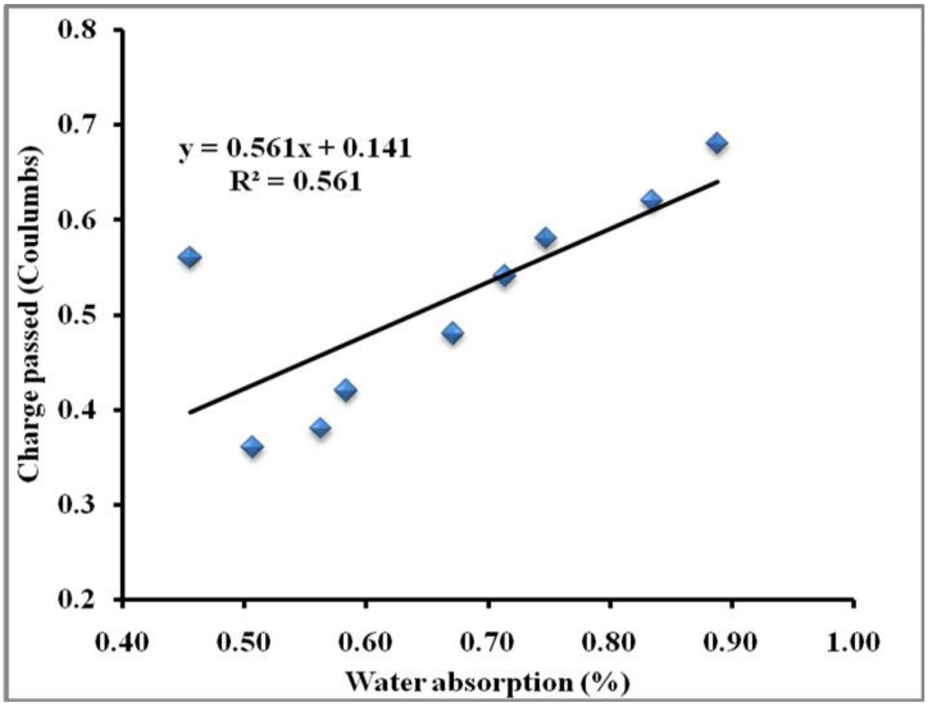


Figure 5.50 Relationship between RCPT and water absorption of PRCM by GGBS added concrete at 28 days

Relationship between water absorption and chloride ion penetration of optimum percentage of PRCM by GGBS, PS and GGBS with PS added concrete in different dosages

Figure 5.50, 5.52 and 5.54 represented the relationship between water absorption and chloride ion penetration of optimum percentage of PRCM by GGBS, PS and GGBS with PS added concrete, respectively. The observations of results clearly indicated that the water absorption increased with decrease in chloride ion penetration. The relationship between water absorption and chloride ion penetration was found to be y=0.561x+0.141% for optimum percentage of PRCM by GGBS added concrete, y=321.69x-820.05 25% for optimum percentage of PRCM by PS added concrete and y=206.74x+424.93 for optimum percentage of PRCM by PS with GGBS added concrete with regression coefficient value of 0.561, 0.7213 and 0.8235 which appeared to be satisfactory.

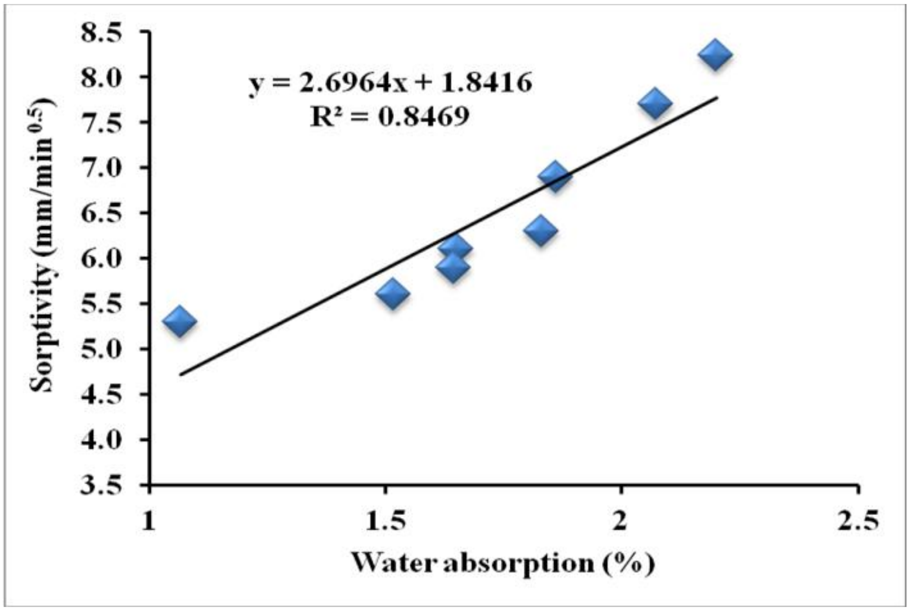


Figure 5.51 Relationship between sorptivity and water absorption of PRCM by PS added concrete at 28 days

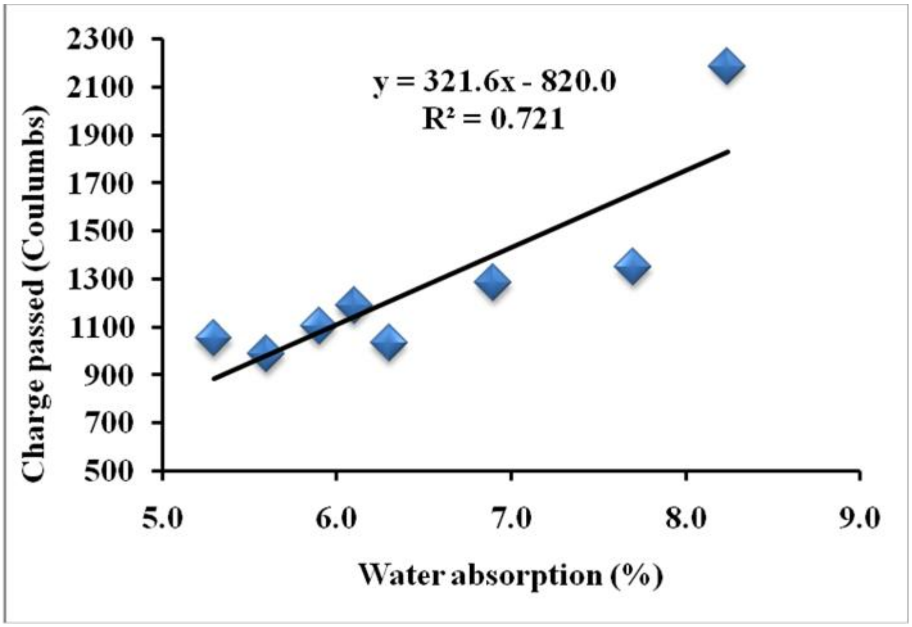


Figure 5.52 **Relationship between RCPT and water absorption of PRCM by PS added concrete at 28 days**

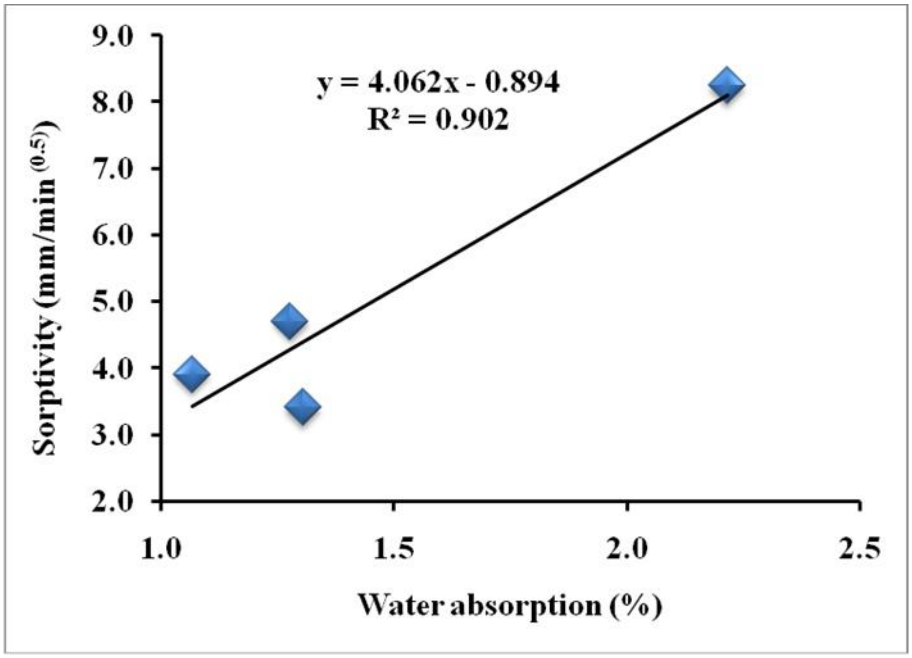


Figure 5.53 **Relationship between sorptivity and water absorption of PRCM by GGBS with PS added concrete at 28 days**

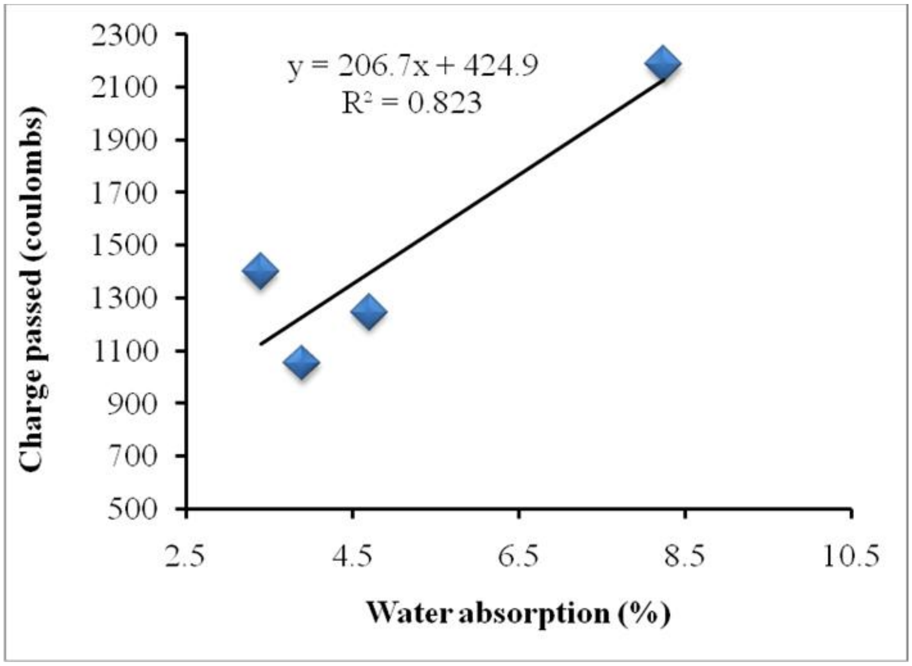


Figure 5.54 Relationship between RCPT and sorptivity of PRCM by GGBS with PS added concrete at 28 days

5.7 SCANNING ELECTRONIC MICROSCOPY (SEM)

The Scanning Electron Microscope was equipped with Energy-Dispersive EDX spectrometer used to describe the micro structure of GGBS, PS, CC, optimum percentage of PRCM by GGBS, PS and GGBS with PS added concrete. The SEM images of GGBS and PS are shown in Figure 5.55 and Figure 5.56, respectively. After 28 days of curing CC, G7 and by self-curing P5 and PG31 the micro-morphology were obtained and SEM images are recorded to describe the effects of concrete pore structure, micro-hardness and morphology were shown in Figure 5.57-5.60. In Figure 5.57, CC is spotted more amorphous C-S-H gels mix with needle like ettringite and CH crystals, expansive destruction from hydration products which result in looser structure and micro-cracks.

In Figure 5.58, 5.59 and 5.60 with addition of GGBS, PS, PS with GGBS composition of changes, specifically, compacting hydration product C-S-H gel forms and content of $Ca(OH)_2$ decreases due to pozzolanic effect. Additionally, microstructure becomes denser and micro-cracks decreased, connection between paste and aggregate is enhanced. SEM images for PS clearly indicated the presence of irregular pores. The PS retains the moisture in these pores envelops providing obstacle for moisture to move towards the surface. The observation of high compressive strength after the addition of PS to the concrete is due to the fact that, PS possesses very high energy absorbing ability. Additionally, the SEM image of PRCM of GGBS and PS indicated that, mechanical performance of pore size distribution has obvious effect on compressive strength of concrete and macro-properties of concrete material are closely related to its microstructure.

From all the above observations, it has been noted that, the concrete mixes prepared using PRCM by 15% of PS with 25% of GGBS (PG31) showed relatively greater strength among all the samples after prolong time of curing. This could be attributed to the shape of PS particles which holds all other concrete particles very closer. In addition, the results showed that PS and GGBS are having high amount of silica and alumina. PS particles are viewed as spherical whereas GGBS particles are observed as granular.

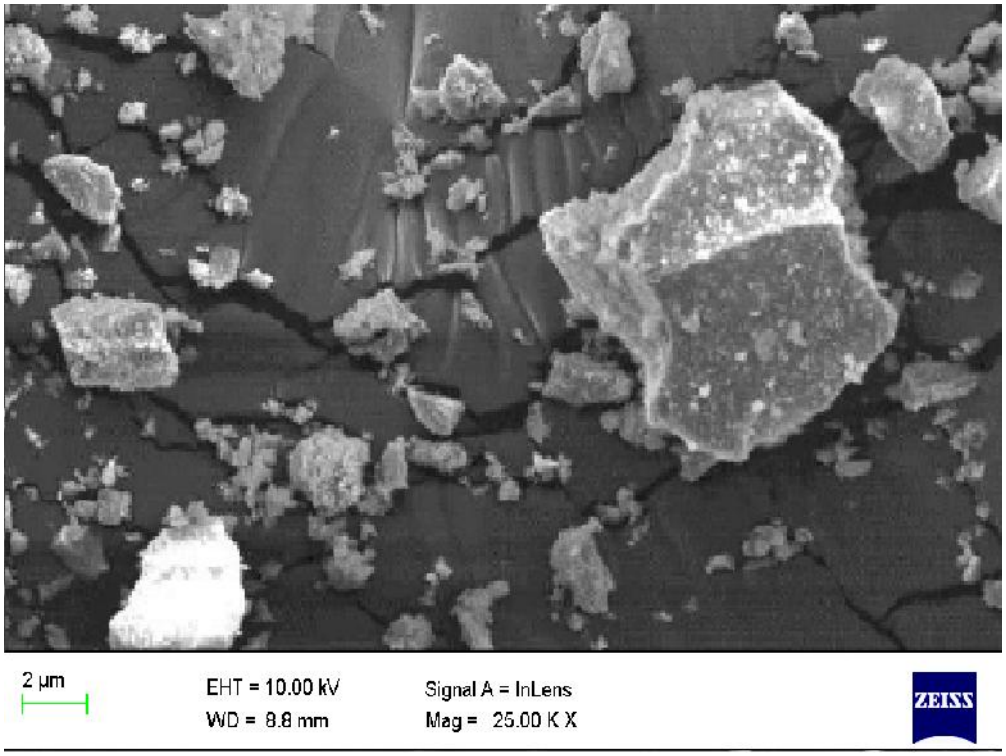


Figure 5.55 SEM image of GGBS

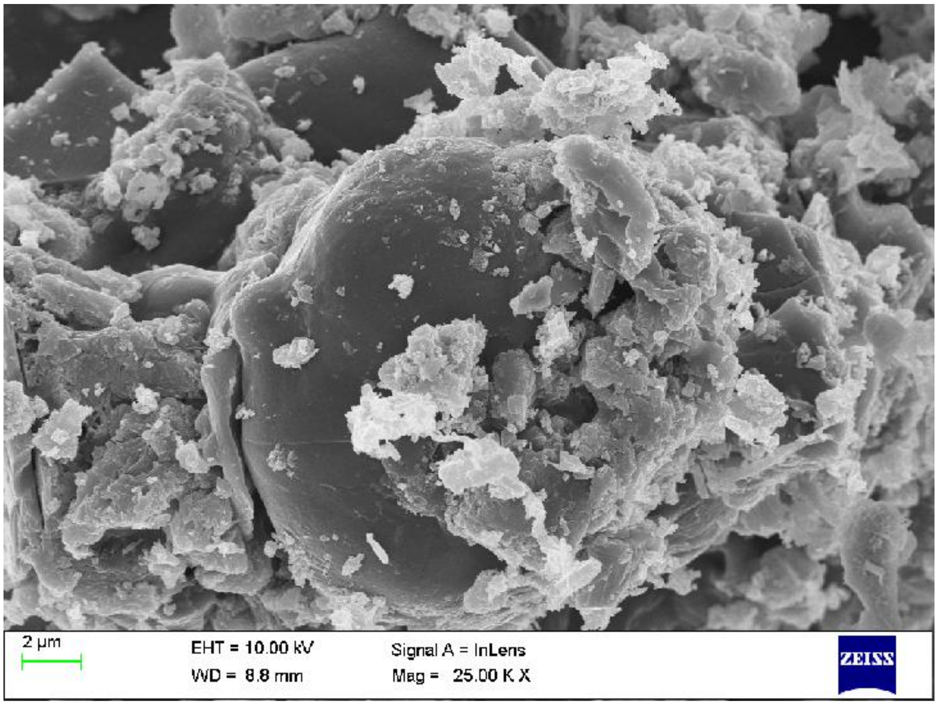


Figure 5.56 SEM image of PS

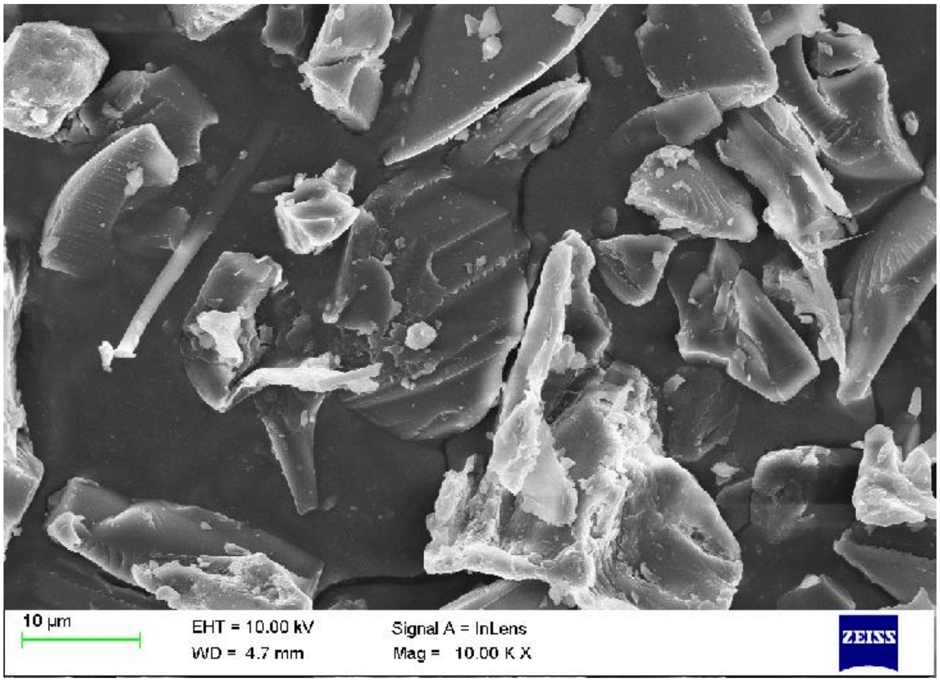


Figure 5.57 SEM image of control concrete at 28 days curing

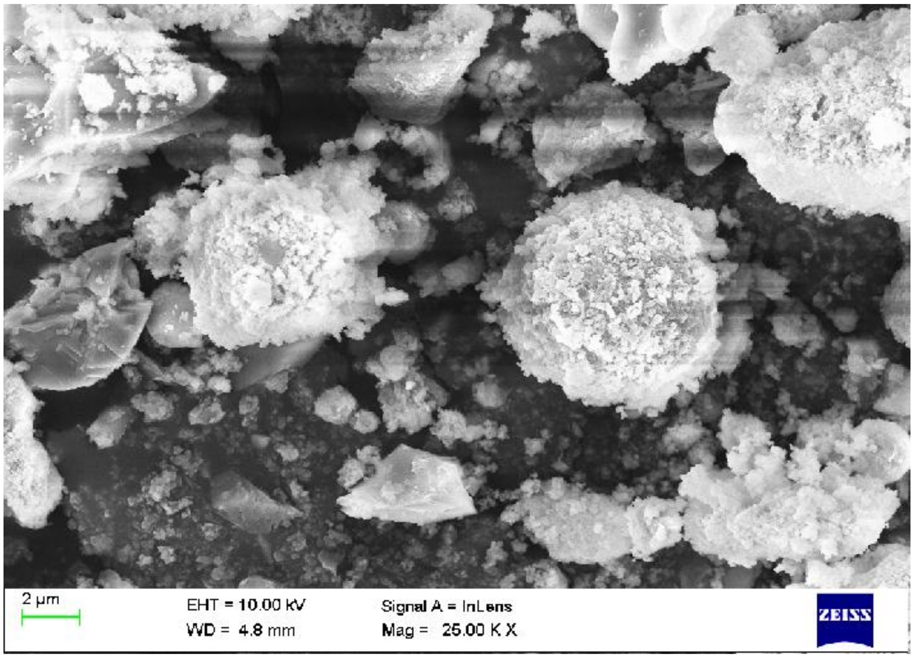


Figure 5.58 SEM image for PRCM by 25% of PS added concrete at 28 days self-curing

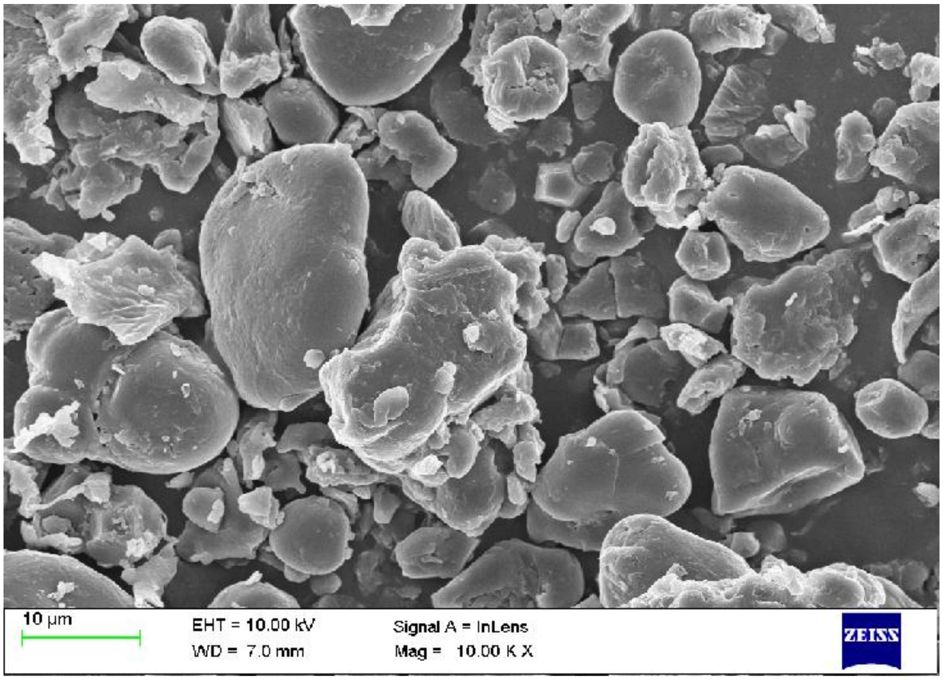


Figure 5.59 SEM image for PRCM by 40% of GGBS concrete at 28 days curing

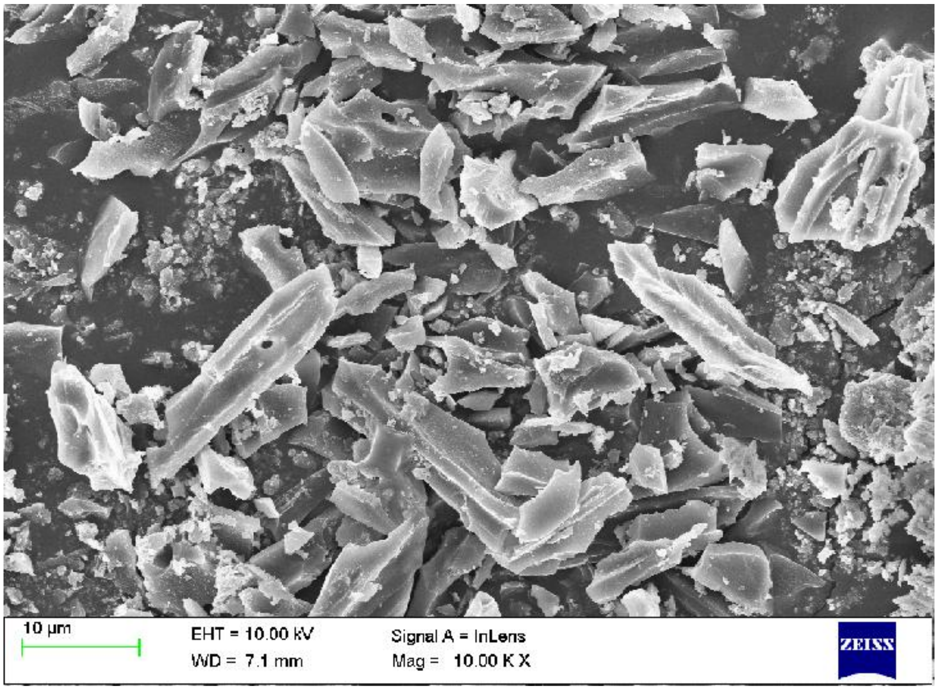


Figure 5.60 SEM image for PRCM by 25% of GGBS and 15% of PS added concrete at 28 days self-curing

5.8 THERMOGRAVIMETRY (TG), DERIVATIVE THERMOGRAVIMETRY (DTG) AND DIFFERENTIAL SCANNING CALORIMETRY (DSC)

TG and DTG analyses have been used as a tool to study the hydration reactions in cementitious pastes. DTG determines the ranges corresponding to thermal decompositions of different phases in paste, while TG calculates the weight loss due to the decomposition. These methods determine the quantitative analysis of hydration products formed. These tests have been carried out to evaluate the carbonation degree of cementitious materials. It is determined through the consumption of $Ca(OH)_2$ and consequent formation of $CaCO_3$ by concrete specimens by the capture of CO_2 in its own matrix. The thermogravimetry properties such as DSC, DTG and TG have obtained for optimum percentage of PRCM by 40% of GGBS (G7), 25% of PS (P5) and 25% of GBBS added with 15% of PS added concrete after 28 days curing (Alessandra *et al*., 2008).

Figures 5.61-5.63 Indicates DSC, TGA-DTG and TGA-DSC plots for 28 days of hydrated PRCM products by 40% of GGBS concrete. The profiles of GGBS and PS added concrete contain several peaks which vary mainly depending on the characteristics of the PS content. The TG curves of the blends exist within most temperature ranges like those of GGBS and PS used to prepare the mixes. Clear and rapid weight loss is observed with all TG curves. This is mainly due to the early emission of volatile matter, which differentiates the burning behavior of PRCM by GGBS from that of PS. From the DSC curves, it is apparent that there main peaks exist in the vicinity of 200.6ºC, 436.5ºC and 726.8ºC for 40% of PRCM by GGBS concrete mix, which can be attributed to the evaporation of free water, decomposition of $Ca(OH)_2$ and decomposition of $CaCO_3$, respectively. In order to quantify the weight loss for each phase formed during hydration, the phases are first identified through DTG. The peak appearing at lower temperature is due to the presence of free water or the evaporable water.

In the 80–400°C region, decomposition of molecular water/ adsorbed water from hydrated phases is reported to occur. The three peaks occurring in this region have been attributed to the decomposition of ettringite, dehydration of C–S–H and C–A–H (Bouaziz *et al.*). The peak at 435ºC represents the crystallized water corresponding to dehydroxylation of Portlandite (CH). The decomposition of $Ca(OH)_2$ to CaO is widely reported to be occurring in the range from 300 to 750ºC. The appearances of broad peak at around 705.3ºC are the result of decarbonation of $CaCO_3$.

Figure 5.62 shows the thermogravimetric (TG) plots in terms of weight loss (%) for the phases identified from DTG analysis. From the obtained TG curves, it can be noticed that 40% of GGBS mix show a similar tendency of losing their weight. However, their weight loss rates in each temperature range are different, which means that the amounts of the substances reacting at each treatment stage are different. It is important to note that the mass loss of Portlandite of the mixture with GGBS is the smallest at 28 days, which implies that the pozzolanic activity of GGBS is relatively higher so that more Portlandite has already been consumed. Thermal properties obtained by DSC analysis the results of heat flow and relative mass changes during heating are shown in Figure 5.63. The peak is in the temperature range from 443.5ºC to 736ºC, it corresponds to the liberation of physically bound water localized in the 40% GGBS Mix.

In another case, 25% of PS replaced for cement material mix id P5, TGA/DTG test results are shown in Figure 5.64-5.66. The mix ID P5 figure TGA curve showed that, three significant weight loss steps. The first at about 100°C has to do with the drying (capillary pore residual water) or with the dehydration of ettringite. This first weight loss step is usually associated with several minor steps that are likely to take place which includes capillary pore water, interlayer water and adsorbed water. The corresponding peaks overlap each other because of the dynamic heating process. This phase accounts for the major part of the weight loss as can be seen from the relatively sharp peak on the derivative curve. The second weight loss step at about 400ºC-450ºC is due to the dehydration of C-H. The third weight loss step at about 700ºC can be attributed to the de-carbonation of $CaCO_3$. As well as the specimen PG31 also indicated dehydration ettringite and weight loss (Figure 5.67-5.69). Among all the TGA/DTG results clearly indicate that the Mix ID PG31 15% of PS with added 25% of GGBS specimens are better than others. In addition, the co-combustion of GGBS and PS is improved and enhanced by blending. The result may suggest synergistic interactions between GGBS and PS during the co-combustion process.

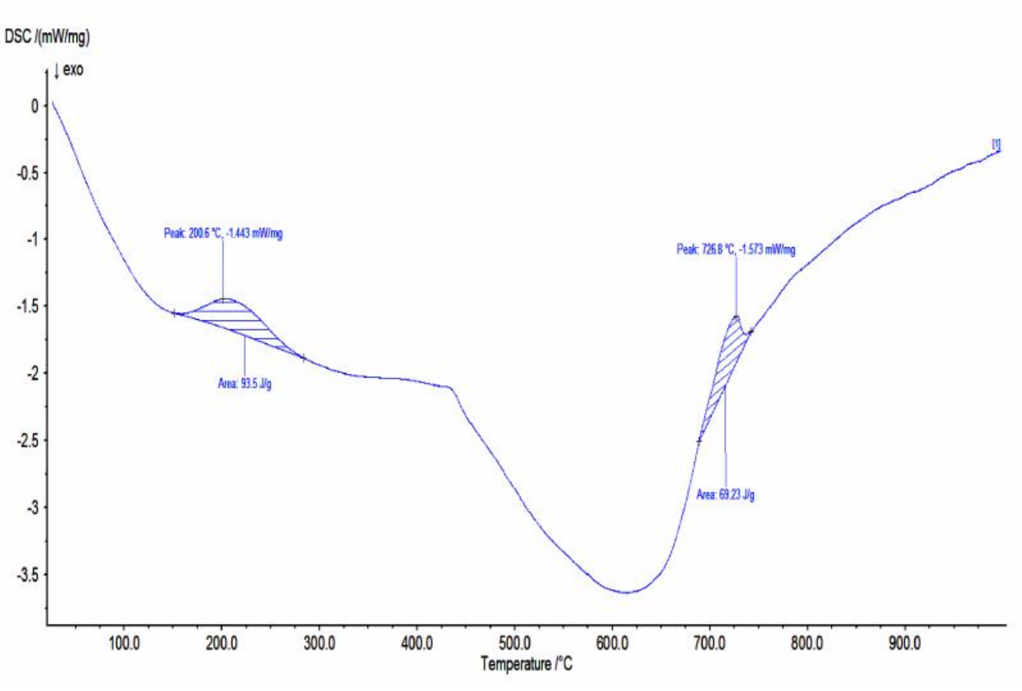


Figure 5.61 DSC image for PRCM by 40% of GGBS added concrete

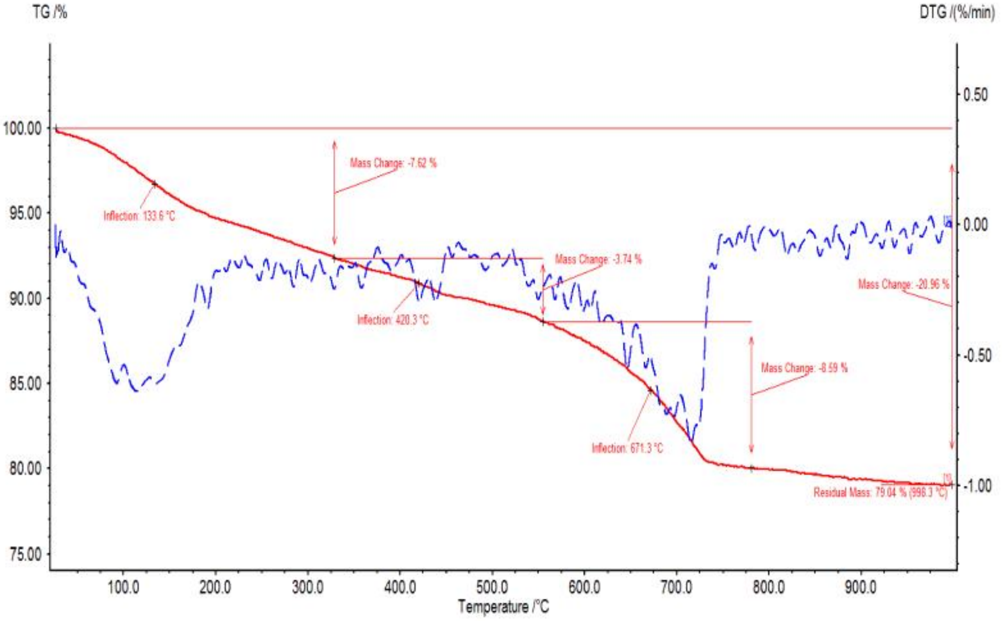


Figure 5.62 TG and DTG image for PRCM by 40% of GGBS added concrete

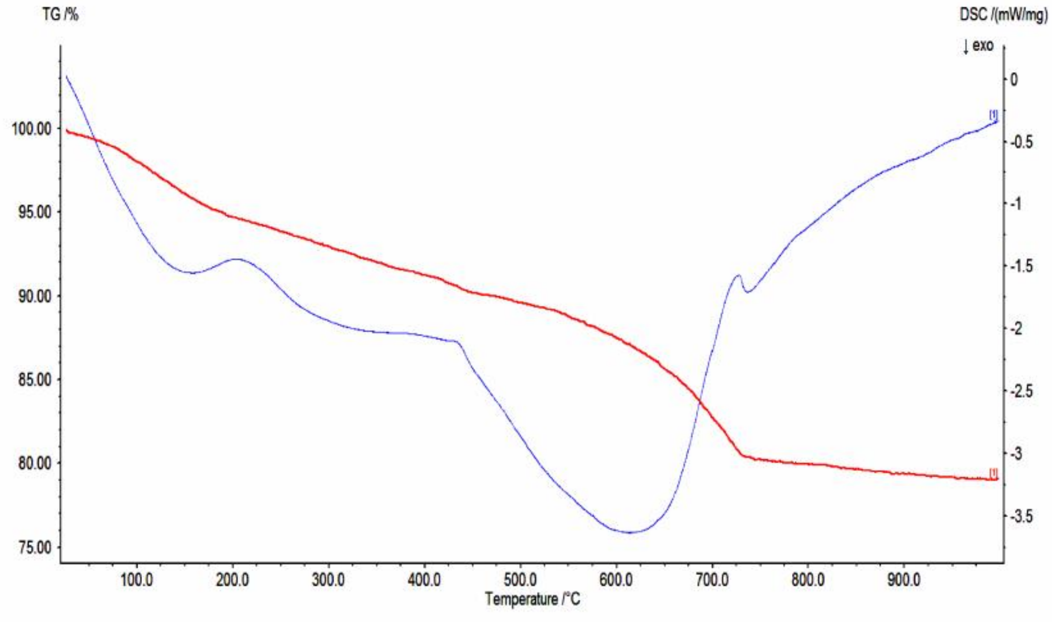


Figure 5.63 TG and DSC image for PRCM by 40% of GGBS added concrete

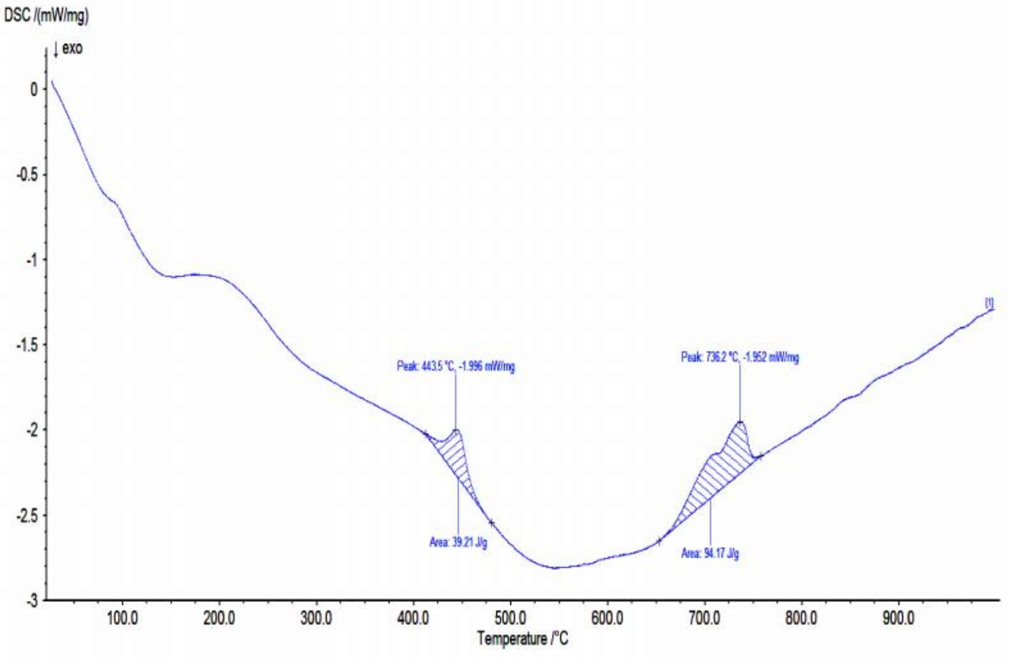


Figure 5.64 DSC image for PRCM by 25% of PS added concrete

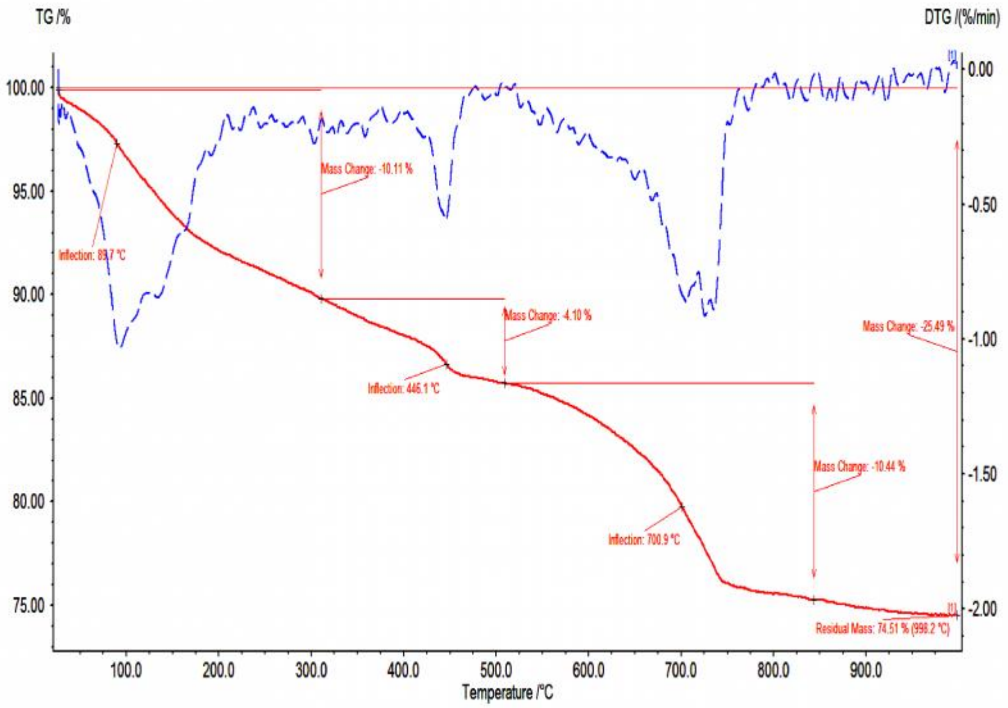


Figure 5.65 TG and DTG image for PRCM by 25% of PS added concrete

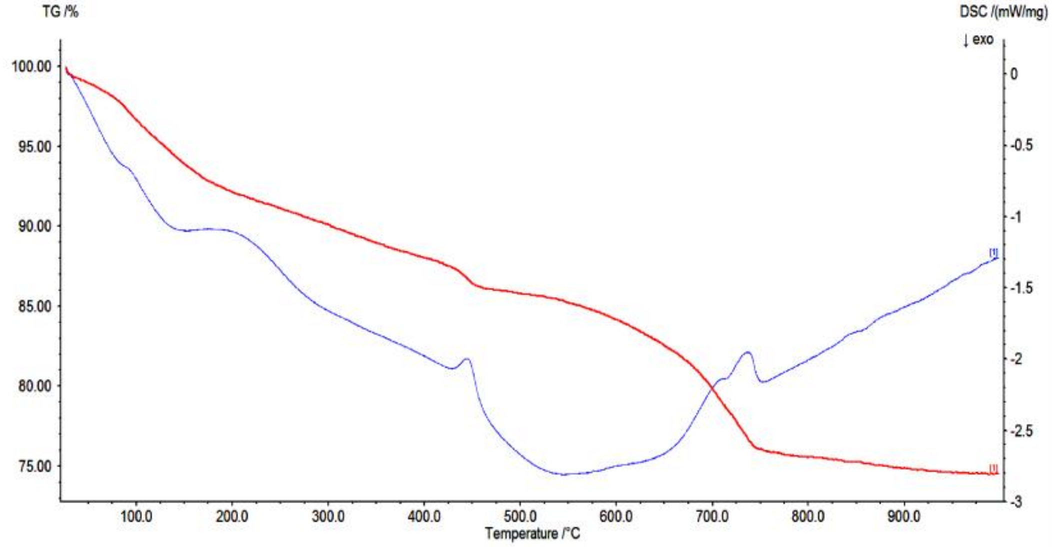


Figure 5.66 TG and DSC image for PRCM by 25% of PS added concrete

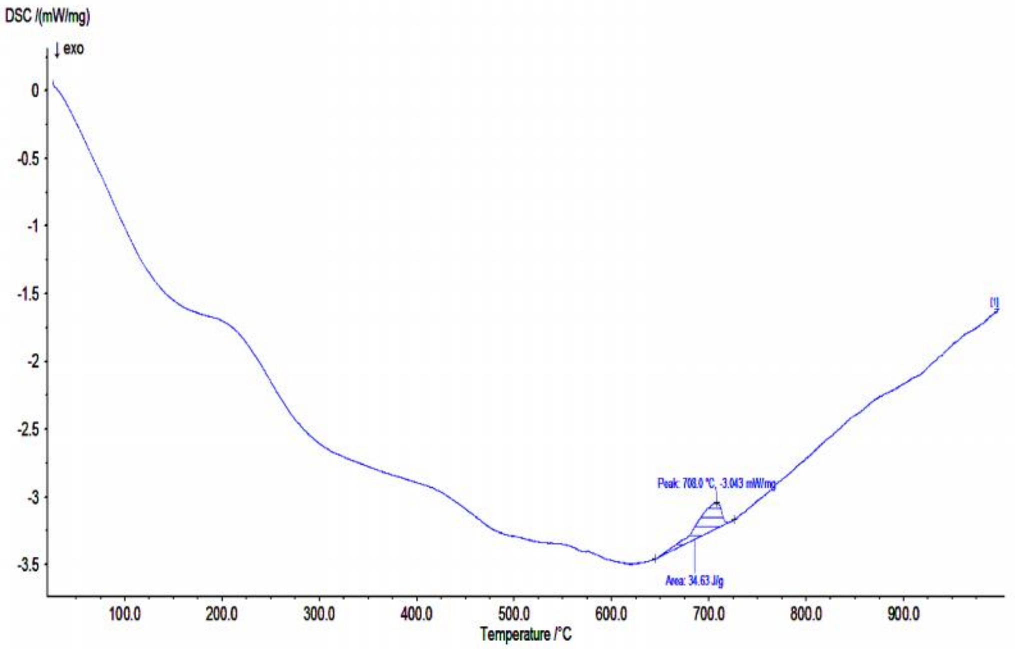


Figure 5.67 DSC image for PRCM by 25% of GGBS and 15% of PS added concrete

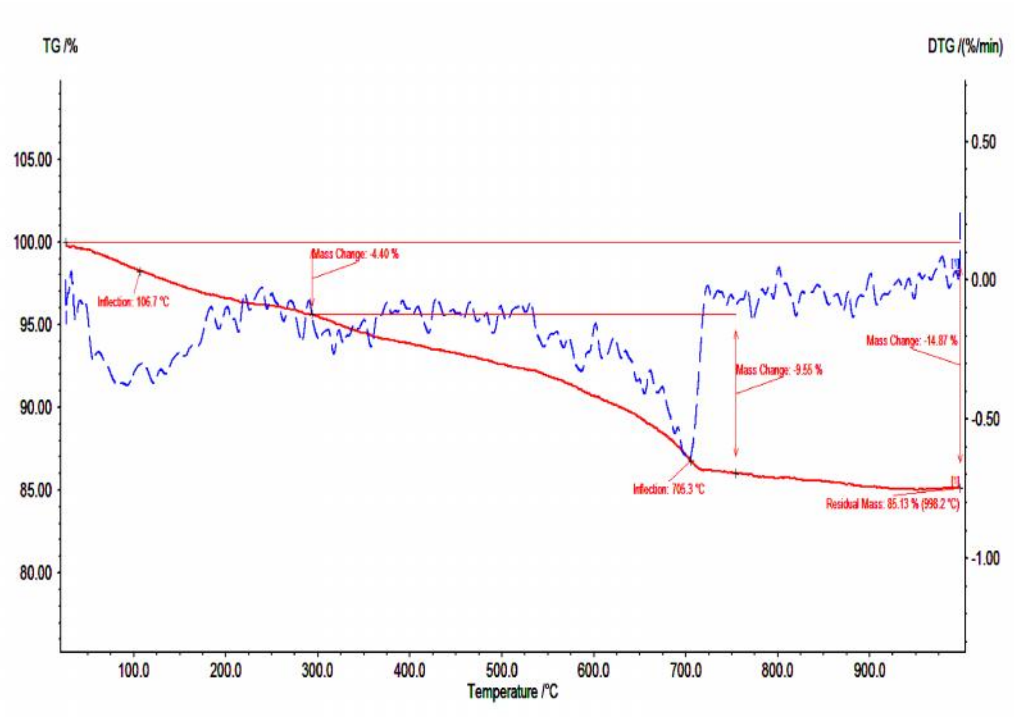


Figure 5.68 TG and DTG image for PRCM by 25% of GGBS and 15% of PS added concrete

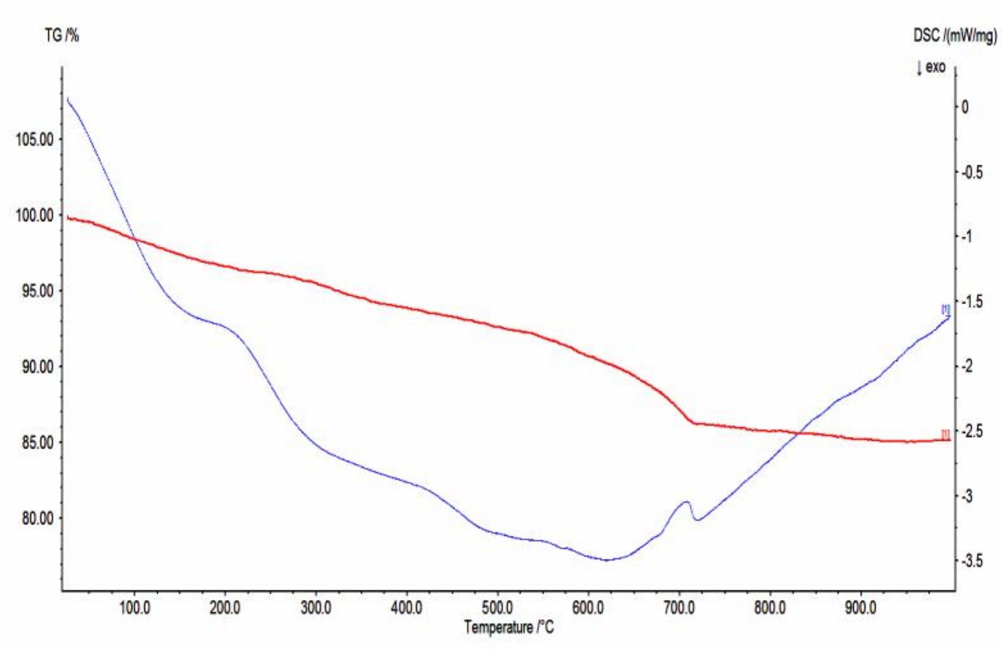


Figure 5.69 TG and DSC image for PRCM 25% of GGBS and 15% of PS added concrete

5.9 ENERGY DISPERSIVE SPECTROSCOPY (EDS) ANALYSIS

Energy dispersive spectroscopy is carried out to establish the composition of elements present in the sample. Any smaller size particles can be analyzed at large magnification using EDS. Based on the samples, several points are selected on the SEM image and analyzed through EDS. EDS detects the elements present in a specimens based on the detection of X-Rays emitted by the test specimen. EDS of PRCM by 40% of GGBS, 25% of PS and 15% of PS with 25% of GGBS added concrete have been obtained after 28 days by different curing methods and is compared to that of control concrete.

The EDS analysis was used over a PRCM concrete by GGBS and PS surface area to characterize the reaction products. EDX highlights the presence of calcium (Ca), silicon (Si), sodium (Na), aluminum (Al), and oxygen (O), indicating the coexistence of an aluminium-modified C–S– H gel with Sodium Aluminosilicate Hydrate (N–A–S–H) gel. It was however difficult to distinguish C–S–H and N–A–S–H gels through their morphology. Furthermore, Figure 5.70 showed the crystal of CH, the product of cement hydration and the reactants of pozzolanic reaction, which has a laminar morphology in and supported by EDX analysis. The GGBS and PS particles in the concrete mix react slowly with CH to form C–S–H gels, and the process goes on for years.

Besides, from the Figure 5.71, it is found that the minerals present in the GGBS concrete specimens are silica, calcium and oxides. Here the calcium reacts with silica and oxides, and produces the hydrated calcium silicates, which impart strength to the concrete at early and later periods. Furthermore, Figure 5.72 provides the test result of PRCM by PS concrete sample. From the Figure, it becomes evident that the concrete sample contains silica, calcium, alumina and oxides. The calcium reacts with alumina and oxides, and produces tri calcium aluminate, which impart strength to the concrete at early and later periods. Figure 5.73 showed that result of PRCM by 25% GGBS and 15% PS concrete at the age of 28 days self curing.

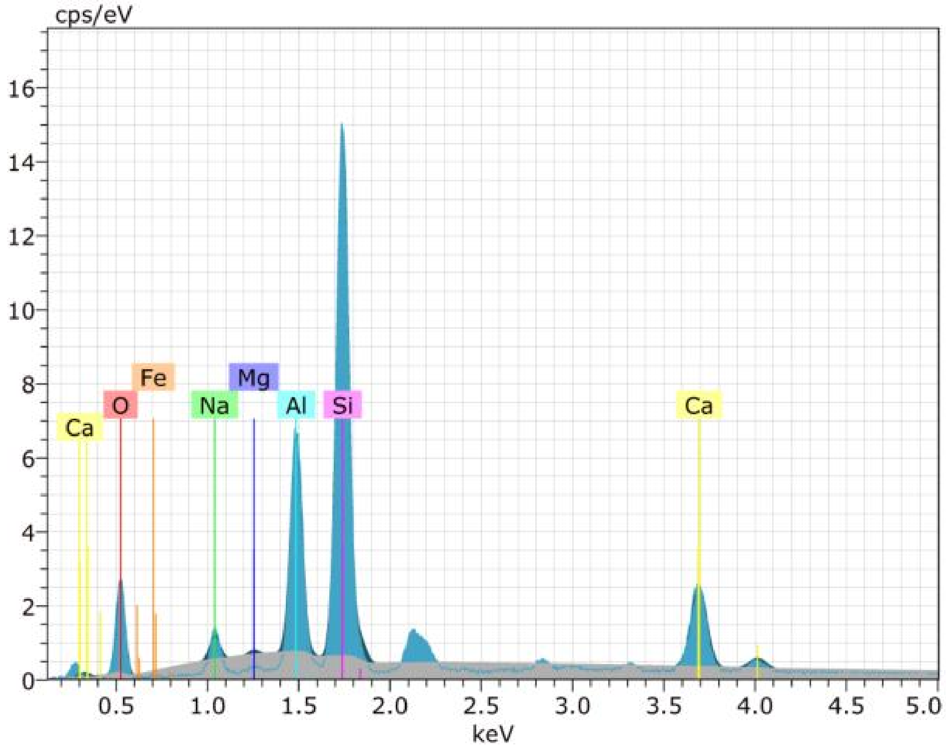


Figure 5.70 EDX image of Control concrete at 28 days curing

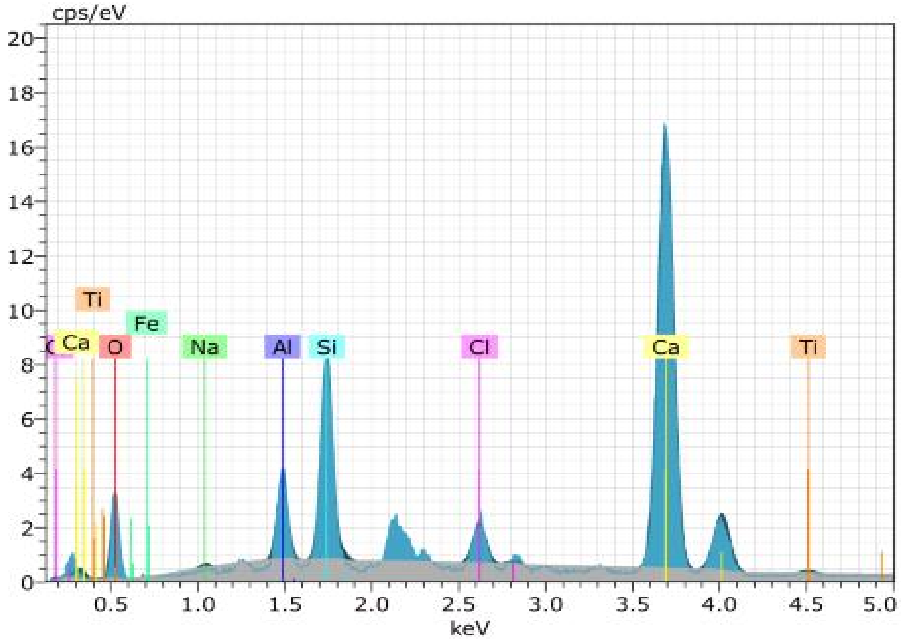


Figure 5.71 EDX image for PRCM by GGBS added concrete at 28 days of curing

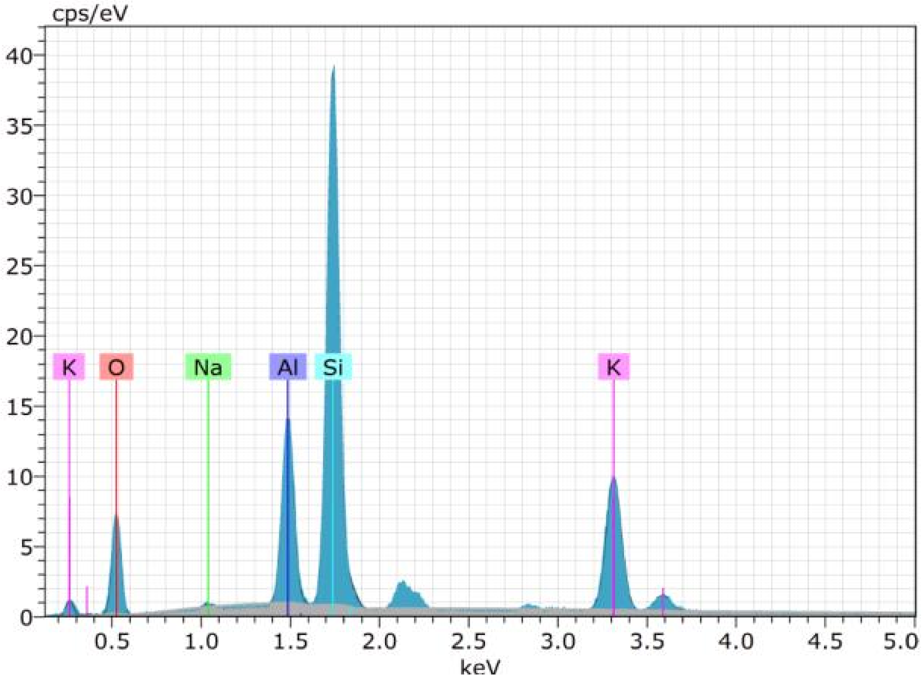


Figure 5.72 EDX image for PRCM by 25% of PS added concrete at 28 days (self curing)

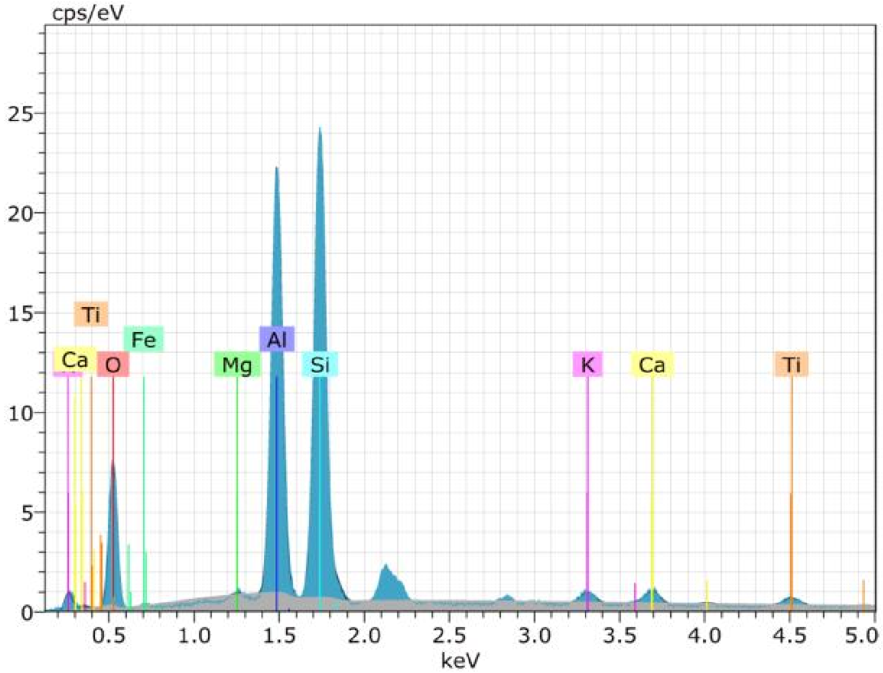


Figure 5.73 EDX image for PRCM by 25% of GGBS and 15% of PS added concrete at 28 days (self curing)

5.10 X-RAY POWDER DIFFRACTION (XRD) ANALYSIS

XRD technique is used to gain a better understanding of the possible transformations underway in the selected samples. In order to elucidate the crystalline nature of the concrete specimens of the partially replaced cement using GGBS, PS and PS with GGBS, XRD analysis has been carried out after 28 days by different curing methods (Gao *et al*., 2005). The results of XRD analysis Figure 5.74 shows the control concrete and partially replaced concrete using 40% of GGBS, 25% of PS and 15% of PS with added 25% of GGBS for cement. Furthermore, the Figure 5.74 indicates of amorphous phase is confirmed by the presence of the dominant amorphous hump located between 25° and 35° (2θ). This amorphous hump increased with the inclusion of PRCM by 40% of GGBS and 25% of PS and 15% of PS with 25% of GGBS. This increment in the amorphous hump is a part of the reason why higher compressive strength was obtained with the inclusion of

PRCM by 40% of GGBS and 25% of PS and 15% of PS with 25% of GGBS, when compared to control concrete. As well as the XRD pattern (G7, P5 and PG31) clearly indicated that, in all admixtures added specimens, there is a phase of $Ca(OH)_2.SiO_2.H_2O$ with mixes phase of $CaO.Al_2.SiO_2.H_2O$ are presented.

The peak characteristic for CSH became more distinguishable for PRCM concrete compared to control concrete. The area and intensity of this peak increased with the inclusion of PRCM concrete. This could be a part of the reason why PRCM mixes compressive strength was higher than that of control concrete. The phase of calcium alumino silicate hydrate (CASH) was detected for 25% of PS, while it is not present for control concrete. This result is quite predictable because the PRCM by 25% of PS pozzolan contains a relatively large quantity of Al_2O_3. The inclusion of cash in PRCM by 25% of GGBS with 15% of PS is a part of the reason why PRCM showed a higher compressive strength than control concrete.

The XRD image corresponds to 28 days curing time clearly illustrated that, partial replacements of binding have improved mechanical properties which could be supported in the present study. Similar kinds of results have been obtained for all other materials.

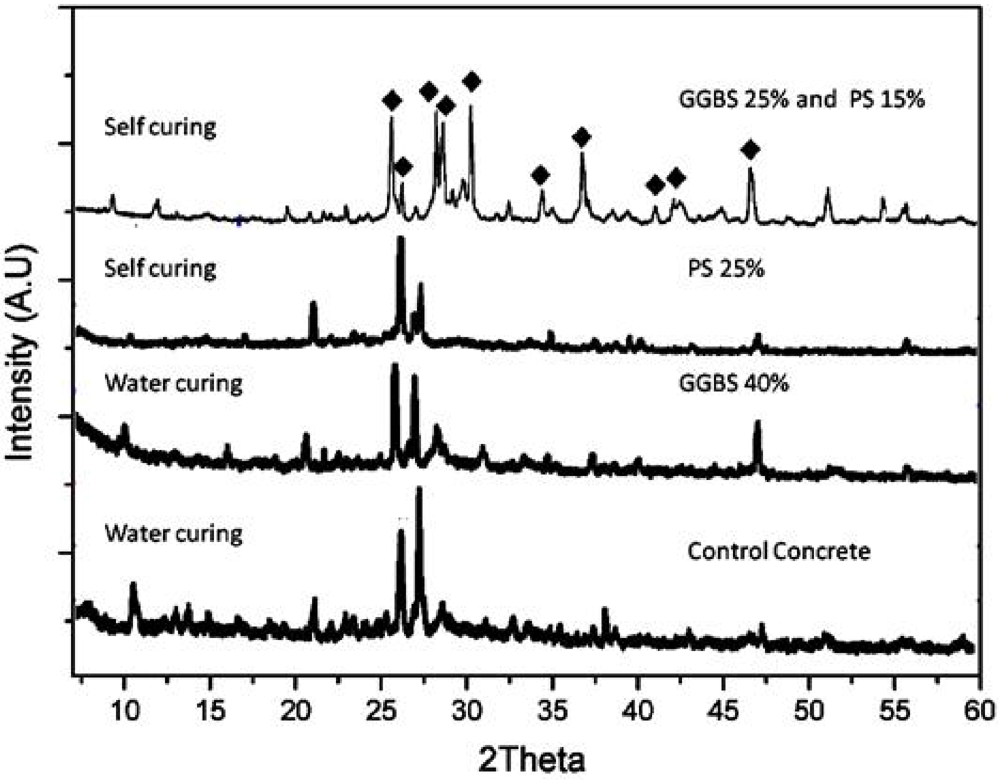


Figure 5.74 XRD image of control concrete, 40% of GGBS, 25% of PS concrete and 25% of GGBS and 15% of PS added concrete at 28 days

5.11 ACID RESISTANCE STUDY

The PRCM by GGBS, PS and GGBS with PS concrete cubes of size 150 mm X 150 mm X 150 mm were cast and cured for a period of 28 days. After 28 days curing of specimens, cube surfaces were cleaned using standard preliminary surface cleaning process and weighed. The identified specimens were fully immersed in 3% of dilute sulfuric acid solution. The solution was checked periodically. After the prescribed duration, the specimens were removed from the solution, water washed and weighed under surface dried condition. Using weight loss method, percentage weight loss was determined.

To study the effect of sulphuric acid attack of control concrete and PRCM by 40% of GGBS, 25% of PS and 15% PS with 25% of GGBS were considered. The PRCM by 40% of GGBS mixes were cured in potable water and 25% of PS mix and 15% of PS with 25% of GGBS mix concrete have followed self-curing. The identified specimens were then immersed in 3% H_2SO_4 (sulphuric acid) solution for 90 days. The solution was checked periodically for ensuring constant concentration throughout the study. The percentage weight loss of the sample was determined. The test results are presented in Table 5.25 and 5.26 and Figure 5.75, 5.76, 5.77. The table reveled the low weight lose for PRCM by GGBS and PS concrete mixes when compared with control concrete.

Table 5.25 Acid Durability and Acid Attack Factors for PRCM by GGBS added concrete mixes immersed in 3% of H_2SO_4

Mix ID	**% of PRCM by GGBS**	**Dry weight (kg)**	**Wet weight (kg)**	**Weight loss (%)**
CC	**0**	**7.98**	**7.66**	**4.01**
G1	5	7.65	7.35	3.92
G2	10	7.42	7.14	3.77
G3	15	7.25	6.98	3.72
G4	20	7.12	6.86	3.65
G5	25	6.86	6.62	3.50
G6	30	6.58	6.35	3.50
G7	40	6.37	6.15	3.45
G8	50	6.18	5.97	3.40

Table 5.26 Acid Durability and Acid Attack Factors for PRCM by PS added concrete mixes immersed in 3% of H_2SO_4

Mix ID	% of PRCM by PS	Dry weight (kg)	Wet weight (kg)	Weight loss (%)
P1	5	6.86	6.59	3.94
P2	10	6.62	6.37	3.78
P3	15	6.44	6.19	3.88
P4	20	6.36	6.12	3.77
P5	**25**	**6.00**	**5.78**	**3.67**
P6	30	5.78	5.57	3.63
P7	40	5.57	5.38	3.41

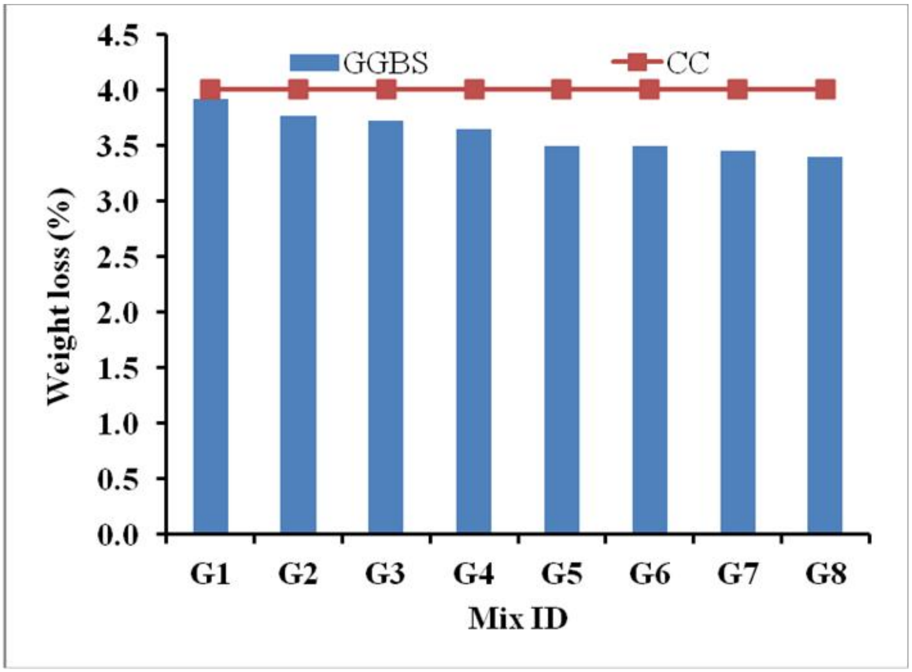


Figure 5.75 **Acid Durability, Acid Attack Factors and 90 days of immersion for control concrete and PRCM by GGBS concrete immersed in 3% of H_2SO_4**

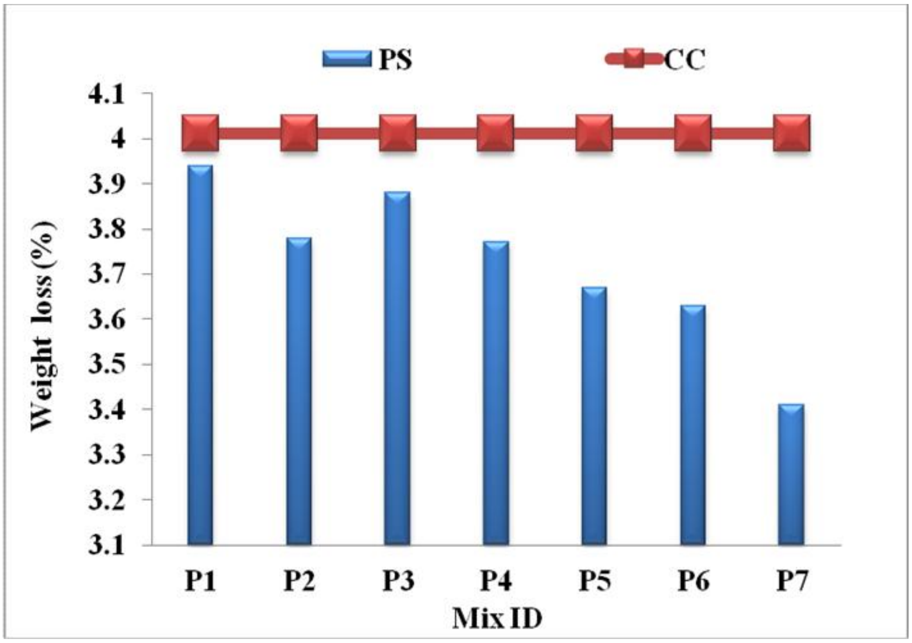


Figure 5.76 Acid Durability, Acid Attack Factors and 90 days of immersion for control concrete and PRCM by PS mixes immersed in 3% of H_2SO_4

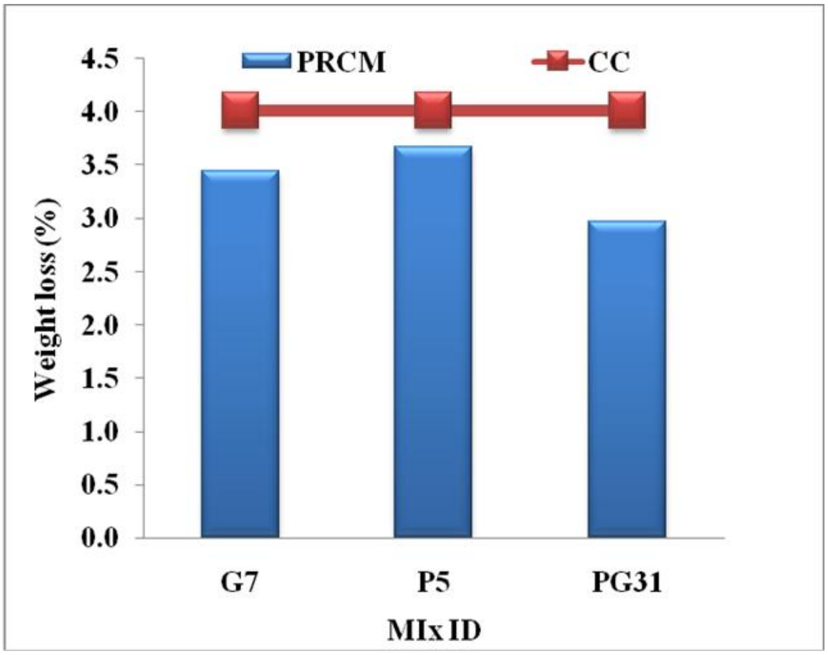


Figure 5.77 Acid Durability, Acid Attack Factors and 90 days of immersion for control concrete and PRCM added concrete immersed in 3% of H_2SO_4

5.12 CONCLUDING REMARKS

The detailed experimental investigation and the results discussed on various aspects such as slump test, compressive strength, split tensile strength, flexural strength, water absorption, sorptivity, chloride ion penetration and micro structural analysis such as SEM, EDX and XRD leads to following conclusions.

The experiments conducted on compressive strength indicated that, the PRCM by GGBS concrete specimens exhibited early strength gain when compared to control concrete specimens. 40% replacement of cement by GGBS showed greater strengths than the control concrete specimens. In addition, 25% replacement of cement by PS added self-curing concrete illustrates greater strengths than the control concrete specimen and the optimum percentage of PRCM by 15% of PS with 25% of GGBS added self-curing concrete indicated higher compressive strength than control concrete.

The results of water absorption test revealed that, at the age of 28 days the water absorption ability of all replacement of PRCM by GGBS added concrete specimens were lower than that of control concrete. PRCM by PS added concrete specimens were higher than that of control concrete

The results of micro structural analysis obtained from SEM images confirmed the shape of GGBS and PS particles as spherical. EDS analysis confirmed the presence of the minerals of silica, calcium, alumina and oxides for optimum percentage of PRCM by GGBS, PS and GGBS with PS. Further, XRD results, confirmed the major component present is silica content and is in crystalline form.TG and DTG analyses have identified the phase of the hydration reactions in GGBS and PS cementitious pastes.

CHAPTER 6

SUMMARY AND CONCLUSIONS

6.1 GENERAL

This chapter presents the summary and conclusions of the research based on the experimental investigations carried out on concrete specimens prepared by partial replacement of cement with ground granulated blast furnace slag (GGBS), Paper sludge (PS) and combined PS with GGBS. The experiments for mechanical properties include the compressive strength, split tensile strength and flexural strength of concrete. Further, durability properties are determined by water absorption, sorptivity, chloride ion penetration and acid attack test. Micro structural analysis has been done using EDX and XRD. Morphology of the structure has been determined by SEM analysis. The suggestions for future investigations are also indicated at the end of the chapter.

6.2 SUMMARY

The entire study is divided into three distinct phases. The first phase is to study the mechanical properties and durability properties of concrete with PRCM by 5%, 10%, 15%, 20%, 25%, 30%, 40% and 50% GGBS, tests on workability, compressive strength, split tensile strength and flexural strength, water absorption, chloride ion penetration, acid attack and sorptivity were conducted. The relationship between compressive strength and split tensile strength; compressive strength and flexural strength were established.

In the second phase, to study the mechanical properties and durability properties of PRCM by 5%, 10%, 15%, 20%, 25%, 30% and 40% PS, tests on compressive strength, split tensile strength and flexural strength, water absorption, chloride ion penetration, acid attack and sorptivity were carried out. The relationship between compressive strength and split tensile strength and compressive strength and flexural strength were obtained. Results showed that, PRCM by GGBS upto 40% replacement were observed and showed better result on compressive strength, split tensile strength and flexural strength values when compared to control concrete. But there is a gradual decrease in the strength for PRCM by PS above 25% of PS as self-curing when compared to control concrete.

In the third phase, to study the mechanical properties and durability properties of concrete with 5%, 10%, 15%, 20%, 25%, 30% and 40% PS with 5% GGBS added concrete tests on compressive strength, split tensile strength and flexural strength, water absorption, chloride ion penetration, and sorptivity were performed. From the experimental results, it was noted that, among all the other test specimens evaluated throughout the present study including the control concrete, the specimen cast using PRCM by 15% of PS with 25% GGBS replacement showed the maximum compressive strength, split tensile strength and flexural strengths at a prolonged curing periods.

The micro structural properties of control concrete and optimum percentage of PRCM by GGBS, PS and GGBS with PS are investigated by SEM, XRD and EDX analyses. Using the differential scanning calorimetry and thermogravimetry, the hydration and pozzolanic reaction occurred in the concrete are also investigated with respect to the optimum percentage of GGBS, PS and GGBS with PS.

6.3 CONCLUSIONS

The following conclusions can be drawn from the experimental investigation.

6.3.1 Workability

1) The workability of PRCM by GGBS added concrete has enhanced upto 40% and decreased above 40% and beyond that the mix was quite stiff. At the same time for 40% PRCM by GGBS the flow table test results 4% higher than CC and 1sec lower than CC in Vee-Bee test.

2) The workability of PRCM by PS added concrete increased with replacement level upto 25% and decreased beyond that. At the same time for 25% PRCM by PS the flow table test results 4% higher than CC and 2 sec lower than CC in Vee-Bee test.

3) Similarly, The workability of PRCM by GGBS with PS added concrete increased with replacement level upto 25%GGBS with 15% of PS and decreased beyond that. At the same time flow table test results 6% higher than CC and 1sec lower than CC in Vee-Bee test.

6.3.2 Compressive Strength

1) The compressive strength of concrete mix with PRCM by GGBS upto 40% exhibited an increasing trend when compared to control concrete. But beyond 40% there was reduction in the strength of concrete

2) PRCM by 25% of PS had the maximum compressive strength of 17.4% when compared to control concrete at 28 days of self-curing.

3) In the case of PRCM by 25% of GGBS with 15% of PS compressive strength were increased than that of control concrete and other optimum percentage of PRCM by GGBS, PS added concrete at different self-curing days (Mix ID PG31 6.2%, 9.5%, 12.2%, 34.6%, 39.3%, 40.9% and 59.7).

4) The increase in compressive strength could be due to (i) highly active mineral admixtures (ii) reduction of pores (iii) high rate of dissolution in reactant solution.

5) The observation clearly indicated that, GGBS, PS and combined form of GGBS with PS can be used as an alternate of cement material which reduces the consumption of cement and pollution.

6.3.3 Split Tensile Strength

1) There is a decrease in the split tensile strength for the specimens containing 5%, 10% and 50% of PRCM by GGBS than control concrete has been observed.

2) Among all the specimens prepared using PRCM by GGBS, specimens made using PRCM by 40% of GGBS replacements exhibited greater split tensile strength than the control concrete.

3) The maximum split tensile strength of the specimens prepared using PRCM by PS, specimens made by PRCM by 25% of PS were found to be optimum and higher than the control concrete.

4) Further, it is noted that, the Mix ID PG31 PRCM by GGBS with PS, the optimum percentage of 15% of PS with 25% of GGBS as self-curing concrete has achieved maximum split tensile strength than other PRCM by GGBS, PS added concrete specimens including to control concrete.

6.3.4 Flexural Strength

1. The specimens prepared using PRCM by GGBS, specimens made using PRCM by 40% of GGBS optimum percentage of PRCM by GGBS showed better flexural strength.

2. The optimum PRCM by 15% PS with 25% of GGBS added concrete has archived maximum flexural strength when compared to control concrete.

3. The flexural strength increases with increase in compressive strength, with optimum percentage of PRCM by 40% of GGBS, 25% of PS and 15% of PS with 25% of GGBS added concrete specimens (G7, P5 and PG31).

4. The regression coefficient values derived for the establishment of the relationships between compressive strength with split tensile and compressive strength with flexural strength were also observed for the optimum percentage of PRCM by GGBS, PS and PS with GGBS added concrete.

5. The square of the correlation, measures the proportion of variation in the dependent variable that can be attributed to the independent variable. R-squared values should accurately reflect the percentage of the dependent variable that the linear model explains and have very good measurements, R-squared values over 90% were also observed for the optimum percentage of PRCM by GGBS, PS and PS with GGBS added concrete.

6.4 DURABILITY PROPERTIES OF GGBS AND PS ADDED CONCRETE

After the optimization of replacement level and curing period, the durability properties are investigated with a view to explore the features of concrete specimens manufactured in the present study.

6.4.1 Saturated Water Absorption

The incorporation of PRCM by GGBS added concrete reduced the water absorption, whereas the addition of PRCM by PS, GGBS with PS added self-curing concrete showed increases in water absorption when compared to control concrete. This is due to the fact that, the micro structure in the cement paste is improved due to pozzolanic action and micro-pore filler effect of mineral admixtures, which resulting fine and continuous pore structure.

6.4.2 Sorpvitity Test

Sorptivity of PRCM by GGBS, PS and PS with GGBS added concrete shows higher sorptivity than control concrete. Incorporation of PRCM by GGBS with PS increases the sorptivity. The results of sorptivity test indicated that PS and PS with GGBS added self-curing concrete specimens had significantly higher absorption rate, since they have more connected pores in concrete structure, when compared to control concrete.

6.4.3 Rapid Chloride ion Penetration Test

The optimum percentage of PRCM by GGBS, PS and GGBS with PS added concrete showed lower chloride ion penetration than control concrete. In addition, lower chloride ion permeability and higher binding capacity are also determined for the Mix ID’s G7, P5 and PG31 respectively.

6.4.4 Outcome from Micro Structural Properties

The core properties are investigated for optimized percentage of PRCM by GGBS, PS and GGBS with PS added concrete, from electron microscope and the following results are drawn.

1. SEM images confirmed that the GGBS and PS particles are spherical (elongated) and angular in shape.

2. TG, DTG and DSC images revealed that the hydration and weight loss of PRCM by GGBS, PS and GGBS with PS (Mix IDs G7, P5 and PG31). The results confirmed that synergistic interaction between GGBS and PS during the combustion process.

3. EDS analysis confirmed that optimum percentage of PRCM by GGBS, PS and GGBS with PS revealed the presences of minerals of silica, calcium, alumina and oxides.

4. XRD results, confirmed that the major component is silica content and it is in crystalline form.

6.5 MAJOR CONTRIBUTIONS FROM THE RESEARCH

1) The study contributes to the development of new eco-friendly binder in concrete. Use of industrial waste products saves the environment and conserves natural resources. Reuse of the GGBS and PS helps to protect the environment from pollution.
2) The optimum mix proportions for replacement of ordinary Portland cement with GGBS, PS and GGBS with PS was found out.
3) The GGBS used in the investigations exhibited good pozzolanic properties and can be used in the production of high strength, high volumes of slag concrete i.e. cement can be replaced with GGBS upto 50% to reduce the cement content in concrete, as well as cement can also be replaced with PS upto 25% to reduce the cement content in concrete by self-curing method thereby reducing the cost of concrete.
4) In this present study, it was suggested that an optimum percentage of partial replacing cement material by 40% of GGBS (normal curing), 25% of PS (self-curing) and 25% of GGBS with 15% of PS (self-curing) provided maximum strength.

Annexure -I

CONTROL CONCRETE (CC) - MIX DESIGN

Grade = M25

Specific gravity of cement = 3.15

Specific gravity of Fine aggregate = 2.6

Specific gravity of Coarse aggregate = 2.8

Specific gravity of water = 1.0

Type of cement = OPC 53 grade

Characteristic strength @ 28 days = 25 N/mm^2

Target mean strength = fck + 1.65 X S

= 25+ 1.65 X 5

= 33.25 N/mm^2

Maximum water cement ratio 0.45

Water cement ratio Adopt 0.45

From table 2 IS 10262: 2009

Maximum water content = 186 litres

Estimation water content = 138+ 0.03 X 186

Water content for 100 mm slump = 143.58 liters

Minimum of cement content = 310 kg/m^3

Maximum cement content = 540 kg/m^3

Water/cement = 0.45

Cement = 319 $\simeq$ 320 kg/m^3

= 310 < 320 kg/m^3

Calculation of volume of all aggregate

For Zone 2 refer table 3 = 0.62

Volume of coarse aggregate = 1-0.62

Volume of fine aggregate = 0.38

Mix calculation = 1 m^3

Volume of concrete = (320/ 3.15) X (1/1000)

Volume of cement = 0.102 m^3

Volume of water = (144/ 1) X (1/1000)

= 0.144 m^3

Volume of all in aggregate = 1(0.102+0.144)

= 0.754 m^3

Mass of coarse aggregate = 0.658 x0.62 X 2.8 X 1000

= 1308.944 kg/m^3

Mass of fine aggregate = 0.754 X 0.378 X 2.6 X 1000

= 745 kg/m^3

Mix id	**Cement Kg/m^3**	**Fine aggregate kg/m^3**	**Coarse aggregate kg/m^3**	**Water kg/m^3**
CC	320	745	1308.944	144
Ratio	1	2.33	4.1	0.45

Annexure -II

Compressive Strength of Control Concrete and PRCM (GGBS and PS) Added Concrete

Mix ID	% of PRCM		Compressive strength (N/mm^2)							
			3 days	7 days	28 days	60 days	90 days	120 days	180 days	365 days
CC	-		5.20	18.00	25.80	30.61	31.80	36.20	38.70	42.60
G1	5% GGBS		4.68	16.20	23.80	28.71	29.88	34.74	37.44	41.85
G2	10% GGBS		5.10	17.82	26.40	31.26	32.84	37.83	40.77	45.57
G3	15% GGBS		5.36	18.62	27.60	32.86	34.20	39.76	42.85	47.90
G4	20% GGBS		5.46	19.20	27.80	33.50	34.86	40.53	43.68	48.83
G5	25% GGBS		5.62	19.40	28.63	34.45	35.86	41.69	44.93	50.22
G6	30% GGBS		5.72	20.20	29.80	35.09	36.52	42.46	45.76	51.15
G7	40% GGBS		6.24	21.80	31.93	38.28	39.84	46.32	49.92	55.80
G8	50% GGBS		5.18	18.30	26.54	31.58	32.87	38.21	41.18	46.04
P1	5% PS		4.30	18.80	25.00	31.00	34.60	41.40	44.10	49.60
P2	10%PS		4.50	20.70	26.20	31.70	36.60	42.80	46.40	52.90
P3	15%PS		4.70	22.20	27.00	32.30	37.00	43.70	47.20	54.50
P4	20%PS		4.90	23.60	28.30	33.10	39.00	45.80	49.40	55.90
P5	25%PS		5.10	26.00	30.30	34.00	41.30	48.80	52.40	59.50
P6	30%PS		5.00	23.20	28.00	30.30	38.00	47.60	48.00	49.10
P7	40%PS		4.70	20.80	24.60	26.80	29.30	34.80	38.60	40.20
PG1	5% PS	5% GGBS	2.28	10.05	13.36	16.57	18.47	22.81	23.57	26.51
PG2	10% PS	5% GGBS	2.39	11.08	14.01	16.95	19.56	23.90	24.77	28.25
PG3	15% PS	5% GGBS	2.56	12.51	14.45	17.93	22.35	26.54	28.05	30.73
PG4	20% PS	5% GGBS	2.61	12.60	13.97	15.36	20.86	24.44	26.40	29.88
PG5	25% PS	5% GGBS	2.56	12.45	13.27	14.67	20.08	23.57	25.03	28.17
PG6	30% PS	5% GGBS	2.66	12.38	12.92	14.26	20.32	25.42	25.64	26.24
PG7	40% PS	5% GGBS	2.45	11.39	12.69	13.85	18.69	23.39	23.59	24.14
PG8	5% PS	10% GGBS	2.99	13.18	17.52	21.73	24.22	29.92	30.91	35.42
PG9	10% PS	10% GGBS	3.13	14.53	18.38	22.22	25.64	31.34	32.48	37.74
PG10	15% PS	10% GGBS	3.36	16.41	18.95	23.51	29.31	34.80	36.79	41.06
PG11	20% PS	10% GGBS	3.38	15.41	18.32	20.15	27.35	32.05	34.62	39.92
PG12	25% PS	10% GGBS	3.24	14.98	17.40	19.23	26.33	30.91	32.82	37.64
PG13	30% PS	10% GGBS	3.02	13.97	16.94	18.70	26.64	33.34	33.62	35.05
PG14	40% PS	10% GGBS	3.21	13.25	16.64	18.16	24.51	30.67	30.93	32.25
PG15	5% PS	15% GGBS	3.52	15.52	20.64	25.59	28.52	35.24	36.41	43.29
PG16	10% PS	15% GGBS	3.69	17.11	21.65	26.18	30.20	36.91	38.26	46.13
PG17	15% PS	15% GGBS	4.05	19.81	22.87	28.38	35.38	42.01	44.41	51.44
PG18	20% PS	15% GGBS	3.69	16.79	19.96	21.95	29.80	34.92	37.72	45.13

PG19	25% PS	15% GGBS	3.53	16.32	18.96	20.95	28.69	33.67	35.75	42.55
PG20	30% PS	15% GGBS	3.29	15.22	18.46	20.37	29.02	36.32	36.63	39.63
PG21	40% PS	15% GGBS	3.50	14.43	18.13	19.79	26.70	33.41	33.70	36.46
PG22	5% PS	20% GGBS	3.74	16.45	21.88	27.12	30.24	37.35	38.60	48.48
PG23	10% PS	20% GGBS	3.91	18.14	22.94	27.75	32.01	39.13	40.55	51.66
PG24	15% PS	20% GGBS	4.46	21.79	25.16	31.22	38.92	46.22	48.85	59.15
PG25	20% PS	20% GGBS	3.91	17.79	21.15	23.27	31.59	37.02	39.98	50.54
PG26	25% PS	20% GGBS	3.74	17.29	20.09	22.21	30.41	35.69	37.90	47.66
PG27	30% PS	20% GGBS	3.49	16.13	19.57	21.59	30.77	38.50	38.83	44.39
PG28	40% PS	25% GGBS	3.71	15.30	19.21	20.98	28.30	35.42	35.72	40.84
PG29	5% PS	25% GGBS	3.96	17.44	23.19	29.84	32.05	41.83	40.91	55.75
PG30	10% PS	25% GGBS	4.15	18.23	24.32	30.52	33.94	43.82	42.98	59.41
PG31	15% PS	25% GGBS	4.91	19.12	28.24	34.34	42.81	50.42	54.74	68.02
PG32	20% PS	25% GGBS	4.25	19.37	23.03	26.29	34.39	42.58	43.52	59.70
PG33	25% PS	25% GGBS	4.07	18.83	21.88	25.09	33.10	41.06	41.26	56.28
PG34	30% PS	25% GGBS	3.80	17.56	21.30	24.39	33.49	44.28	42.27	52.42
PG35	40% PS	25% GGBS	4.04	16.66	20.92	23.70	30.81	40.74	38.89	48.23
PG36	5% PS	30% GGBS	3.21	14.15	18.81	23.33	26.00	32.12	33.19	41.69
PG37	10% PS	30% GGBS	3.37	15.60	19.73	23.86	27.53	33.65	34.87	44.43
PG38	15% PS	30% GGBS	3.74	18.28	21.11	26.19	32.65	38.78	40.99	49.63
PG39	20% PS	30% GGBS	3.63	16.54	19.36	21.63	29.37	34.42	37.17	46.99
PG40	25% PS	30% GGBS	3.48	16.08	18.68	20.65	28.27	33.19	35.24	44.31
PG41	30% PS	30% GGBS	3.25	15.00	18.19	20.08	28.60	35.79	36.10	41.27
PG42	40% PS	30% GGBS	3.45	14.22	17.86	19.50	26.31	32.93	33.21	37.97
PG43	5% PS	40% GGBS	2.89	12.73	16.93	20.99	23.40	28.91	29.87	37.53
PG44	10% PS	40% GGBS	3.03	14.04	17.76	21.48	24.78	30.29	31.39	39.99
PG45	15% PS	40% GGBS	3.37	16.45	19.00	23.57	29.39	34.90	36.89	44.67
PG46	20% PS	40% GGBS	3.27	14.89	17.42	19.47	26.43	30.97	33.45	42.29
PG47	25% PS	40% GGBS	3.13	14.47	16.81	18.58	25.44	29.87	31.71	39.88
PG48	30% PS	40% GGBS	2.92	13.50	16.37	18.07	25.74	32.21	32.49	37.14
PG49	40% PS	50% GGBS	3.10	12.80	16.08	17.55	23.68	29.64	29.89	34.17
PG50	5% PS	50% GGBS	2.46	10.84	14.41	17.87	19.92	24.60	25.42	31.93
PG51	10% PS	50% GGBS	2.58	11.95	15.11	18.28	21.09	25.77	26.71	34.03
PG52	15% PS	50% GGBS	2.87	14.00	16.17	20.06	25.01	29.70	31.39	38.01
PG53	20% PS	50% GGBS	2.78	12.67	14.83	16.57	22.49	26.36	28.47	35.99
PG54	25% PS	50% GGBS	2.66	12.32	14.31	15.82	21.65	25.42	26.99	33.93
PG55	30% PS	50% GGBS	2.49	11.49	13.93	15.38	21.91	27.41	27.65	31.61
PG56	40% PS	50% GGBS	2.64	10.89	13.68	14.94	20.15	25.22	25.44	29.08

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LIST OF PUBLICATIONS

INTERNATIONAL JOURNAL

1 **Yuvaraja, R,** Maheswaran, G & Geetha Selva Rani, A 2018, ‘Perspective appraisal of ground-granulated blast-furnace slag infused e-concrete with hypo-sludge as the self-curing systemic catalyst’, Journal of Environmental Protection and Ecology, vol. 19, no. 4, pp. 1640-1649. **(Annexure I) (IMPACT FACTOR 0.734) ISSN 1311-5065.**