PROPERTIES OF CEMENT MORTAR CONTAINING GGBS AND SUBJECTED TO CARBON DIOXIDE CURING

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Submitted by:

ABHINAV AGARWAL

(ROLL NO: 801322001)

UNDER THE SUPERVISION OF

DR. SHWETA GOYAL

Associate Professor

Department of Civil Engineering

Thapar University, Patiala

DEPARTMENT OF CIVIL ENGINEERING

THAPAR UNIVERSITY,

PATIALA-147004

JULY 2015

DECLARATION

I, Abhinav Agarwal, hereby declare that this thesis entitled **"Properties of Cement Mortar containing GGBS and Subjected to Carbon Dioxide Curing"** is an authentic record of my study carried out as requirements for the award of degree of **Master of Engineering** in **Structural Engineering** in the Civil Engineering Department, Thapar University, Patiala under the supervision of **Dr. SHWETA GOYAL, Associate Professor,** Department of Civil Engineering, Thapar University, Patiala during July 2014 to July 2015. This matter embodied in this report has not been submitted in part or full to any other university or institute for the award of any degree.

(Abhinav Agarwal)

Roll No. : 801322001

CERTIFICATE

This is to certify that above statement made by the student concerned is correct and true to the best of my knowledge and belief.

Dr. Shweta Goyal
Associate professor
Department of Civil Engineering
Thapar University, Patiala

Countersigned by

Dr. Naveen Kwatra
Professor and Head
Department of Civil Engineering
Thapar University, Patiala

Dr. S.S Bhatia
Dean of Academic Affairs
Thapar University
Patiala

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Abhinav Agarwal

(801322001)

ABSTRACT

The aim of this study was to evaluate the effect of carbon dioxide curing and normal water curing on mortar specimen incorporating GGBS as partial replacement of cement. An effort has been made to generate a mortar mix with optimum replacement of GGBS.

The focus of the study was to compare the strength development on mortar specimen incorporating different percentage of GGBS, cured with CO_2 and water. The other properties such as water absorption, apparent weight, porosity, SEM and XRD are also examined on the mortar specimen. The level of replacement of cement with GGBS was varied from 10% to 50%. In all, six mixes, including the control mix, was studied.

For each mix twelve 70X70X70 mm cubes and six 100mm diameter and 150mm height cylindrical mortar specimens were casted incorporated with varying percentage of GGBS as partial replacement of cement. These specimens were de-molded after 22 hours. After de-molding half of the samples were water cured and remaining samples were kept for carbon di-oxide curing. For carbon di-oxide curing, the curing chamber with specimens was closed, vacuumed to a pressure of around 600 mm of Hg and maintained for 2 min before CO_2 was injected to remove all the gases from the chamber and then a constant pressure of 10psi was maintained for a period of 6 hours. The pressure inside the curing chamber was monitored by a pressure gauge attached on the curing chamber.

It was found that the short term CO_2 curing promoted early strength development, which is almost equal to that of water curing at 28-day. Durability performance of the carbon-dioxide cured mortar samples was compared with normally water cured. The CO_2 cured mortar specimens were exhibited more resistance to water absorption and chloride permeability. The micro-structural analysis i.e. SEM and XRD of the mortar samples were also observed during the study. It was concluded that slower strength development due to GGBS can be compensated by small duration of CO_2 curing of the specimen.

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CHAPTER 1

INTRODUCTION

1.1 IMPACT OF MODERN CONCRETE

Sustainability is important to the well-being of the planet, continued growth of the society, and human development. Concrete is the most widely used construction materials in the world. However, the production of Portland cement, an essential constituent of concrete, leads to the release of significant amounts of CO_2, a greenhouse gas. The environmental issues associated with greenhouse gases, in addition to natural resources issues, will play a leading role in the sustainable development of the cement and concrete industry.

To build structures and infrastructures that are cost-efficient, environmentally friendly, and durable, the impact of the building materials on local and worldwide air conditions must be examined. At the current rate of increase of cement production, worldwide cement production is expected to rise from about 2.5 billion tonnes in 2006 to about 5 billion tonnes by 2020 (Rubenstein, 2012). Thus, CO_2 emissions caused by Portland cement production are expected to rise by 100% from the current level (2020). For each metric ton of Portland cement clinker, 1.5 to 10 kg of NO_x is also released into the atmosphere. If the challenges associated with reducing CO_2, NO_x and other greenhouse gas are to be met.

A Proper disposal of waste materials that are produced from various industries is a serious problem in many countries. Generation of industrial waste materials and by-products is increasing as a result of industrialization as is the need for higher amounts of raw materials and fuel to accommodate the rapid increase in the world's population.

This obviously causes many environmental problems in the form of waste generation and raises the potential to contaminate water, air and soil resources. The safe disposal of waste is costly, and there is a lack of disposal sites that are suitably designed to handle such materials without causing detrimental effects on the environment. Therefore,

research has been directed towards finding alternative methods of utilizing waste materials and industrial by-products, where their harmful effects are minimized or even eliminated. The construction industry is one of the areas where the safe use of waste materials could have a promising future.

1.2 CONCRETE CURING

Curing is the maintaining of an adequate moisture content and temperature in concrete at early ages so that it can develop properties the mixture was designed to achieve. Curing begins immediately after placement and finishing so that the concrete may develop the desired strength and durability.

Without an adequate supply of moisture, the cementitious materials in concrete cannot react to form a quality product. Drying may remove the water needed for this chemical reaction called hydration and the concrete will not achieve its potential properties.

Temperature is an important factor in proper curing, since the rate of hydration, and therefore, strength development, is faster at higher temperatures. Generally, concrete temperature should be maintained above 50°F (10°C) for an adequate rate of strength development (Burg 1996). Further, a uniform temperature should be maintained through the concrete section while it is gaining strength to avoid thermal cracking.

For exposed concrete, relative humidity and wind conditions are also important; they contribute to the rate of moisture loss from the concrete and could result in cracking, poor surface quality and durability. Protective measures to control evaporation of moisture from concrete surfaces before it sets are essential to prevent plastic shrinkage cracking

Several important reasons for why we need curing are

- **Predictable strength gain**. Laboratory tests show that concrete in a dry environment can lose as much as 50% of its potential strength compared to similar concrete that is moist cured. Concrete placed under high temperature conditions will gain early strength quickly but later strengths may be reduced.

Concrete placed in cold weather will take longer to gain strength, delaying form removal and subsequent construction.

- **Improved durability**. Well-cured concrete has better surface hardness and will better withstand surface wear and abrasion. Curing also makes concrete more water- tight, which prevents moisture and water-borne chemicals from entering into the concrete, thereby increasing durability and service life.

- **Better serviceability and appearance**. A concrete slab that has been allowed to dry out too early will have a soft surface with poor resistance to wear and abrasion. Proper curing reduces crazing, dusting and scaling.

1.2.1 Importance of Curing

Curing is the process of controlling the rate and extent of moisture loss from concrete to ensure an uninterrupted hydration of Portland cement after concrete has been placed and finished in its final position. Curing also ensures to maintain an adequate temperature of concrete in its early ages, as this directly affects the rate of hydration of cement and eventually the strength gain of mortars. Curing of concrete must begin as soon as possible after placement & finishing and must continue for a reasonable period of time as per the relevant standards, for the concrete to achieve its desired strength and durability. Uniform temperature should also be maintained throughout the concrete depth to avoid thermal shrinkage cracks. Also protective measures to control moisture loss from the concrete surface are essential to prevent plastic shrinkage cracks. In a nut shell, curing process is designed primarily to keep the concrete moist by controlling the loss of moisture from the body of concrete, during the given period in which it gains strength.

Reasons to Cure Concrete

There are several important reasons why one should cure concrete:

- Concrete strength gain - Concrete strength increase with age as moisture and a favorable temperature is present for hydration of cement. An experimental investigation was conducted by "Cement, Concrete & Aggregates Australia" (CCAA) and the same was published in their data sheet on "Curing of Concrete," which has

been included in this article for reference. Fig.1.1 illustrates a comparison of the strength of concrete at 180 days of moist curing with various periods of moist curing (0, 3, 7, 14 & 28 days) and then allowing it to dry out (Gonnerman and Shuman 1928). From the graph, it can be observed that concrete allowed to dry out immediately, achieves only 40% of the strength of the same concrete water cured for the full period of 180 days.

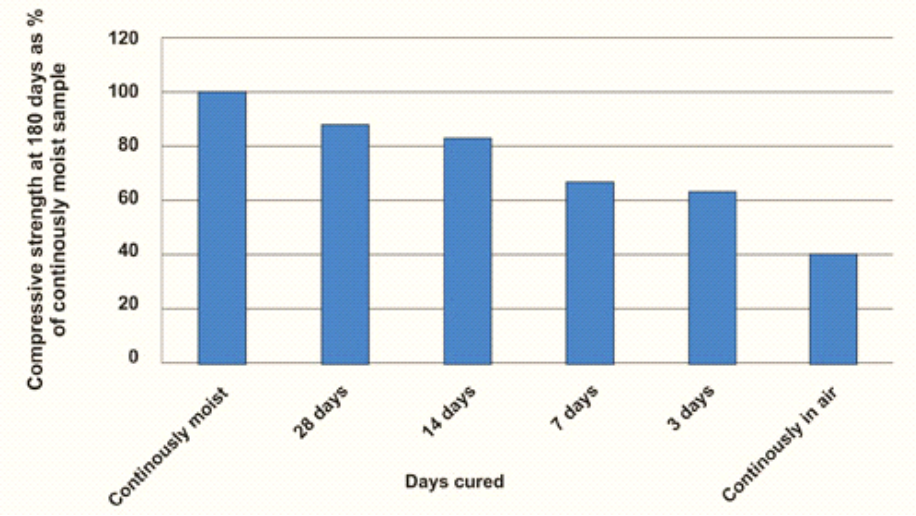


Fig. 1.1: Effect of duration of water curing on strength of concrete

- Improved durability of concrete – The durability of concrete is affected by a number of factors including its permeability, porosity and absorptivity. Well cured concrete can minimize thermal, plastic & drying shrinkage cracks, making concrete more water tight, thus preventing moisture and water borne chemicals from entering into the concrete and thereby increasing its durability.
- Enhanced serviceability - Concrete that is allowed to dry out quickly undergoes considerable early age shrinkage. Inadequate curing contributes to weak and dusty surfaces having a poor abrasion resistance.
- Improved microstructure - Material properties are directly related to their microstructure. Curing assists the cement hydration reaction to progress steadily and develops calcium silicate hydrate gel, which binds the aggregates leading to a rock solid mass, makes the concrete denser, decreases the porosity and enhances the physical and mechanical properties of concrete.

Right Time to Cure Concrete

- After concrete has been placed in its final position and during the initial set, bleed water rises to the concrete surface as plastic settlement occurs. During this period, if the rate of evaporation of bleed water is greater than the rising water, plastic shrinkage of the concrete occurs. Initial mist curing is necessary to keep the surface moist to prevent the surface from drying out.
- Between initial set and final set, intermediate curing would be needed if the finishing is complete prior to final set. This may be in the form of a barrier which prevents the loss of moisture from the concrete surface. e.g. covering the concrete surfaces with plastic sheets, waterproof paper, etc.
- After final set, meticulous curing will have to be done as per the procedures selected. Example water curing methods-Ponding, Misting, wet coverings with hessian cloth, Impermeable membrane curing, Curing compounds, etc.

Duration of Curing

The duration of curing of concrete depends on the grade and type of cement, mix proportion, desired concrete strength, shape and size of the concrete member and environmental & exposure conditions. The duration may vary from few days to a month. IS-456:2000 provisions for duration of Curing (Indian Standard-Plain & Reinforced concrete-Code of Practice).
Exposed surfaces of concrete shall be kept continuously damp or in a wet condition by ponding or by covering with sacks, canvas, hessian or other similar material and kept continuously wet for at least 7 days from the date of placing, in case of Ordinary Portland Cement (OPC) and at least 10 days when mineral admixtures or blended cements are used. In case of concrete where mineral admixtures or blended cements are used, it is recommended that the above minimum periods may be extended to 14 days, for assisting the secondary reaction.

1.2.2 Curing Methods and Materials

Concrete can be kept moist (and in some cases at a favorable temperature) by three curing methods:

- Methods that maintain the presence of mixing water in the concrete during the early hardening period. These include ponding or immersion, spraying or fogging, and saturated wet coverings. These methods afford some cooling through evaporation, which is beneficial in hot weather.

- Methods that reduce the loss of mixing water from the surface of the concrete. This can be done by covering the concrete with impervious paper or plastic sheets, or by applying membrane-forming curing compounds.

- Methods that accelerate strength gain by supplying heat and additional moisture to the concrete. This is usually accomplished with live steam, heating coils, or electrically heated forms or pads.

The method or combination of methods chosen depends on factors such as availability of curing materials, size, shape, and age of concrete, production facilities (in place or in a plant), esthetic appearance, and economics. As a result, curing often involves a series of procedures used at a particular time as the concrete ages. For example, fog spraying or plastic covered wet burlap can precede application of a curing compound. The timing of each procedure depends on the degree of hardening of the concrete needed to prevent the particular procedure from damaging the concrete surface.

- ***Ponding and Immersion***

  On flat surfaces, such as pavements and floors, concrete can be cured by ponding. Earth or sand dikes around the perimeter of the concrete surface can retain a pond of water. Ponding is an ideal method for preventing loss of moisture from the concrete; it is also effective for maintaining a uniform temperature in the concrete. The curing water should not be more than about 11°C (20°F) cooler than the concrete to prevent thermal stresses that could result in cracking. Since ponding requires considerable labor and supervision, the method is generally used only for small jobs.

- ***Wet Coverings***

  Fabric coverings saturated with water, such as burlap, cotton mats, rugs, or other moisture-retaining fabrics, are commonly used for curing. Treated burlaps that reflect light and are resistant to rot and fire are available.

- ***Fogging and Sprinkling***

  Fogging and sprinkling with water are excellent methods of curing when the ambient temperature is well above freezing and the humidity is low. A fine fog mist is frequently applied through a system of nozzles or sprayers to raise the relative humidity of the air over flat-work, thus slowing evaporation from the surface. Fogging is applied to minimize plastic shrinkage cracking until finishing operations are complete. Once the concrete has set sufficiently to prevent water erosion, ordinary lawn sprinklers are effective if good coverage is provided and water runoff is of no concern. Soaker hoses are useful on surfaces that are vertical or nearly so.

- ***Impervious Paper***

  Impervious paper for curing concrete consists of two sheets of craft paper cemented together by a bituminous adhesive with fiber reinforcement. The efficient means of curing horizontal surfaces and structural concrete of relatively simple shapes. An important advantage of this method is that periodic additions of water are not required. Curing with impervious paper enhances the hydration of cement by preventing loss of moisture from the concrete

- ***Plastic Sheets***

  Plastic sheet materials, such as polyethylene film, can be used to cure concrete. Polyethylene film is a lightweight, effective moisture retarder and is easily applied to complex as well as simple shapes. Its application is the same as described for impervious paper .Curing with polyethylene film (or impervious paper) can cause patchy discoloration, especially if the concrete

contains calcium chloride and has been finished by hard-steel troweling. This discoloration is more pronounced when the film becomes wrinkled, but it is difficult and time consuming on a large project to place sheet materials without wrinkles. Flooding the surface under the covering may prevent discoloration, but other means of curing should be used when uniform colour is important.

- ***Membrane-Forming Curing Compounds***

  Liquid membrane-forming compounds consisting of waxes, resins, chlorinated rubber, and other materials can be used to retard or reduce evaporation of moisture from concrete. They are the most practical and most widely used method for curing not only freshly placed concrete but also for extending curing of concrete after removal of forms or after initial moist curing. However, the most effective methods of curing concrete are wet coverings or water spraying that keeps the concrete continually damp. Curing compounds should be able to maintain the relative humidity of the concrete surface above 80% for seven days to sustain cement hydration.

- ***Internal Moist Curing***

  Internal moist curing refers to methods of providing moisture from within the concrete as opposed to outside the concrete. This water should not affect the initial water to cement ratio of the fresh concrete. Lightweight (low-density) fine aggregate or absorbent polymer particles with an ability to retain a significant amount of water may provide additional moisture for concretes prone to self-desiccation. When more complete hydration is needed for concretes with low water to cement ratios (around 0.30 or less), 60 kg/m^3 to 180 kg/m^3 (100 lb/yd^3 to 300 lb/yd^3) of saturated lightweight fine aggregate can provide additional moisture to extend hydration, resulting in increased strength and durability. All of the fine aggregate in a mixture can be replaced with saturated lightweight fine aggregate to maximize internal moist curing. Internal moist curing must be accompanied by external curing methods.

- ***Steam Curing***

  Steam curing is advantageous where early strength gain in concrete is important or where additional heat is required to accomplish hydration, as in cold weather. Two methods of steam curing are used: live steam at atmospheric pressure (for enclosed cast-in-place structures and large precast concrete units) and high-pressure steam in autoclaves (for small manufactured units). Only live steam at atmospheric pressure will be discussed here. A typical steam-curing cycle consists of (1) an initial delay prior to steaming, (2) a period for increasing the temperature, (3) a period for holding the maximum temperature constant, and (4) a period for decreasing the temperature.

- ***Insulating Blankets or Covers***

  Layers of dry, porous material such as straw or hay can be used to provide insulation against freezing of concrete when temperatures fall below 0°C (32°F).Formwork can be economically insulated with commercial blanket or insulation that has a tough moisture proof covering. Suitable insulating blankets are manufactured of fiberglass, sponge rubber, cellulose fibers, mineral wool, vinyl foam, and open-cell poly-urethane foam. When insulated formwork is used, care should be taken to ensure that concrete temperatures do not become excessive. Framed enclosures of canvas tarpaulins, reinforced polyethylene film, or other materials can be placed around the structure and heated by space heaters or steam. Portable hydric heaters are used to thaw subgrades as well as heat concrete without the use of an enclosure

- ***Electrical, Oil, Microwave, and Infrared Curing***

  Electrical, hot oil, microwave and infrared curing methods have been available for accelerated and normal curing of concrete for many years. Electrical curing methods include a variety of techniques: (1) use of the concrete itself as the electrical conductor, (2) use of reinforcing steel as the heating element, (3) use of a special wire as the heating element, (4) electric blankets, and (5) the use of electrically heated steel forms (presently the most

popular method). Electrical heating is especially useful in cold-weather concreting. Hot oil may be circulated through steel forms to heat the concrete. Infrared rays and microwave have had limited use in accelerated curing of concrete. Concrete that is cured by infrared methods is usually under a covering or enclosed in steel forms. Electrical, oil, and infrared curing methods are used primarily in the precast concrete industry.

1.3 CARBON DIOXIDE CURING OF CONCRETE

Carbon dioxide (CO_2) is a colourless, odourless, non-toxic gas that it is known as "Green House Gas". While carbon dioxide occurs naturally, it is the most common of the man-made greenhouse gases and is believed to be a significant contributor to global warming. Carbon dioxide is produced when any substance containing carbon is burned. It is also a product of breathing and of fermentation. Plants absorb carbon dioxide through photosynthesis, and plants and soil return some carbon dioxide to the atmosphere through respiration. However, man-made carbon dioxide emissions have created an imbalance in environment. There are now more carbon dioxide emissions going into the atmosphere than are being removed. This is primarily due to the burning of fossil fuel, thermal power plants and cement plants.

The current strategy on CO_2 mitigation is focused on the removal, recovery and disposal of CO_2 at the control sources. While carbon capture and storage (CCS) in geologic formation is promising, carbon capture and utilization (CCU) appears to be more rewarding. Flue gas carbon dioxide collected from cement kiln can be beneficially utilized in precast concrete production to reduce carbon emission, accelerate early strength, and improve durability of the products. It is accomplished through a carbonation curing of precast products at very early age. Carbon Dioxide curing is a short term curing regime which is used to accelerate the formation of CSH gel and Calcite by converting calcium tri-silicate and calcium di-silictae, formed during the hydration of cement.

1.3.1 Advantages

- Concrete can be an even more environmental friendly green building product if CO_2 curing is used in place of steam curing or water curing.
- Carbonation curing is a chemical reaction of the cement binder with CO_2 rather than water. This method of curing can make precast products stronger, less porous, and more durable.
- Carbonation curing using CO_2 could improve production cycle efficiency as compare to steam curing.
- The technology, if successfully demonstrated, will provide a useful application for CO_2 that will reduce CO_2 emission associated with concrete production cycle.
- Reduces curing time, so concrete productivity can be increased.
- Decreases the cost of curing, as it is one time curing process and cost of extraction of CO_2 is very less.
- Reduces energy consumption and produces dimensionally more stable products

1.3.2 Disadvantages

- Not possible for cast-in-situ structures, as it required a proper chamber for curing.
- Require skilled workers for curing
- Large capital investment is required for initial set-up

1.4 OBJECTIVE OF PRESENT WORK

The main objective of the proposed work is to compare the effect of CO_2 curing on the properties of mortar made by GGBS as partial replacement of cement. The overall objective is to use industrial bi-product in materials as well as in curing. The effect of Carbon Dioxide curing and water curing has been studied on the various parameters and compared.

1.5 ORIENTATION OF THE THESIS

In chapter-1 we explain about the introduction of the study, it enlighten the curing types and methods. It also clarifies about CO_2 curing, its advantages and disadvantages. Chapter-2 illuminates about the study of the published papers regarding CO_2 curing and GGBS, which helps in showing a path to a new study and also help as a reference. Chapter-3 describes about the experimental programme done during the present study, it also explains about the materials required during the study and also the properties of that materials. It gives detailed information about the experimental procedure adopted during the study. Chapter-4 explains about results and gives reasons for those results. It describes the results of the test performed during the study. Chapter-5 gives the conclusion drawn from the results and discussion during the study.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

An investigation was conducted into the beneficial utilization of captured CO_2 for early-age curing of precast concrete products. The performance of the carbonation-cured mortar specimens were compared to that of water cured mortar specimens to investigate the possibility of replacing water curing with CO_2. The early-age carbonation curing was performed for a short period after an initial curing in a controlled environment and then sealed. The effect of the carbonation curing was studied in terms of accelerated strength, and durability. Durability performance of the carbonation-cured mortar specimen was compared with normally hydrated references.

A beneficial use of carbonation as an auxiliary curing regime for mortar cubes was studied in an attempt to reduce water curing time, improve durability performance and explore the possibility of using mortar cubes to sequester carbon dioxide. The process is unique in promoting enhanced durability performance of concrete. The aim of this study is to promote the use of available GGBS from cement industry as a partial cement

replacement. Binary combinations of Portland cement (PC) and ground granulated blast furnace slag (GGBS) were investigated for their effects on the compressive strength of mortar cured under Carbon-Dioxide curing and Water curing conditions.

The environmental concerns related to the production of cement in terms of the energy consumption and the emission of CO_2 lead to the search for more environmentally viable alternatives to cement. One of those alternative materials is ground granulated blast-furnace slag is used as a partial replacement to cement. The utilisation of supplementary cementitious materials is well accepted because of the several improvements possible in the concrete composites and due to the overall economy. The present study is an effort to quantify the 3, 7, 28-day cementitious efficiency of ground granulated blast furnace slag (GGBS) in concrete at the various replacement levels.

3.2 EFFECT OF GGBS AS PARTIAL REPLACEMENT OF CEMENT

Hwang and Lin (1986), this paper explains the GGBS mortars at different ages and at the various replacement levels have been re-plotted (Fig. 2.1). This shows that there is a maximum percentage for obtaining an equivalent strength (equivalent to the normal mortar at that age) and also, that there is a specific percentage of GGBS at which the maximum strength can be obtained at that age. From this, it can be said that the compressive strength of GGBS concretes depend both on percentage replacement level and on the age

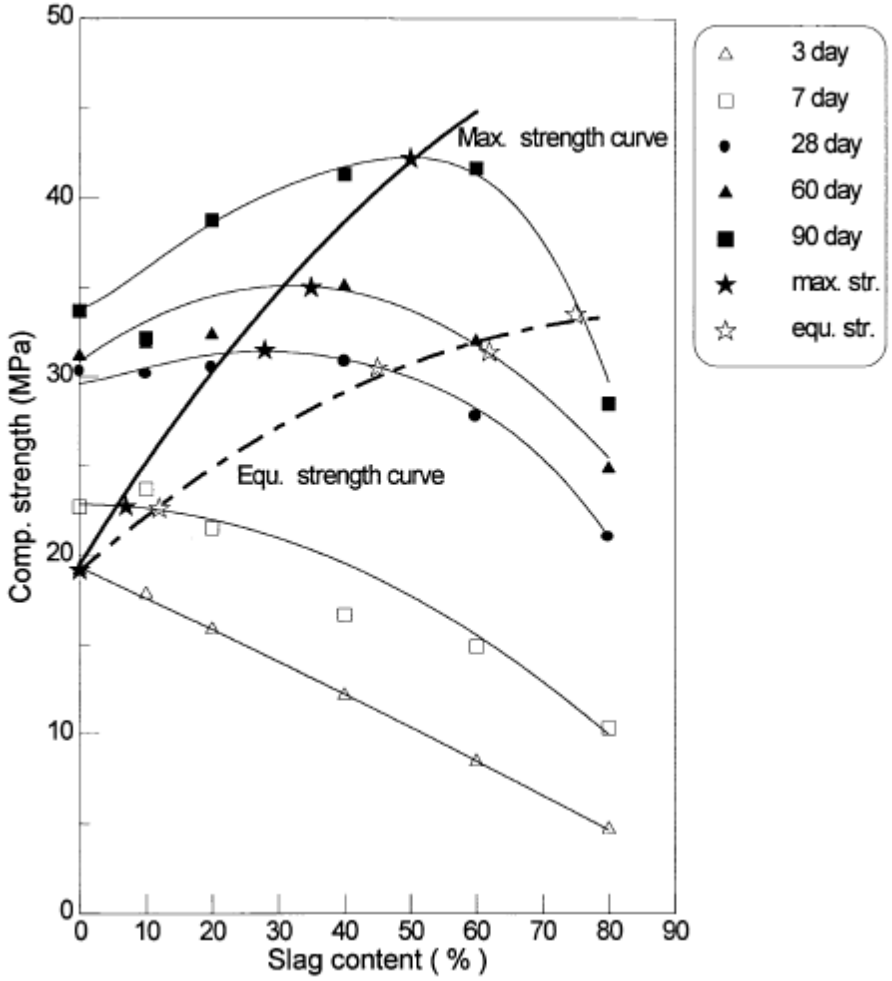


Fig.2.1. Effect of slag content on strength development in cement mortars**,** Hwang and Lin (1986)

Babu and Kumar (2000), this paper presents an effort to quantify the 28-day cementitious efficiency of ground granulated blast furnace slag (GGBS) in concrete at the various replacement levels. It was observed that this overall strength efficiency of GGBS concretes can also be defined through a procedure adopted earlier for other cementitious materials like fly ash and silica fume. The overall strength efficiency was found to be a combination of general efficiency factor, depending on the age and a percentage efficiency factor, depending upon the percentage of replacement as was the case with a few other cementitious materials like fly ash and silica fume reported earlier. This study was primarily concerned with the evaluation of the efficiency of GGBS in concretes

containing normal Portland cements. The replacement levels in the concrete studied varied from 10% to 80% and the strength efficiencies at the 28 days were calculated.

According to the study of the following paper it is seen that the earlier proposed method for evaluating the efficiency of pozzolans like fly ash and silica fume was also found to be appropriate for the evaluation of GGBS. This method recognises that the ``overall strength efficiency factor (k)" of the pozzolan is a combination of the two factors the ``general efficiency factor (ke)" and the ``percentage efficiency factor (kp)." The evaluations have shown that at 28days, 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 seen that the ``overall strength efficiency factor (k)" was an algebraic sum of a constant ``general efficiency factor (ke)," with a value of 0.9 at 28 days, and a ``percentage efficiency factor (kp)," varying from +0.39 to ÿ0.20, for the cement replacement levels varying from 10% to 80% studied. Overall, the prediction of the strength of concretes varying from 20 to 100 MPa with GGBS levels varying from 10% to 80% by this method was found to result in a regression coefficient of 0.94, which was also the same for normal concretes, it was observed that for obtaining equal strength in concretes at 28 days, by adopting the efficiencies evaluated in the present investigation, it will be required to have an additional 8.5% and 19.5% increase in the total cementitious materials at 50% and 65% cement replacement levels, agreeing well with the values 10% and 20% additional material reported earlier.

Otaibi (2007), the main aim of the study is the environmental concerns related to the production of cement in terms of the energy consumption and the emission of CO_2 lead to the search for more environmentally viable alternatives to cement. One of those alternative materials is ground granulated blast-furnace slag is used not only as a partial replacement to cement but also as the sole binder in the form of alkali-activated slag (AAS) to produce concrete. In addition to a control OPC mix, an OPC/slag mix with 60% cement replacement by GGBS, and also AAS mixes were prepared with slag as the sole binder, activated with water glass at two dosages, 4% and 6% Na_2O (by weight of slag). Two types of water glass were used, one in a solution form and the other in a solid granules form.

This paper presents the results of the durability related tests that were carried out which included, chloride penetration resistance, porosity, carbonation, and alkali–silica reaction. The effect of the different parameters including the activator type and dosage are discussed. The results give indications on the good durability of alkali-activated slag concrete compared to conventional OPC concrete.

According to this paper it was concluded that, choice of the type of activator and dosage is very important in AAS concrete with the higher dosage resulting in higher strength and the higher silicate modulus of the activator resulting in higher strength.

Replacing 60% of OPC by GGBS results in an increase in porosity compared to the OPC mix of the same w/c ratio while it results in lower porosity when compared to the OPC mix with the same workability level. The increase of the Na2O dosage in AAS concrete, where the activator has an Ms = 1.0, results in a decrease in porosity. But in the case of the AAS concrete, with the activator having Ms = 1.65, the porosity increases with the increase of the Na2O dosage.

Oner and Akyuz (2007), this paper presents a laboratory investigation on optimum level of ground granulated blast-furnace slag (GGBS) on the compressive strength of concrete. GGBS was added according to the partial replacement method in all mixtures. A total of 32 mixtures were prepared in four groups according to their binder content. Eight mixes were prepared as control mixtures with 175, 210, 245 and 280 kg/m3 cement content in order to calculate the Bolomey and Fe´ret coefficients (KB, KF). For each group 175, 210, 245 and 280 kg/m3 dosages were determined as initial dosages, which were obtained by removing 30 percentage of the cement content of control concretes with 250, 300, 350, and 400 kg/m3 dosages. Test concretes were obtained by adding GGBS to concretes in an amount equivalent to approximately 0%, 15%, 30%, 50%, 70%, 90% and 110% of cement contents of control concretes with 250, 300, 350 and 400 kg/m3 dosages. All specimens were moist cured for 7, 14, 28, 63, 119, 180 and 365 days before compressive strength testing. The test results proved that the compressive strength of concrete mixtures containing GGBS increases as the amount of GGBS increase. After an optimum point, at around 55% of the total binder content, the addition of GGBS does not improve the compressive strength.

The early age strength of GGBS concretes was lower than the control concretes with the same binder content. However, as the curing period is extended, the strength increase was higher for the GGBS concretes. The reason is that, the pozzolanic reaction is slow and the formation of calcium hydroxide requires time. The compressive strength of GGBS concrete increases as the GGBS content is increased up to an optimum point, after which the compressive strength decreases. There is an optimum level for the efficient use of GGBS content, which yields the highest strength. The optimum level of GGBS content for maximizing strength is at about 55–59% of the total binder content.

Pavía and Condren (2008), according to this study, it has been demonstrated that GGBS improves the general performance of PC concrete, decreasing chloride diffusion and chloride ion permeability, reducing creep and drying shrinkage, increasing sulfate resistance, enhancing ultimate compressive strength, and reducing heat of hydration and bleeding. It has also been suggested that GGBS may increase concrete durability in the aggressive environment of silos. In order to investigate this theory, a simulation study was carried out by immersing samples of mortars incorporating increasing amounts of GGBS in a silage effluent solution and a magnesium sulphate solution. Over the course of an experiment consisting of three, 28-day cycles of immersion in the silage effluent, the sample performance was evaluated by testing permeability, porosity, water absorption, capillary suction, compressive strength, and mass loss.

According to the results obtained, the OPC samples suffered the highest rise in permeability and porosity, and the greatest loss in both mass and compressive strength. In addition, the durability of the mortars, when subjected to both salt crystallization and silage effluent cycles, increased with increasing amounts of GGBS. The significant rise in capillary suction, water absorption, and permeability over the course of the experiment indicates that the damage induced by the effluent is not as superficial as previously reported. Loss in mass and increase in permeability were found to be the most reliable indicators of corrosion, as they gave the most dramatic and uniform results.

Alhozaimy et al (2011), the aim of this study is to promote the use of available natural dune sand from desert areas as a partial cement replacement. Binary and ternary combinations of ground dune sand (GDS), Portland cement (PC) and ground granulated

blast furnace slag (GGBS) were investigated for their effects on the compressive strength of mortar cured under standard or autoclave curing conditions. The results showed that the compressive strength decreased significantly with increasing GDS and GGBS contents under standard curing. However, with autoclave curing, all of the binary and ternary mixtures yielded mortar with a compressive strength higher than that of the control sample. The autoclave-cured ternary combination of 30% GDS, 50% PC and 20% GGBS showed the highest compressive strength.

Siddique and Bennacer (2012), this paper presents comprehensive details of the physical, and chemical properties, and hydration reaction. It also covers the workability, setting times, compressive strength, chloride and sulphate resistance of cement paste and mortar.

Use of GGBS accelerates the hydration of ordinary Portland cement at early hours of hydration. Consistency of cement decreased with the increase in GGBS content. Inclusion of GGBS enhanced the workability of mortar/concrete, and also increased the setting times of cements. Strength of mortar incorporating GGBS is related to the surface area and particle size distribution (PSD) of GGBS. Blended cements containing slag (60% replacement) demonstrated superior sulphate resistance than ordinary Portland cement. Use of GGBS enhances the chloride binding capacity increased of cement mortar.

Sabet et al (2013), Ground granulated blast-furnace slag (GGBS) is a green construction material used to produce durable concrete. The secondary pozzolanic reactions can result in reduced pore connectivity; therefore, replacing partial amount of Portland cement (PC) with GGBS can significantly reduce the risk of sulphate attack, alkali–silica reactions and chloride penetration. However, it may also reduce the concrete resistance against carbonation. Due to the time consuming process of concrete carbonation, many researchers have used accelerated carbonation test to shorten the experimental time. However, there are always some uncertainties in the accelerated carbonation test results. Most importantly, the moisture content and moisture profile of the concrete before the carbonation test can significantly affect the test results.

In this work, more than 200 samples with various water–cementitious material ratios and various replacement percentages of GGBS were cast. The compressive strength, electrical resistivity, chloride permeability and carbonation tests were conducted. The moisture loss and microstructure of concrete were studied. The partial replacement of PC with GGBS produced considerable improvement on various properties of concrete.

2.3 EFFECT OF CARBON DIOXIDE CURING

Rostami et al (2011)(a), describes the microstructure of Ordinary Portland Cement paste subjected to early age carbonation curing was studied to examine the effect of early carbonation on performance of paste at different ages. The study was intended to understand the mechanism of concrete carbonation at early age through the microstructure development of its cement paste. Early carbonation was carried out after 18-hour initial controlled air curing.

The microstructure characterized by XRD, TGA, 29Si NMR and SEM was correlated to strength gain, CO_2 uptake and pH change. It was found that early carbonation could accelerate early strength while allowing subsequent hydration. The short term carbonation created a microstructure with more strength-contributing solids than conventional hydration. Calcium hydroxide was converted to calcium carbonates, and calcium–silicate–hydrate became intermingled with carbonates, generating an amorphous calcium–silicate–hydro-carbonate binding phase.

Table 2.1: Different Curing regimes of batches was shown

Batch ID	Initial Curing	Subsequent Curing	Test Age
B_1 20A	20h air curing	0	20h
B_2 20S	20h sealed curing	0	20h
B_3 18A+2C	18h air curing+2h carbonation	0	20h
B_8 20A	20h air curing	27 days in sealed bag	28 days
B_9 20S	20h sealed curing	27 days in sealed bag	28 days
B_{10} 18A+2C	18h air curing+2h carbonation	27 day in sealed bag	28 days

Table 2.2: Strength Development and Ph of different batches was shown

Batch ID	Strength (MPa)	pH
B_1	31	12.6
B_2	35.8	13
B_3	50.0	11.3
B_8	47.2	12.9
B_9	97.2	13.1
B_{10}	76.8	11.8
B_{11}	123.7	12.3

Rostami et al (2012), an investigation was conducted into the beneficial utilization of captured CO_2 for early-age curing of precast concrete products. The performance of the carbonation-cured concrete was compared to that of steam curing to investigate the possibility of replacing steam curing with carbonation. The early-age carbonation curing was performed for a short period after an initial curing in a controlled environment. The effect of the carbonation curing was studied in terms of carbon uptake, accelerated strength, and durability.

It was found that the short term carbonation promoted early strength development, while subsequent hydration was essential to obtain later age properties. Durability performance of the carbonation-cured concrete was compared with steamed and normally hydrated references. The carbonation-cured concrete exhibited more resistance to chloride permeability, ion migration, sulphate attack, and freeze-thaw damage. The improved durability by carbonation is attributed to the significantly reduced calcium hydroxide content at the carbonated concrete surface.

Rostami et al (2011)(b), explains a beneficial use of carbonation as an auxiliary curing regime for concrete pipes was studied in an attempt to reduce steam curing time, improve durability performance and explore the possibility of using concrete pipe to sequester carbon dioxide. Durability performance of the carbonated concretes was characterized by carbon uptake, strength gain, pH, calcium hydroxide content, permeability, sorptivity and sulfate and acid resistance. It was found that initial curing using steam is necessary to facilitate carbonation. Although the contribution of early carbonation to strength gain is not noticeable after initial steam curing, the process is unique in promoting enhanced

durability performance of concrete. The early carbonation leads to a reduction in calcium hydroxide near the surface while maintaining a pH above the corrosion threshold value at the core. Carbonated concretes also exhibit improved resistance to sulfate attack, water absorption, and chloride ion penetration.

According to the study it was observed that the carbonated concretes are not more susceptible to strong acid attack. The early carbonation treatment of concrete resulted in decreased chloride ion migration, possibly as a result of the elimination of hydroxyl ions and precipitation of calcium carbonate within the surface layer. Thus, early carbonation could lower the conductivity of the pore solution. Although this result was obtained through RCPT, which is an electrically induced chloride migration test, the reduced ion migration through the carbonated concrete might be indicative of improved resistance to ion diffusivity in the carbonated surface zone, serving as a barrier to ion movement.

The resistance to initial sorptivity of carbonated concrete could be noticeably enhanced. This improvement suggests a microstructural modification in the carbonated surface zone in terms of a reduction in capillary water suction through the unsaturated concrete. This decrease in capillary suction and total capillary porosity of the carbonated concrete could be considered as another enhancement in the durability performance due to the carbonation treatment.

An early carbonation process applied after steam curing did not make noticeable contribution to the rapid strength gain, nor did immediate carbonation after compact forming without steam curing. Steam seems to be necessary to facilitate carbonation. Subsequent hydration with additional moisture is needed for carbonated concrete to be comparable to hydration reference.

Shi et al (2012), this study investigated the strength development and weathering properties of steam- and CO2-cured full size lightweight concrete blocks. Some freshly moulded lightweight concrete blocks were taken from a block manufacture plant and cured in a CO2 curing tank in lab. Steam-cured lightweight concrete blocks were randomly taken from the same plant. Several hundreds of concrete blocks after steam and CO_2 curing were stockpiled outside for winter exposure.

The compressive strength of CO_2-cured blocks was similar to that of steam-cured ones. It continued to increase when blocks were placed in a moist environment after steam and CO_2 curing. However, steam-cured blocks showed faster strength development rate than CO_2-cured ones did, and they behaved the same during the outdoor winter exposure, CO_2-cured blocks demonstrated lower drying shrinkage and water absorption than steam-cured ones after 180 days of outdoor winter exposure. This indicated that CO_2-cured concrete blocks had better dimensional stability, but similar weathering properties to steam-cured ones.

Liwu and Panesar (2013), investigates pastes containing 0–40% reactive MgO and the effect of accelerated carbonation curing on the: formation of new carbonate phases, microstructural development, and micro-hardness. Outcomes from this study revealed that the primary Ca and Mg-bearing carbonates formed are calcite, aragonite, magnesium calcite, and nesquehonite. The combined effect of carbonation and reactive MgO resulted in: a reduction in pore size and total pore volume, increase in apparent density, and greater micro-hardness compared to OPC paste. The chemical processes, and physical properties revealed that the dense inter-connected network structure consisting of Ca and Mg carbonates is a significant factor that influences the micro-hardness.

Cong et al (2013), the paper presents the results of an experimental study on properties of concrete prepared with recycled mortar aggregate (RMA) that has been modified by a CO_2 curing method. The experimental investigation was conducted in two parts. Firstly, the properties such as density, 10% fine value, and water absorption of CO_2 improved RMA were determined. Secondly, the fresh, hardened and durability properties including slump, compressive and tensile splitting strength, drying shrinkage and chloride penetrability of the concretes prepared with RMA and CO_2 cured aggregates (CI-RMA) were determined. It was found that the density, and 10% fine value of the CI-RMA was higher, and the water absorption of the CI-RMA was lower when compared to the untreated RMA. For the concrete, not only was there an improvement in the mechanical properties and resistance to chloride ion penetration for the concrete prepared with CI-RMA, but also the drying shrinkage was decreased.

CHAPTER-3

EXPERIMENTAL PROGRAMME

3.1 GENERAL

The aim of this study is to analyse and compare the effect of carbon dioxide curing and normal water curing on mortar specimen incorporating GGBS as partial replacement of cement. An effort has been made to generate a mortar mix with GGBS which is a by-product of the industrial waste, and to introduce CO_2 curing in the system.

GGBS concrete has slightly slower strength development at early ages, but will have equal, if not greater strength after 28 days compared to non GGBS concrete cured with water (Hwang,1986). Compared to this, CO_2 curing leads to early strength development (Goodbrake,1979). Therefore the focus of the study was to compare the strength development on mortar specimen incorporating different percentage of GGBS, cured with CO_2 and water. The other properties such as water absorption, apparent weight, porosity, SEM and XRD are also examined on the mortar specimen.

3.2 MATERIALS

For the casting of mortar specimens, the basic materials required were sand, cement and GGBS and water. The properties of these materials required were discussed here under.

3.2.1 Cement

Fig 3.1: Cement used in the present study.

Cement is a binding material that sets and hardens when water is added to it causing initiation of hydration reaction, which further results in the formation of CSH gel around other particles which acts as link between them and can bind them together. Other supplementary cementing materials can also be used with cement but cement is considered necessary component for the initiation of the hydration reaction without which other pozzolonas cannot show any binding property.

In the present study, 43-grade Ordinary Portland Cement (OPC) manufactured by JK Lakshmi Cement Company was used. Figure 3.2 shows the cement being used for developing different mixes. Various physical properties of cement are shown in Table 3.2. It can be observed from the table that the physical properties of the cement was complying with the specifications of IS 8112: 1989. XRF (X-Ray Florescence) was performed on the sample of cement and different compounds with their percentage, i.e. the chemical composition of cement used is presented in Table 3.3.

Table 3.1: Physical Properties of Cement used in the study

Property	**Value**	**IS 8112:1989 Specifications**
Grade	OPC-43	OPC-43
Specific Gravity	3.12	3.10-3.25
Initial Setting time	100 min	30 minutes, minimum
Final Setting time	170 min	600 minutes, maximum
Blaine Fineness	3250 cm^2/g	2250 cm^2/g
28-Day Compressive Strength	48.21 MPa	43-58 MPa

Table 3.2: Chemical composition of cement observed present study

Constitient	**Cement Used**	**IS 8112:1989 Specifications**
CaO	63.49 %	Max 67%
SiO_2	21.25 %	Max 25%
Al_2O_3	4.74 %	Max 8%
Fe_2O_3	4.30 %	Max 6%
SO_3	2.92 %	Max 3.5%
MgO	1.02 %	Max 6%
Ratio of aluminia to iron oxide	1.12	Min 0.66%

3.2.2 Sand

Figure 3.2: River Sand being used in the study

Sand used in this study was natural river sand, which belongs to Zone II. River sand from Pathankot as shown in Figure 3.1 was used. River sand has a specific gravity of 2.59 and water absorption of 1.63%. Sieve analysis of the sand used in the study is shown in table 3.1. Sand was used in oven dry condition, to minimize the change in moisture content of sand due to various environmental factors.

Table.3.3: Sieve Analysis of Fine Aggregate

Sr. No.	**IS-Sieve (mm)**	**Wt. Retained (gm)**	**%age Retained**	**%age passing**	**Cumulative % retained**
1	4.75	26	2.6	97.4	2.6
2	2.36	107	10.7	86.7	13.3
3	1.18	164	16.4	70.3	29.7
4	600 µ	146	14.6	55.7	44.3
5	300 µ	198	19.8	35.9	64.1
6	150 µ	272	27.2	8.7	91.3
7	Pan	87	8.7		
TOTAL		1000		SUM	245.3
Zone II		FM= 2.45			

3.2.3 Ground Granulated Blast-furnace Slag (GGBS)

GGBS is a by-product obtained from the blast furnace in the production iron, copper and steel. When molten slag is quickly quenched from a high temperature with water in pond

or powerful water jets, most of the lime, magnesia, silica and alumina are held in non-crystalline or glassy state. This GGBS should be finely grounded into particle size of less than 45μm (Sheen et al. 2013) to be used for replacing cement. GGBS is commonly used as a cementitous material and may be used as substitute of Portland cement in the replacement percent of 0% to 50% (Buokini et al. 2009) to enhance the workability and durability properties. The use of blended cement in construction is widely agreed to provide an important benefit of environmental protection.

Fig 3.3: GGBS being used in the study

In the present study, a product Alcofine of Counto Microfine Products Pvt. Ltd., has been used as is shown in Figure 3.10. The GGBS was having specific gravity of 2.9 and Blaine's fineness value of 4490cm^2/g. The SEM image of the GGBS shown in Figure 3.4 indicates that particle size of GGBS being less than 45μm. As shown in Table 3.4, GGBS was having a high SiO_2 content of 73.47% and lime (CaO) as 12.40%. Figure 3.5 indicates peaks being observed for different elements when their electrons returned to their K shell. Figure 3.6 shows XRD graph of GGBS at reference angles (2θ) varying from 20^o to 80^o and it was found from the results that GGBS was containing Fe_3Si, AlFe and $FeAl_2Si$ with a SemiQuanit of 6, 17 and 77% respectively.

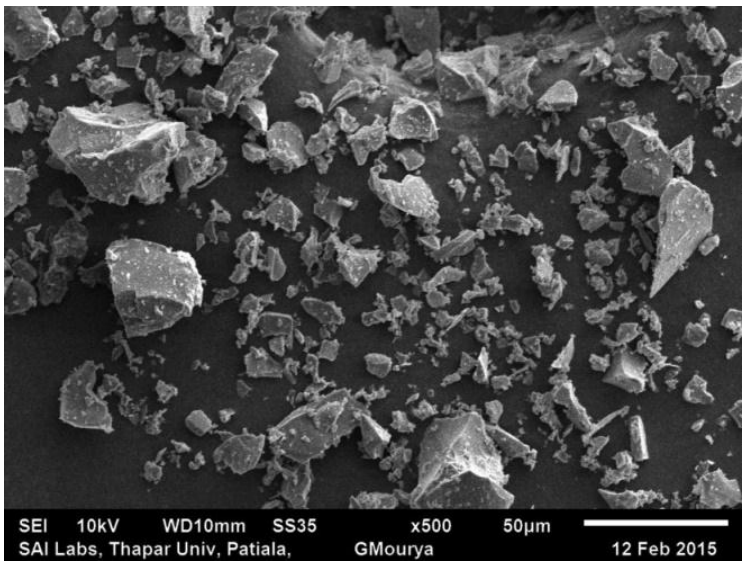


Fig. 3.4: SEM image of the GGBS at 50µm scale

Table 3.4: Chemical composition of GGBS

Constituent	Composition
CaO	12.40
SiO_2	73.47
Al_2O_3	4.35
SiO_2	5.48
MgO	2.14

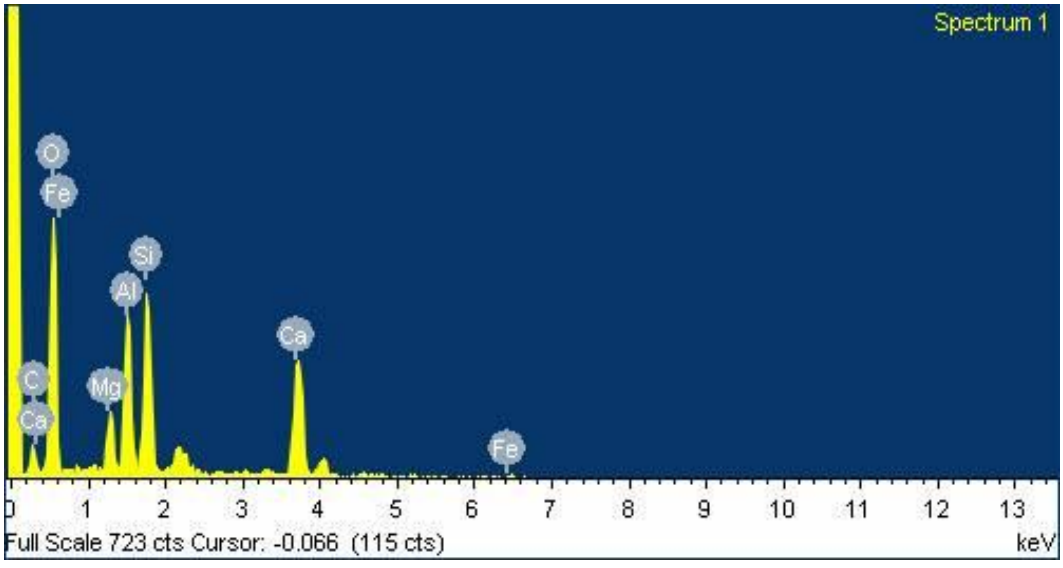


Fig. 3.5: Peaks observed for the sample of GGBS under EDS

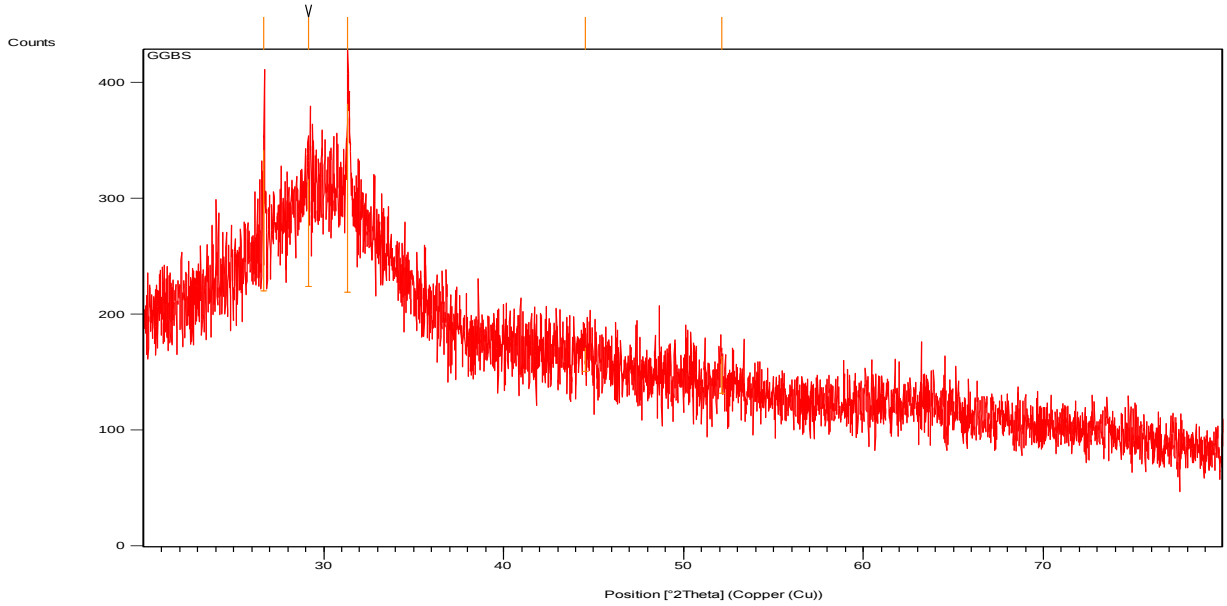


Fig. 3.6: XRD graph of GGBS at various reference angles (2θ)

3.2.4 Water

Water is an important ingredient of concrete as it actively participates in the chemical reaction with cement. Since it helps to form the strength giving cement gel, the quantity and quality of water is required to be looked into very carefully. Potable water is generally considered satisfactory. In the present investigation, tap water was used for both mixing and curing purposes.

3.3 MIX PROPORTIONS

A total of six mixtures (S_0-S_5) as summarized in table were designed and tested during the preliminary laboratory study. All the mixes were tested in the Structural Laboratory of Thapar University, Patiala. The idea was to get the optimum level of replacement of Portland cement with GGBS, to make the mix more economical, environmentally friendly. GGBS was replaced with cement by weight and tests were performed accordingly. In the mix water to binder ratio and sand to binder ratio was kept constant.

Table: 3.5. Mix Proportion of Mortar Samples

NO.	GGBS (Kg/m^3)	Cement (Kg/m^3)	GGBS % Replacement of Cement	Sand (Kg/m^3)	Added Water (Kg/m^3)	W/C Ratio
S_0	0	550	0%	1100	247.5	0.45
S_1	55	495	10%	1100	247.5	0.45
S_2	110	440	20%	1100	247.5	0.45
S_3	165	385	30%	1100	247.5	0.45
S_4	220	330	40%	1100	247.5	0.45
S_5	275	275	50%	1100	247.5	0.45

During mixing, fine sand was measured in a tray by weight and subsequent ratio of cement and GGBS was added to it. After that, dry mixing was done till all the particles gets uniformly mixed and water was added to it. Firstly half of the water was added and mixing was done for some time and after that all the water was poured and proper mixing was done. After mixing the mortar paste was filled in the moulds and these moulds were vibrated with the help of plate-vibrater for about 2 minutes to remove the air bubbles, after that all the moulds were placed on the floor for final setting.

3.4 CURING METHODS

Curing is the maintaining of an adequate moisture content and temperature in concrete at early ages so that it can develop properties of the material, for which the mixture was designed to achieve. Curing begins immediately after placement and finishing so that the concrete may develop the desired strength and durability.

CO_2 curing and water-curing was used during the study. However, the CO_2 curing was seldom used in large-scale industry production, whereas water curing has been well accepted and marketed. The limiting factor for carbonation curing can be associated with the cost of carbon dioxide (CO_2) gas production. The high cost of CO_2 could not be justified economically by the accelerated curing. The non-uniform microstructure created by carbonation was a concern toward durability performance. With recently developed carbon-capture technologies, high-purity carbon dioxide can be mass produced at

relatively low cost [Intergovernmental Panel on Climate Change (IPCC) 2005]. Because of the significantly reduced energy consumption in the CO_2 recovery process, the cost of CO_2 curing can be comparable to or even lower than that of water curing. The low-cost CO_2 could make it possible for concrete plants to utilize carbon dioxide through carbonation curing and concurrently achieve carbon storage in concrete. The details of both CO_2 curing and water curing are mentioned in the following section:

3.4.1 Carbon Di-oxide Curing

Carbon Di-oxide gas used in this study was purchased from "lalit gas services", Patiala (Punjab). Carbon Di-oxide cylinder was provided with a pre-heater so as to avoid interruption in the gas flow as the property of CO_2 is to freeze when released. The CO_2 curing set-up is shown in Fig. 3.8, consisting of inlet, outlet, vacuum pump, inlet pressure gauge, outlet pressure gauge and safety valve. Inlet and outlet was provided with a stop valve, to control the entry and exit of the gas flow. The safety valve pins up when the gas inside the chamber fills beyond the limit.

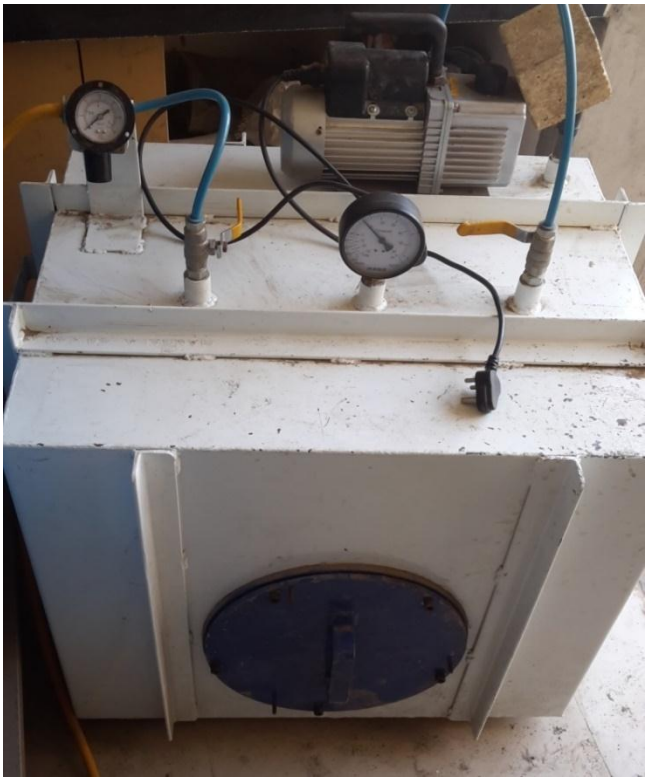


Fig. 3.7: CO_2 Curing Chamber

The pressure inside the curing chamber was monitored by a pressure gauge attached on the curing chamber. The pressure of 10psi was maintained during the study. After casting is done, the specimens were put into a curing chamber for CO_2 curing. Then the curing chamber with specimens was closed and vacuumed to a pressure of around 600 mm of Hg and maintained for 2 minutes before CO_2 gas was injected. The pressure of CO_2 inside the chamber was controlled by a regulator on the CO_2 tank and was monitored constantly during the CO2 curing period. After 6-hr of curing is done, the extra CO_2 gas was released in the environment and the specimens were taken out of the curing tank. These specimens after curing were sealed using polythene and stock piled in the lab

3.4.2 Water Curing

Out of the total specimen casted, half of the specimens were taken to water curing. Water curing was performed in the curing tank filled with normal tap water. The curing temperature was maintained at 27 ^{0}C and the relative humidity was kept at 100%.

3.5 EXPERIMENTAL PROGRAMME

3.5.1 Introduction

The primary purpose of this study is to compare carbon dioxide curing with water curing using GGBS as partial replacement of cement. The main aim of the study is to see the effect of carbon-oxide curing on mixes with different percentage of GGBS varying from 0%-50% as partial replacement of cement in the mortar specimens with binder to sand ratio 1:2 and w/c ratio as 0.45. The mixes must also have sufficient flow-ability for a successful concreting operation. This objective will be achieved using trial mixes.

Table 3.6: Tests and Codes

TEST	Code
Compressive strength	IS:516-1959
Water Absorption and Porosity	ASTM 642
Rapid Chloride Permeability Test	ASTM 642

The desired destructive test performed was Compressive strength whereas non-destructive performed were Water Absorption, Porosity, Rapid Chloride Permeability,

SEM and XRD. These entire tests were performed to compare the effect of carbon-dioxide curing and water curing. The details of the tests performed with the corresponding standards used, is described in the table 3.6.

3.5.2 Compressive Strength

Compressive strength is the capacity of a material or structure to withstand axially directed pushing forces. When the limit of compressive strength is reached, materials are crushed. Compressive strength is often measured on a universal testing machine.

Figure 3.8: Universal Testing Machine.

After curing period was completed, three mortar specimens of each mix and curing condition was taken. Water cured specimens were kept in air for surface drying until then, the CO_2 cured samples were kept for testing purposes, the test cubes were placed on the platform of a compressive testing machine without any packing between the cube and the plate of the testing machine. The cubes were tested perpendicular to the face of casting, and uniform and steady load was applied. Compressive strength of mortar cubes were tested with a pace rate of 0.4 KN/sec. Three cubes were tested for each mix and the

average compressive strength of these three cubes was considered as the compressive strength of the mix.

The compressive strength was then calculated according to the formula:

$$\sigma = P / A$$

Where, σ = Compressive Strength (N/mm^2)

P = Maximum load (N) and

A = Cross section area of cube (mm^2)

3.5.3 Water Absorption and Porosity

The water absorption test was conducted as per ASTM C 642 in order to determine the increase in resistance towards water penetration in concrete.

The mortar specimens were prepared and cured with carbon-dioxide curing and water curing using GGBS as partial replacement of cement as described earlier. After curing period was completed, two mortar specimens of each mix and curing condition was taken, the specimens were oven dried at 110˚C in oven, establishing a mass equilibrium of less than 0.5% between two measurements at 24 hours intervals. After that the cubes were taken out and allowed to cool, then the cubes were immersed in water at room temperature for 48 hours and saturated mass after immersion was calculated with the help of a weighing balance with an accuracy of 0.05 kg.

After the water absorption was measured, then the specimens were placed in suitable receptacle, filled with tap water and were boiled for 5 hours at a temperature of 100ºC, after that again the saturated mass after boiling was calculated with the help of weighing scale with an accuracy of 0.05kg. Then with the help of a wire the specimen was suspended in the tub full of water, the specimen must get completely immersed and the apparent mass in water was calculated.

Porosity was calculated as per the formula given in ASTM 642:

$$\text{Volume of permeable voids \%} = \frac{(C-A)}{(C-D)} * 100$$

Where in; A = mass of the oven dried sample in air, in grams

C = mass of sample after immersion and boiling, grams

D = apparent mass of sample in water after immersion and boiling, grams.

3.5.4 Rapid Chloride Permeability

A durable concrete is the one that performs satisfactorily under anticipated exposure condition during its service life span. One of the main characteristics influencing the durability of concrete is its permeability to the ingress of chloride. The chloride ion present in the concrete can have harmful effect on concrete as well as on the reinforcement. Swelling of concrete due to chloride ion penetration is 2 to 2.5 times larger than that observed with water penetration. So this test covers the experimental evaluation of electrical conductance of concrete to provide rapid indication of concrete resistance against chloride ion penetration.

Table 3.7: Chloride Ion Penetrability Based on Charge Passed (ASTM 1202)

Charge passed (Coulomb)	Chloride Ion Penetrability
>4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very Low
<100	Negligble

The test method (according to ASTM C 1202-97) covered the determination of the electrical conductance of concrete to provide a rapid indication of its resistance to the penetration of chloride ions. According to Table 3.7 the chloride ion penetrability was decided on the basis of charge passed. The test method consisted of monitoring the amount of electrical current passed through 2-in. (51-mm) thick slices of 4-in. (102-mm) nominal diameter cores or cylinders for a 6-h period. A potential difference of 60 V dc was maintained across the ends of the specimen, one of which was immersed in a sodium

chloride solution, the other in a sodium hydroxide solution. The total charge passed, in coulombs, was related to the resistance of the specimen to chloride ion penetration.

For the test to be performed six cylinders from each batch of size 100mm×200mm was casted, after casting the core of the cylinder was cut with the help of stone cutter of size 100mmX50mm and allowed to cure. Three pieces were allowed to cure in carbon-dioxide curing and remaining three pieces were water cured as done earlier. After the curing age was completed, specimens were placed in the vacuum desiccator's bowl. The vacuum of 600mm-Hg was maintained in the desiccators bowl for 3 hours. The de-aerated water was allowed to flow into the desiccator, so that it completely covers the specimens and no air was allowed to enter. Again the vacuum was maintained for another one hour. Then the specimens were left in the container to soak water for another 18 hours. The specimens were removed from the desiccator, dried and placed in gasket. The liquids (3.0% NaCl and 0.3 N NaOH solutions) were filled in the two cells. Power supply was set to 60V, and initial current reading was recorded. During the test, the air temperature around the specimens was maintained in the range of 68 to 77°F (20 to 25°C). The value for the current was recorded.

3.5.5 Scanning Electron Microscope

For SEM analysis a sample of approximately 5mm was taken from the core of the crushed mortar specimen tested for compressive strength. For the SEM analysis a samples were collected after the specimens were tested for compressive strength. These collected samples were then put in an air tight zip pouch to restrict the entry of moisture and proper labelling of sample was done. After all the samples were collected, they were taken to the Sophisticated Analytical Lab in Thapar University,Patiala and were tested. The SEM images were taken at various magnifications and were analysed.

An SEM is essentially a high magnification microscope, which uses a focused scanned electron beam to produce images of the sample, both top-down and, with the necessary sample preparation, cross-sections. The morphology and chemical constituents of the concrete samples were analysed with SEM and EDX respectively. The Scanning Electron Microscope (SEM) is a powerful instrument which permits the characterization of

heterogeneous materials and surfaces. Samples were completely dried at room temperature, and then examined at accelerating voltages ranging from 30 to 35 kV by a SEM (Zeiss EVO50). In the present investigation, the SEM was used in its most common mode, the emissive mode. Samples were gold coated with a sputter coating Emitech K575 prior to examination. Primary electrons generate low energy secondary electrons, which tend to emphasis the topographic nature of the specimen. Primary electrons can be backscattered which produces images with a high degree of atomic number (Z) contrast. Ionized atoms can relax by electron shell-to-shell transitions, which lead to either X-ray emission or Auger electron ejection. The X-rays emitted are characteristic of the elements in the top few μm of the sample and are measured by EDX detector. Mineral constituents of the isolates were further characterized by EDX analysis. Presence of high amounts of calcium in the samples confirmed the presence of calcite in the form of calcium carbonate

3.5.6 X-Ray Diffraction

For the microstructure analysis of XRD, the powdered sample of mortar specimen were collected at testing age of 28-day. The samples were collected after the specimens were tested for compressive strength. The core particles were collected and grounded with the help of an iron rod and sieved with help of 150 μm sieve on a paper and the sieved powder was put in an air tight zip pouch to avoid entry of moisture and proper labeling of sample was done. After all the samples were collected they were taken to the Sophisticated Analytical Lab in Thapar University,Patiala and were examined for XRD.

X-ray diffraction is a non-destructive technique used to determine the elements present in any particular substance. X-ray powder diffraction technique is the most prominent technique used for unravelling the structure of the materials in bulk and thin film forms. XRD spectra were obtained using an X'Pert PRO diffractometer with a Cu anode (40 kV and 30 mA) and scanning from 3° to 60°. Each sample was crushed and ground before mounting onto a glass fibre filter using a tubular aerosol suspension chamber (TASC). The components of the sample were identified by comparing them with standards established by the International Center for Diffraction Data. All experiments were performed in triplicate. X-ray diffraction is based on the fact that, in a mixture, the

measured intensity of a diffraction peak is directly proportional to the content of the substance producing it. The samples for X-Ray diffraction analysis were prepared in powdered form. The concrete sample was taken from the inner core of the matrix.

Procedure for Deduction of Minerals

(i) For a given sample, XRD graphs are obtained with intensities on Y-axis and 2θ on X-axis.

(ii) Determine sharp peaks in the graph and represent them on an arbitrary scale as very strong (VS), strong (S), moderate (M), weak (W) and very weak (VW). The intensities corresponding to above are

Table 3.8 Intensity Scale of XRD

VS	75-100
S	50-75
M	25-50
W	10-25
VW	0-10

(iii) Match the d values and intensities of peaks of respective minerals with the fundamental peaks of X-ray powder diffraction files given in the software.

(iv) For any mineral to be present, all the strong peaks should be present in the XRD graph, else the mineral is not present.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 GENERAL

The objective of the present study was to compare the effect of carbon dioxide curing with water curing using GGBS as partial replacement of cement. The main aim of the study is to see the effect of carbon-oxide curing on different percentage of GGBS (0%, 10%, 20%, 30%, 40% and 50%) as partial replacement of cement in the mortar specimens with binder to sand ratio 1:2 and water to binder ratio as 0.45. The benefit of carbon-dioxide curing is that it provides early strength to concrete whereas effect of GGBS is that it delays strength development of concrete. So we intend to overcome this effect of GGBS with help of carbon-dioxide curing. Certain tests were performed to compare the effect of CO_2 curing with water curing incorporating GGBS on mortar specimens. Various tests were conducted including measurement of Compressive Strength, Water Absorption, Porosity, Rapid Chloride Permeability, X-Ray Diffraction and Scanning Electron Microscope.

4.2 Compressive Strength

To investigate the contribution of the CO_2 curing and water curing on varying percentage of GGBS on strength gain, compression test on universal testing was conducted with a pace rate of 0.4 KN/sec on mortar samples with a cross-section of 70mmX70mmX70mm. For all the mixes, Compressive strengths were calculated after 3-days, 7-day and 28-day of casting.

For the testing of compressive strength, six mortar cubes of 70mmX70mmX70mm was casted from each batch, in which half of the cubes were CO_2 cured and remaining cubes were water cured. The set of these six cubes were cast for the curing age of 3-days, 7-days and 28-days. After moulding of the mortar cubes, these cubes were allowed to set for 22hrs. The cubes which were to be cured with CO_2 were immediately put for CO_2 curing, for a period of 6hrs, according to the procedure explained in the section 3.4.2. The

remaining samples were put for water curing in the lab. Compressive strength of mortar specimens incorporated with GGBS was determined with the help of graphs of 3, 7, 28 days of curing. The average of three samples was taken for every testing age.

The comparative study on compressive strength of CO_2 and water cured mortar specimen with GGBS as partial replacement of cement at 3-day, 7-day and 28-day is shown in fig.4.1, fig.4.2, and fig4.3.

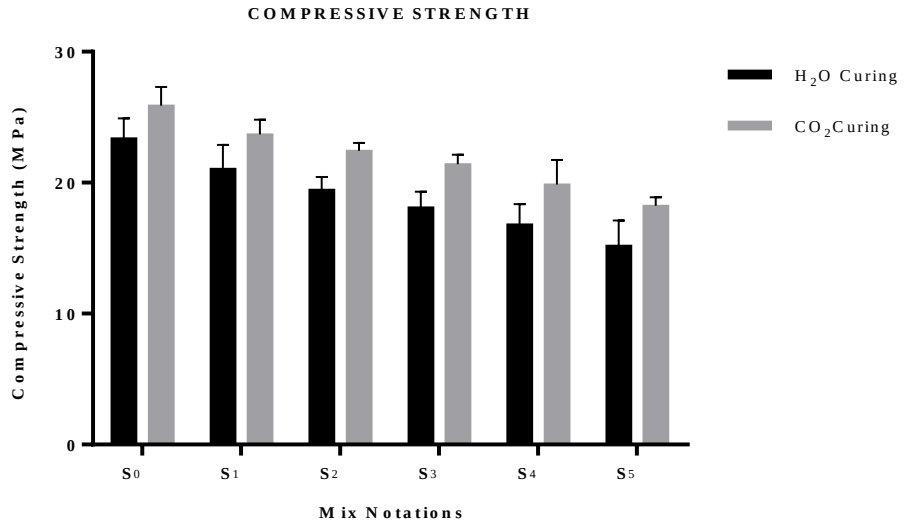


Fig.4.1: 3-Day Compressive Strength

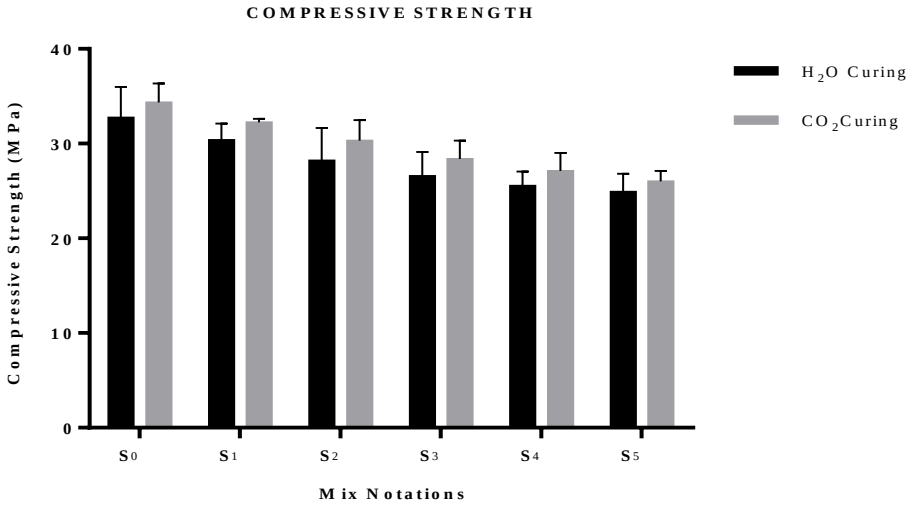


Fig.4.2: 7-Day Compressive Strength

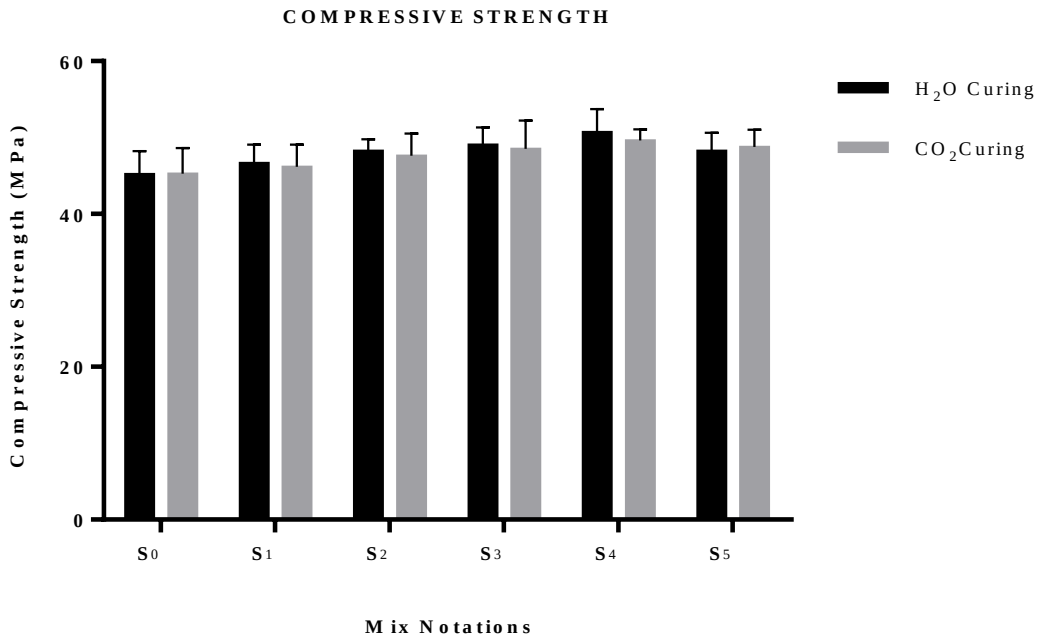


Fig 4.3: 28-Day Compressive Strength

Effect of GGBS on water curing and CO_2 on Compressive Strength

As can be seen from Fig. 4.1, 4.2, and 4.3, in case of water curing, as the percentage of GGBS increases from 0%-50%, decrease in strength was observed in case of 3-day and 7-day. But as the curing period extends to 28-day, the strength gain in case of varying percentages of GGBS is comparable or higher than the mortar with zero percent GGBS. From Fig.4.1 it was observed that with the increase in percentage of GGBS from 0%-50% there was a drastic decrease of 35% in strength gain as compare to that of the mortar with zero percent GGBS. But as the curing period increases to 7-day, with the increase in percentage of GGBS from 0%-50% the decrease in strength observed was 26%. Further, when the curing period is extended to 28-day, some of the mortar mixes with GGBS attain strength even greater then reference mix.

The similar trend can be observed by Hwang(1986) on GGBS mortars cured with water at different ages and at the various replacement levels. According to Hwang in case of water curing the unstable product $Ca(OH)_2$ (CH) formed gets consumed by the SiO_2 (S) available in GGBS in presence of water and forms a CSH-gel as a binder, but in case of

GGBS as the pozzolanic reaction is slow and depends on the calcium hydroxide availability and therefore the strength gain takes longer time for the GGBS concrete.

Effect of Type of Curing on compressive strength

The comparative compressive strength test of carbon di-oxide curing and water curing are shown in Fig 4.1, Fig 4.2 and Fig 4.3. Water curing batch served as the reference. As can be seen from the figures CO_2 cured specimens have greater strength then the corresponding water cured specimens. This trend is seen in all mixes, irrespective of curing age and GGBS replacement level.

On 3-day curing, the strength achieved in case of water cured mortar containing 0% GGBS is comparable to CO_2 cured mortar containing 10% GGBS and it was also observe that the strength achieved in case of water cured mortar containing 30% GGBS was also comparable to CO_2 cured mortar containing 50% GGBS, a similar observations can be seen in case of 7-day water curing and CO_2 curing, but on 28-day curing the strength gain in case of water cured mortar containing 20% GGBS mortar is comparable to CO_2 cured mortar containing 50% GGBS. Thus it can be concluded that, when CO_2 curing is adopted, more amount of GGBS can be used to achieves same strength as water cured specimens thus, CO_2 curing makes mortar more efficient and eco-friendly as compare to that of water cured mortar.

The 6-hr CO_2 cured mortar cubes with 0% GGBS achieved strength which was approximately 10% higher than the reference at 3rd day curing. However, the rate of increase of compressive strength decreases as the curing age increased. For instance the increase in strength of CO_2 cured specimen is 6% at 7-day curing and the strength become almost same on water cured specimen at 28-day of curing. It indicates that the CO_2 curing helps in early age strength development of mortar. Similar observations were made by Rostami(2012), Castellote et al.(2009), Groves et al.(1991), Thiery et al. (2007) and Young et al. (1974). According to the equations (4.1), (4.2), (4.3), (4.4), as it has been observed that the carbonation rate of calcium hydroxide is greater than that of C-S-H at the beginning, but soon after slows down because of the formation of stable calcium carbonate at the surface of calcium hydro-oxide, whereas C-S-H is carbonated at a

constant rate. By continuing carbonation, it was possible to convert entire C-S-H to silica gel and calcium carbonate, while leaving some residual un- reacted calcium hydro-oxide.

$$C_3S + (3\text{-}x)\ CO_2 + yH_2O \rightarrow CxSHy + (3-x)\ CaCO_3 \quad (4.1)$$

$$C_2S + (2\text{-}x)\ CO_2 + yH_2O \rightarrow CxSHy + (2-x)\ CaCO_3 \quad (4.2)$$

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \quad (4.3)$$

$$C\text{–}S\text{–}H + 2CO_2 \rightarrow SiO2 + 2CaCO_3 + H_2O \quad (4.4)$$

The effect of CO_2 curing on GGBS incorporated mixes is similar to that of reference mixes. However, the rate of increase of strength with CO_2 curing is more in the case of mixes containing GGBS. Due to higher rates 3-day and 7-day strength of GGBS mixes is increased to a large extent. Hence, the 28-day strength of CO_2 cured mix is almost same as water cured mix. It indicates that the influence of GGBS on early age strength can be compensated by doing CO_2 curing.

4.3 WATER ABSORPTION AND POROSITY

Water absorption test and Porosity test was conducted as per ASTM C 642 in order to determine the increase in resistance towards water penetration in concrete. The mortar cube specimen of size 70mmX70mmX70mm was prepared and cured both with carbon-dioxide curing and water curing incorporating GGBS as partial replacement of cement. The results are discussed in the following section.

4.3.1 Water Absorption

Water Absorption of mortar cubes incorporated with GGBS was determined at 28 days of curing. The average of three samples was taken for every testing age. The comparative water absorption test for carbon di-oxide curing and water curing are shown in fig. 4.4. Water curing batch served as the reference.

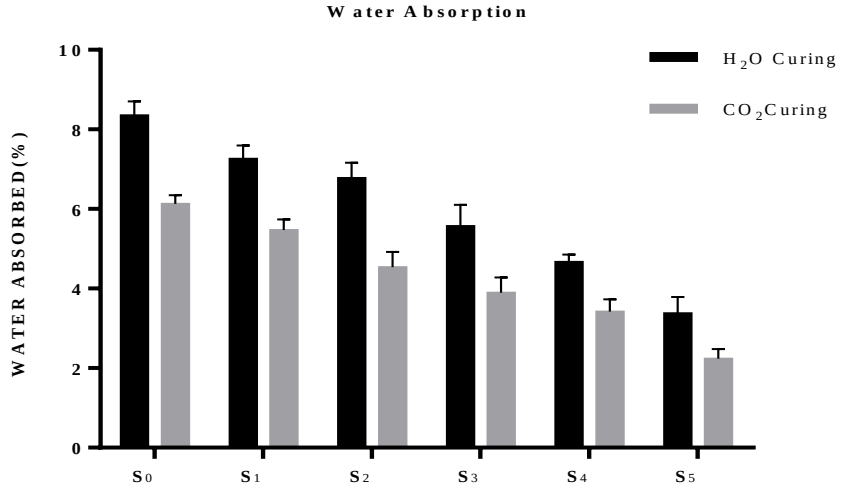


Fig.4.4: 28-Day Water Absorption

On 28-day variation in water absorption on varying percentage of GGBS (0%, 10%, 20%, 30%, 40%, 50%) in case of water curing was 8.4%, 7.3%, 6.8%, 5.6%, 4.7% & 3.4% respectively, while in case of carbon di-oxide curing water absorption observed was 6.2%, 5.5%, 4.3%, 3.9%, 3.4%, & 2.3% respectively.

Effect of water cured GGBS mortar on water absorption

As seen in the Fig.4.4, as the percentage of GGBS increases, a continuous reduction in water absorption was observed for 28-day water cured mortar. From the graph it was observed that with the increase in percentage of GGBS to 0% to 50%, the decrease of 60% of water absorption was observed with reference mix.

Effect of CO_2 curing on water absorption

As seen in the Fig.4.4, water absorption decreases further with the use of CO_2 curing for all the specimens. Minimum value of water absorption is obtained at 50% replacement level of GGBS when it is subjected to CO_2 curing. From the graph it was observed that with the increase in percentage of GGBS to 0% to 50%, the decrease of 62% of water absorption was observed with reference mix. The decrease in absorption of CO_2 cured mortar with no GGBS is 27% as compare to reference mix with no GGBS and cured in water.

Effect of different curing conditions on water absorption

The comparative water absorption at carbon di-oxide curing and water curing are shown in Fig 4.4. Water curing batch served as the reference. As can be seen from the figures water cured specimens have greater porosity then the corresponding CO_2 cured specimens. This trend is seen in all mixes at different GGBS replacement level.

On 28-day curing, the water absorption achieved in case of water cured mortar containing 40% GGBS was comparable to that of CO_2 cured mortar containing 20% GGBS as partial replacement of cement, that is CO_2 curing makes mortar is more efficient and eco-friendly as compare to that of water cured mortar.

According to the graph in Fig.4.4 and values given above it can observed that as the percentage of GGBS increases, there is a continuous reduction in the percentage of water absorption, this is because the size of GGBS particle used in this experiment was around 45μm, which are very small as compared to the size of the cement particle, the finer particles of GGBS gets filled in the pores and makes the matrix denser which makes the mortar sample more resistant to water absorption.

Gao et al. (2005) further stated that for this reduced moisture transport of GGBS mixes is due to the strong microstructure of the interfacial aggregate/binder transition zone of GGBS, which is often an area of weakness in other composites. GGBS significantly decreases both the content and the size of $Ca(OH)_2$ crystals in the aggregate-paste interface, which makes the microstructure of the transition zone aggregate/binder dense and strong .

Whereas due to CO_2 curing the calcium silicate phases react with carbon dioxide in the presence of water, produce calcium silicate hydrates (CxSHy) and chemically stable calcium carbonate instead of calcium hydroxide. The chemically stabled carbonated compound makes the pores more impervious to absorb water.

4.3.2 Porosity

After the process of water absorption is completed, the samples were put into the receptacle for boiling purposes for a period of about 5hrs at a temperature of 100^{o}C then the samples were taken out and weighed, with the help of a wire the specimen was suspended in the tub full of water, so that the specimen must get completely immersed and the apparent mass in water was calculated.

Porosity was calculated as per the formula:

$$\text{Volume of permeable voids \%} = \frac{(C-A)}{(C-D)} * 100$$

Where in; A = mass of the oven dried sample in air, in grams

C = mass of sample after immersion and boiling, grams

D = apparent mass of sample in water after immersion and boiling, grams.

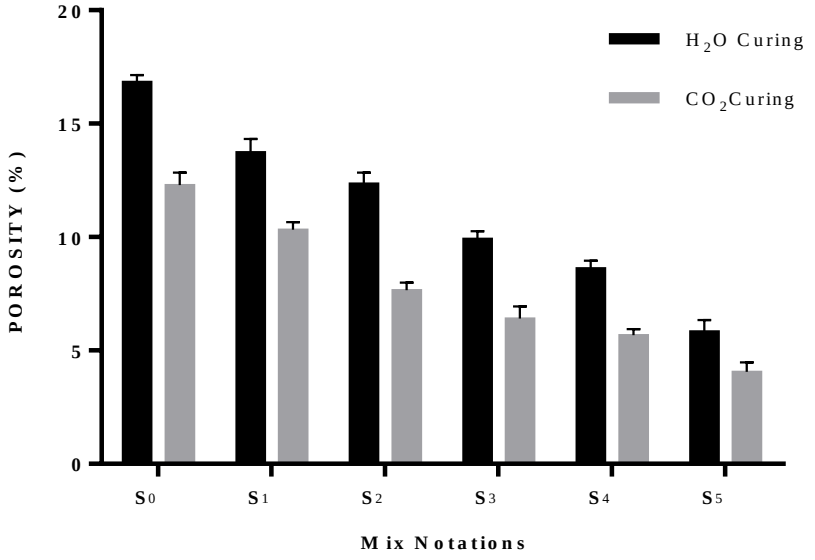


Fig. 4.5: Porosity

On 28- day variation in porosity on varying percentage of GGBS (0%, 10%, 20%, 30%, 40%, 50%) in case of water curing was 16.8%, 13.7%, 12.4%, 9.9%, 8.6% and 5.8%

while in case of carbon di-oxide curing water absorption observed was 12.3%, 10.3%, 7.7%, 6.4%, 5.6%, & 4.1% respectively.

Effect of GGBS cured mortar on porosity

As seen in the Fig.4.5, as the percentage of GGBS increases, a continuous reduction in porosity was observed for 28-day water cured mortar specimens. From the graph it was observed that with the increase in percentage of GGBS to 0% to 50%, around 65% decrease in porosity was observed with respect to the reference mix with no GGBS.

Effect of CO_2 cured GGBS mortar on water absorption

As seen in the Fig.4.5, as the percentage of GGBS increases, a decrease in porosity was observed for CO_2 cured mortar mixes. From the graph it was observed that with the increase in percentage of GGBS to 0% to 50%, the decrease of 63% in porosity was observed with respect to the reference mix with no GGBS and was CO_2cured.

Effect of different curing conditions on water absorption

Water curing batch served as the reference. As can be seen from the fig.4.5, water cured specimens have greater porosity then the corresponding CO_2 cured specimens. This trend is seen in all mixes, irrespective of curing age and GGBS replacement level. There is a decrease of amount for all the mixes when CO_2 curing was adapted instead of water curing.

Similar observations were observed in case of water absorption, as water absorption and porosity are directly proportional to each other.

4.4 RAPID CHLORIDE PENETRATION TEST

The comparative effect of the early CO_2 and water curing on resistance to chloride ion penetration was investigated using the Rapid Chloride Permeability Test (RCPT). Disk samples of 100 mm in diameter and 50 mm thick were tested after 28-day of casting. For the study a cylinder of 100 mm in diameter and 200 mm thick was casted for all mixes.

After 22 hours of casting so that proper setting of mortar is achieved, the cylinder was demoulded and the core of the cylinder was cut with the help of stone cutter. The disc size 100 mm in diameter and 50 mm thick was cut. The set of six cylinders were casted for each mix. Half of these samples were subjected toCO_2 curing and the remaining were water cured for a period of 28-days

Table 4.1: Chloride Ion Penetrability Based on Charge Passed (ASTM 1202)

Charge passed (Coulomb)	Chloride Ion Penetrability
>4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very Low
<100	Negligible

Table4.2: Rapid Chloride Permeability Test of Water curing and CO_2 curing at 28-day

GGBS	R.C.P.T	
	28-DAY H_2O	28 DAY CO_2
0%	3973	1951
10%	3550	1789
20%	1769	943
30%	1253	683
40%	974	503
50%	790	480

Effect of water cured GGBS-mortar on chloride penetration

As can be seen from the table 4.1, as the percentage of GGBS increases, decrease in chloride ion penetration was observed on 28-day water curing. As the percentage of GGBS varies from 0%-50% there is a drastic decrease of 80% in the chloride ion penetration that is chloride penetration in case of water cured mortar specimen varies from "moderate" range to "very low" range. But the maximum decrease of 50% of chloride penetration was observed at 20% GGBS content.

Effect of carbon-dioxide cured GGBS-mortar on chloride penetration

Similar to water cured specimens, even in CO_2 cured specimens, the value of chloride ion penetration decreases as the replacement of cement with GGBS is increased. As the

percentage of GGBS varies from 0%-50% there is a drastic decrease of 75% in the chloride ion penetration. The chloride ion penetration in case of CO_2 cured mortar specimen varies from "low" range to "very low" range. But the maximum decrease of 47% with reference was observed at 20% GGBS content.

Effect of different curing conditions on chloride penetration

The comparative chloride penetration test of carbon di-oxide curing and water curing is shown in Fig 4.7 Water curing batch served as the reference. As can be seen from the fig. 4.6 CO_2 cured specimens have greater chloride resistance then the corresponding water cured specimens. This trend is seen in all mixes of GGBS replacement level.

At 0% GGBS level, the percentage development in charge passed is 50% when CO_2 curing is compared with water curing. Maximum benefit is achieved till 20% replacement level, after that the percentage development between the two curing process decreases.

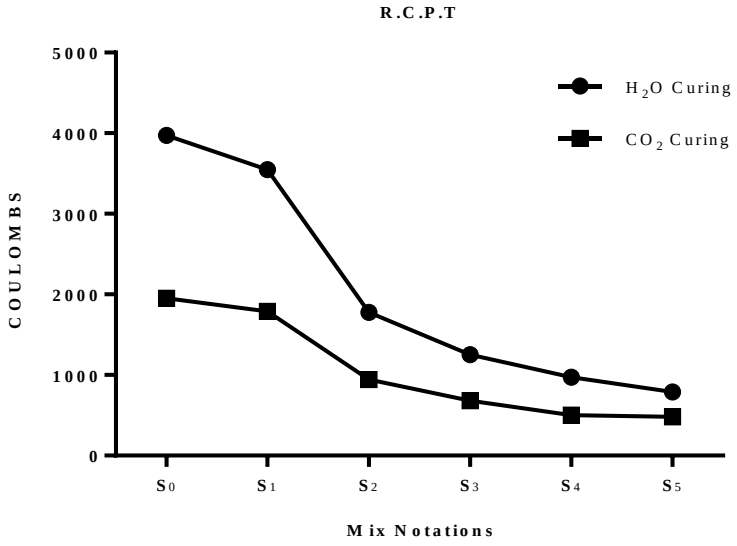


Fig.4.6: Rapid Chloride Penetration Test on Mortar Samples

The similar trend can be observed in Rostami (2011), reports the comparative study of steam curing and steam + carbon di-oxide curing. According to the study the total coulomb passing in carbonated concrete is only half of that in steam cured concrete. This was due to CO_2 curing the calcium silicate phases react with carbon dioxide in the presence of water, produce calcium silicate hydrates (CxSHy) and chemically stable

calcium carbonate instead of calcium hydroxide. The chemically stabled carbonated product does not get reacted with the chloride ions, and thus makes the matrix more resistant to chloride penetration.

Where as in case of water curing the unstable product $Ca(OH)_2$ (CH) formed, which is liable to react with the chloride ions, but with the passage of time $Ca(OH)_2$ (CH) compound gets consumed by the SiO_2 (S) available in GGBS in presence of water and forms a CSH gel that also contributes in densification of the matrix, this pozzolanic reaction due to GGBS is slow and therefore chloride penetration in case of water curing is much more as compare to that of carbon di-oxide curing.

4.5 MICROSTRUCTURE ANALYSIS

For the microstructure analysis of XRD, the powdered sample of mortar specimen were collected at testing age of 28-day. The samples were collected after the specimens were tested for compressive strength. The core particles were collected and grounded with the help of an iron rod and sieved with help of 150 μm sieve on a paper and the sieved powder was put in an air tight zip pouch to avoid entry of moisture and proper labeling of sample was done. After all the samples were collected they were taken to the Sophisticated Analytical Lab in Thapar University,Patiala and were examined for XRD.

For SEM analysis a sample of approximately 5mm was taken from the core of the crushed mortar specimen tested for compressive strength. For the SEM analysis a samples were collected after the specimens were tested for compressive strength. These collected samples were then put in an air tight zip pouch to restrict the entry of moisture and proper labelling of sample was done. After all the samples were collected, they were taken to the Sophisticated Analytical Lab in Thapar University,Patiala and were tested. The SEM images were taken at various magnifications and were analysed.

Effect of GGBS on Micro-Structure

As can see from the fig.4.7, the formation plated crystals were observed in case of control mortar specimen. But as the percentage of GGBS increases from 10% to 50% as can be seen in fig.4.8 to fig.12 the amount of plate crystal i.e. calcium hydroxide decreases with increase in percentage of GGBS. But as the percentage of GGBS increases from 0% to

40% the densification of CSH-gel was observed which directly contributes to the strength. But at 50% GGBS replacement of cement, as the quantity of cement replaced is high, so the density of CSH-gel observed is less as compared to that of 40% replacement of GGBS with cement. Similar observations can be observed in case of XRD analysis, CSH-gel formation increases with the increase in percentage of GGBS which directly contributes to the strength gain. The strength gain in case of water cured mortar specimen at 28-day can be refer with fig.4.3. But as the replacement of GGBS increased from 0% to 50% the number of internal pores decreases constantly, this is due to smaller size of GGBS that fills in the pores, and makes the matrix denser. This densification of pore size makes the mortar specimen more resistant to water absorption; this can be observed from the fig.4.4 and fig.4.5

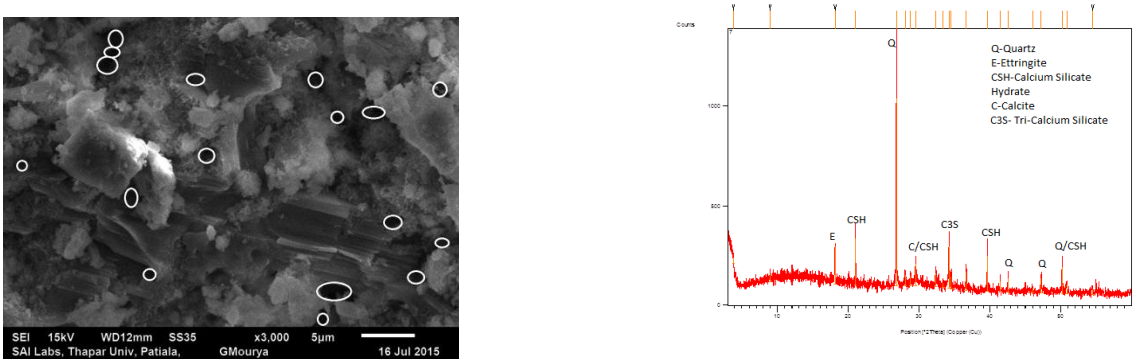


Fig.4.7:0% GGBS Water Cured

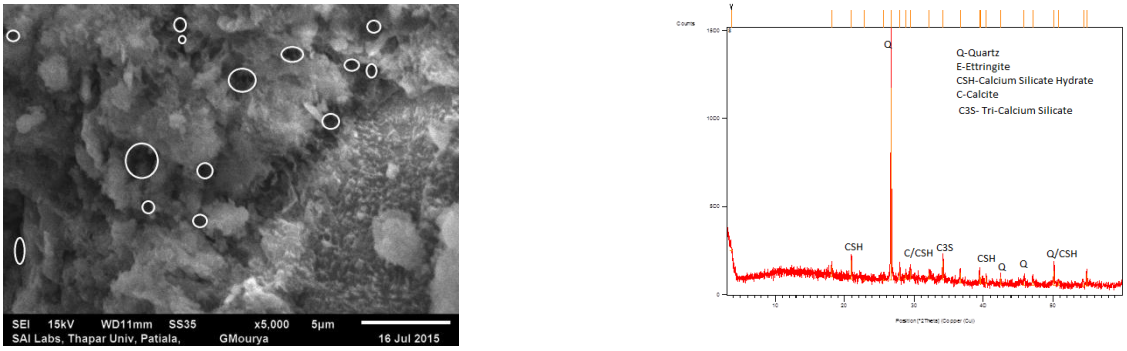
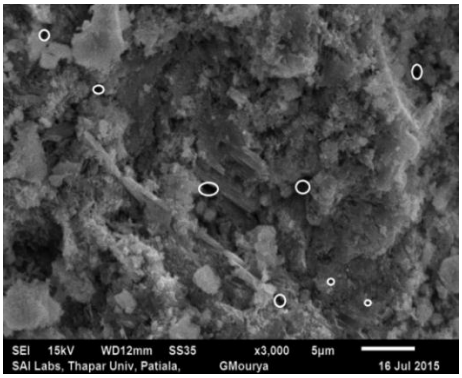


Fig.4.8:10% GGBS Water Cured



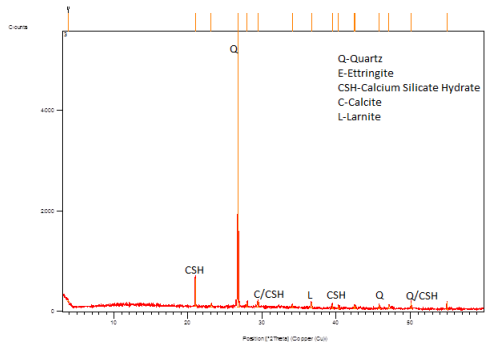
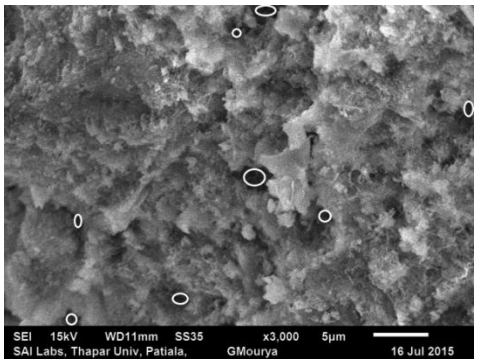


Fig.4.9:20% GGBS Water Cured



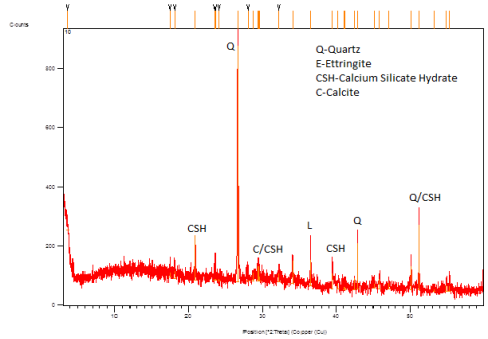
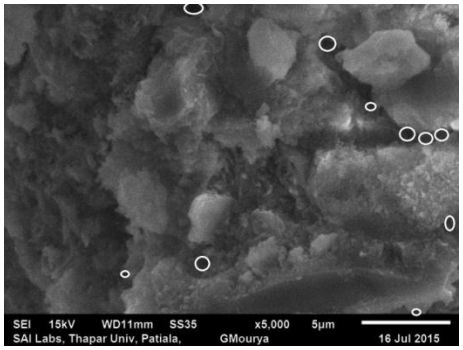


Fig.4.10:30% GGBS Water Cured



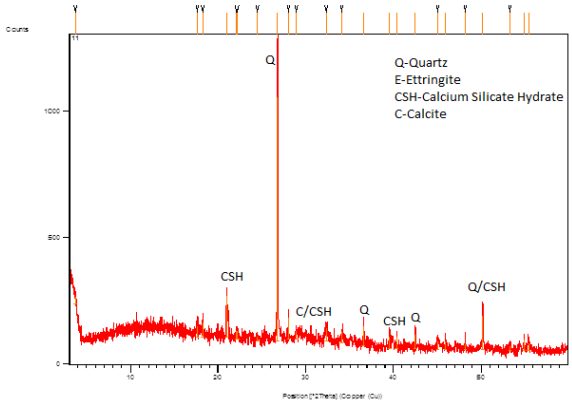


Fig.4.11:40% GGBS Water Cured

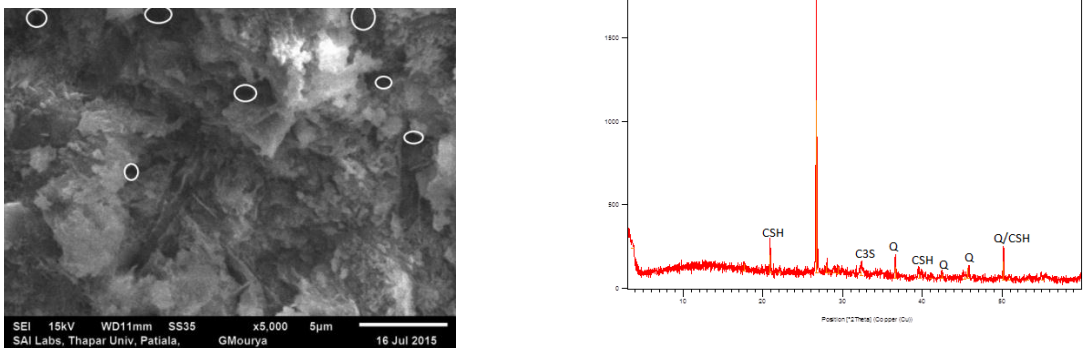


Fig.4.12:50% GGBS Water Cured

Effect of GGBS on Micro-Structure cured with CO_2

As can see from the fig.4.14, the unreacted plated crystals i.e. calcium hydroxide was observed in case of control mortar specimen, but the amount of plated crystals observed were very less. But as the percentage of GGBS increases from 10% to 50% as can be seen in fig.4.14 to fig.4.18 the amount of unreacted plate crystal i.e. calcium hydroxide is not observed. But as the percentage of GGBS increases from 0% to 40% the densification of CSH-gel was observed which directly contributes to the strength. But at 50% GGBS replacement of cement, as the quantity of cement replaced is high, so the density of CSH-gel observed is less as compared to that of 40% replacement of GGBS with cement. Similar observations can be observed in case of XRD analysis, CSH-gel formation increases with the increase in percentage of GGBS which directly contributes to the strength gain. The strength gain in case of water cured mortar specimen at 28-day can be refered with fig.4.3.

But as the replacement of GGBS increased from 0% to 50% the number of internal pores decreases constantly. This is due to small size of GGBS and also due to the formation calcium carbonates that can be observed in case of XRD analysis, which fills in the pores and makes the pores dancer. This densification of pore size makes the mortar specimen more resistant to water absorption; this can be observed from the fig.4.4 and fig.4.5

As can be seen from fig. the comparison of water cured and CO_2 cured micro-structures were observed. From the fig.4.13 and fig.4.14 it was seen that the formation of plated

crystal in case of CO_2 cured SEM analysis was very less as compare to that of reference. But the formation of denser CSH-gel can be observed in case of CO_2 cured mortar specimen. The number of internal pores observed in case of CO_2 cured mortar specimen at 0% GGBS was less as compared to that of reference, this is due to the formation of calcium carbonates in case of CO_2 cured mortar and this can also be observed in case of XRD analysis.

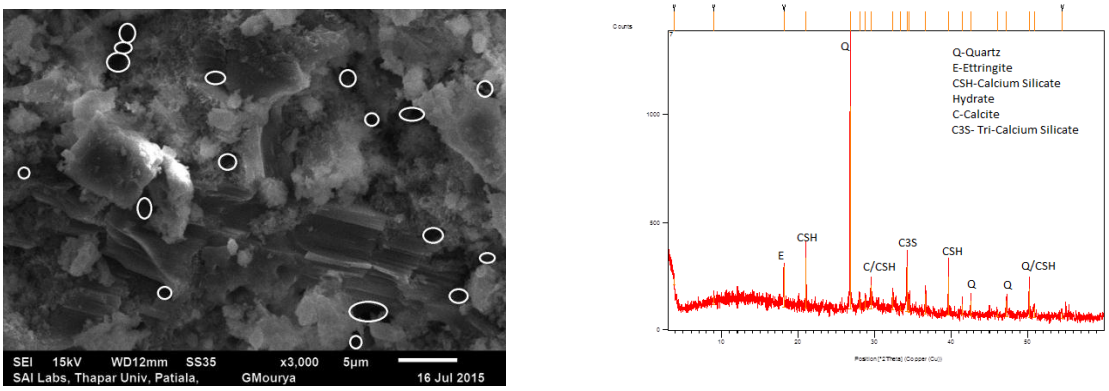


Fig.4.13:0% GGBS Water Cured

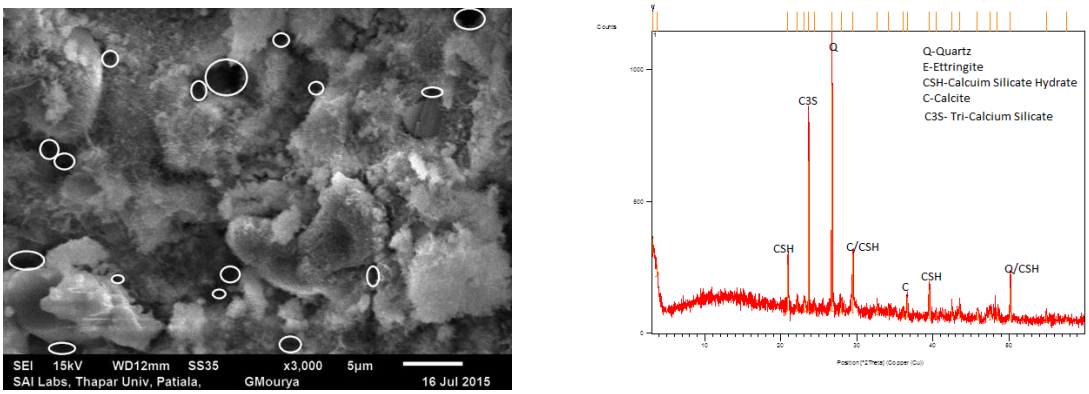


Fig.4.14:0% GGBS CO_2 Cured

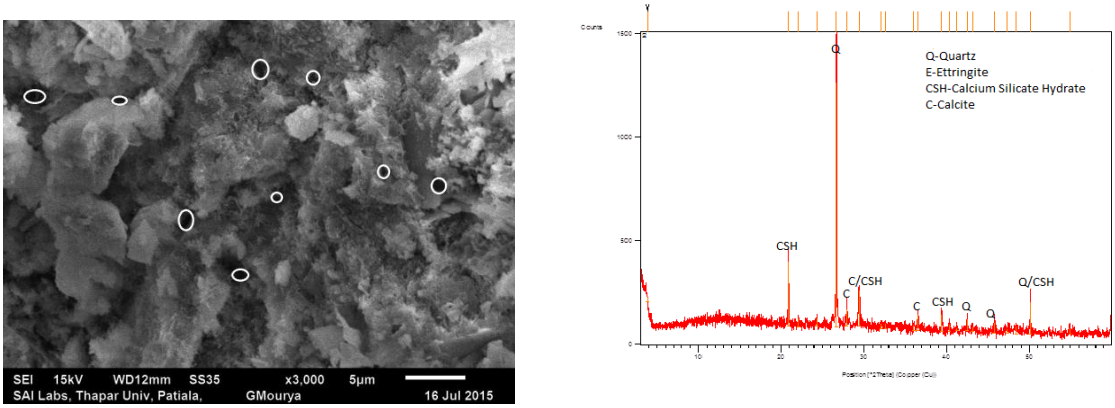


Fig.4.15:10% GGBS CO_2 Cured

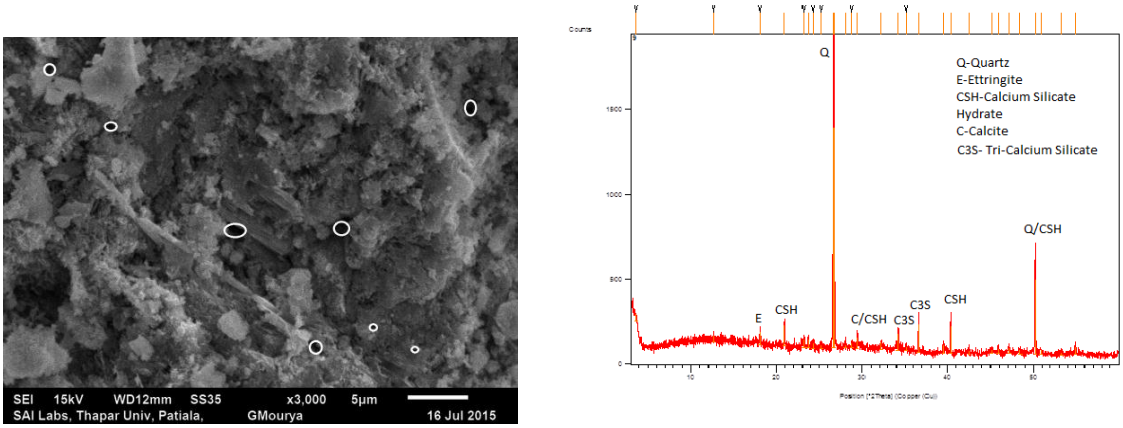


Fig.4.16:20% GGBS CO_2 Cured

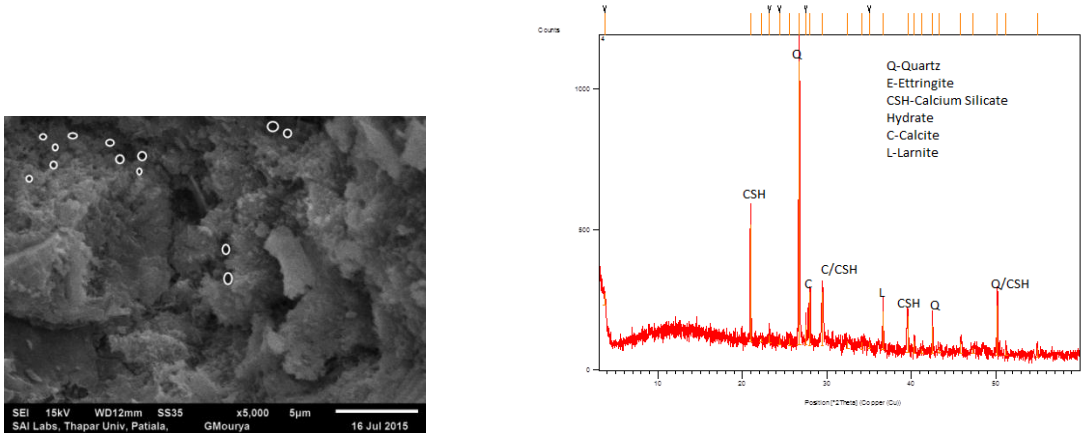


Fig.4.17:30% GGBS CO_2 Cured

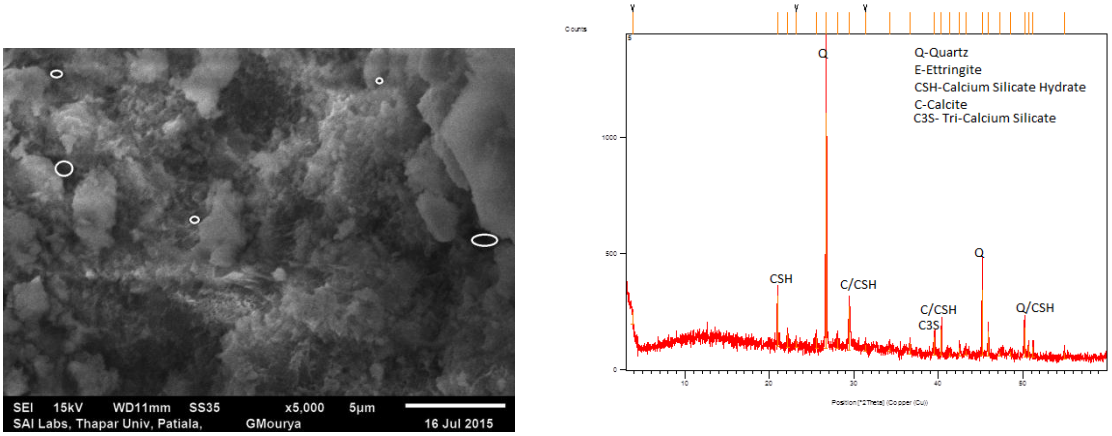


Fig.4.18:40% GGBS CO_2 Cured

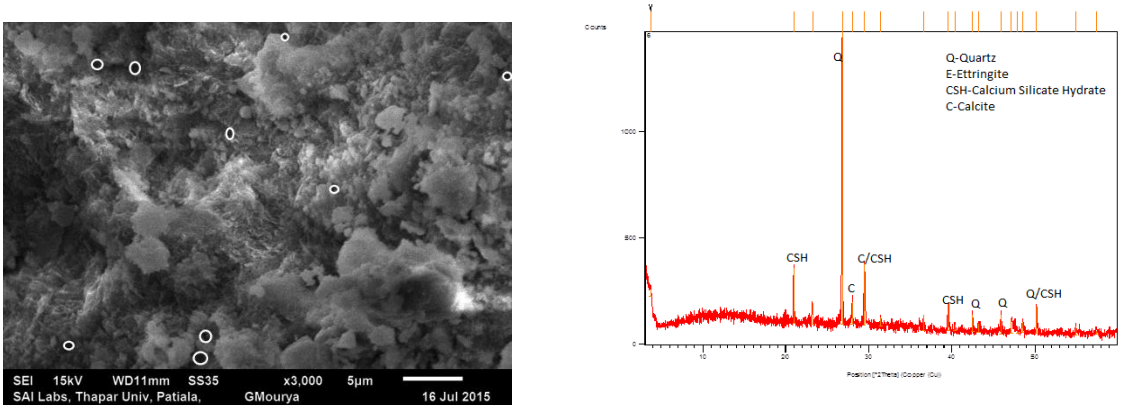


Fig.4.19:50% GGBS CO_2 Cured

CHAPTER 5

CONCLUSIONS

5.1 GENERAL

The objective of the present study was to compare the effect of CO_2 curing and water curing incorporating GGBS as partial replacement. For comparing the curing process certain tests performed were compressive strength, water absorption, porosity, rapid chloride penetration and microstructural analysis using SEM and XRD techniques. From the results of this study, following conclusion were drawn.

5.1.1 Compressive Strength

The short term carbonation curing leads to early strength development as compared to water curing. Early age CO_2 curing of GGBS mortar leads to greater strength development when compared with water cured mortar. But as the curing age increases to 28-day, the strength of CO_2 cured mix was similar to that of water cured mix. So it can be concluded that the influence of GGBS on early strength development can be compensated by doing CO_2 curing.

5.1.2 Water Absorption and Porosity

CO_2 cured mortar specimen were more resistant to water absorption as compared with water cured mortar specimen with varying percentages of GGBS. This is due to reduction in pores size in the carbonated surface zone due to the formation of calcium carbonates instead of calcium hydroxide.

5.5 Rapid Chloride Penetration

The early carbonation treatment of concrete resulted in decreased chloride ion migration as compared with water cured concrete with varying percentages of GGBS. This is due to the elimination of hydroxyl ions and precipitation of calcium carbonate within the surface layer. The chloride ion penetration decreased by about 50% when CO_2 curing was adopted instead of water curing.

5.6 Micro-structural Analysis

SEM analysis of mortar specimens with 0% GGBS at 28-day with different curing regimes shows similar observation of CSH gel formation with more number of pores in case of water cured mortar specimen, so the strength achieved in case of CO_2 cured specimen was almost equal to that of water cured specimen, but porosity and water absorption in case of water cure specimen was more than that of CO_2 cured specimen. But as the as the percentage of GGBS increased from 10% to 50% the formation of denser CSH-gel formed was shown in case of CO_2 curing than that of water curing which results in increase in compressive strength and decrease in water absorption and porosity.

XRD analysis confirmed the formation of CSH (21, 26, 29 degree 2Θ) within the matrix of CO_2 cured and water cured mortar specimen incorporated with varying percentages of GGBS, which cause an improvement in the strength of material.

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