EFFECT OF ACCELERATED CARBONATION CURING ON STRENGTH AND DURABILITY PROPERTIES OF GGBS CONCRETE

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Submitted By

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DECLARATION

I, Harvir Singh, hereby declare that the work presented in this thesis entitled "**EFFECT OF ACCELERATED CARBONATION CURING ON THE STRENGTH AND DURABILITY PROPERTIES OF GGBS CONCRETE**" in fulfillment of the requirement for the award of degree of Master of Engineering in Structural Engineering submitted at Civil engineering Department , Thapar Institute of Engineering & Technology (Deemed to be University), Patiala is an authentic record of work carried out under supervision of Dr. Shweta Goyal, Associate Professor, Department of Civil Engineering, Thapar Institute of Engineering & Technology, Patiala from January 2018 to June 2018. The matter presented in this has not been submitted either in part or full to any other university or institute for the award of any other degree.

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CERTIFICATE

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

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ABSTRACT

The effect of Accelerated Carbonation curing (ACC) was studied on the strength and durability properties of concrete containing varying percentages of Ground Granulated Blast furnace Slag (GGBS) (0% to 60%) as a partial replacement of cement. Strength property included compressive strength while the durability properties included water absorption, chloride permeability, sorptivity and acid resistance. Microstructure of the concrete specimens containing 0% and 40% GGBS was studied through SEM and XRD analysis. Specimens were cured under two types of curing regimes. One set of specimens were water cured while the other set of specimens were carbonation cured for 12 hours then they were placed in water till the age of 3 days and after that they were placed in sealed plastic bags till the testing age. From the experiments it was found that although the early carbonation improved the strength of the concrete the strength gain was not noticeable at the later ages. The carbonated specimens showed lesser water absorption at the ages of 1 day, 3 days and 28 days. Carbonated specimens exhibited lesser sorptivity value, more resistance to chloride permeability and acid attack when compared to the water cured samples. Addition of GGBS resulted in improved strength and lesser value of water absorption while 40% replacement was determined to be optimum. The GGBS concrete also exhibited lesser sorptivity value and more resistance to chloride permeability and acid attack when compared to the control mix. Microstructure analysis of the concrete samples showed the presence calcium carbonate ($CaCO_3$) in place of calcium hydroxide ($Ca(OH)_2$) in carbonated concrete which provided strength to the concrete. A denser microstructure was observed in concrete containing 40% GGBS when compared to the control mix.

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CHAPTER 1

INTRODUCTION

1.1 GENERAL

Emission of carbon dioxide (CO_2) through human activities is the major cause of problems like global warming and climate change. Global warming already has observable effects on the environment. Glaciers have shrunk and lakes are breaking up earlier. Global warming is projected to increase over century. The degree of climate change will depends largely on the amount of heat trapping gases (e.g CO_2, CH_4, N_2O) released and Earth's sensitivity to those emissions. Therefore there is a need to find ways in which CO_2 can be captured and stored to reduce its effect on the atmosphere.

Concrete is one of the most used materials in the world. It is estimated that the cement industry produce approximately 5% of the global CO_2 emission *(Worell et al., 2001).* This CO_2 is released in the fossil fuel combustion and limestone decomposition during the cement manufacturing. It could be beneficial for the environment if this CO_2 can be sequestered in concrete production.

Curing of the freshly cast concrete is done to promote the hydration reaction in cement. This process improves early age strength as well as durability properties of concrete. Curing of concrete happens right after placement and finishing and it involves maintenance of desired temperature and moisture over a long period of time. The time and type of curing depends upon the following factors.

- Mixture proportions
- Size & shape of the concrete
- Specified strength
- Future exposure conditions
- Ambient weather condition

1.2 COMMONLY USED CURING TECHNIQUES

The type and age of curing is generally decided on the basis of working procedure and weather condition. Some basic curing techniques that are widely followed around the world with their advantages and disadvantages are discussed below.

1.2.1 Sprinkling water

In this method the concrete surface is sprinkled with water continuously or after some time gaps. This is an efficient method of curing and is generally used for the curing of floor slabs. A sufficient time is provided for the concrete to set before the start of curing. To sprinkle water perforated plastic box is generally used.

Fig 1.1: Sprinkling Water Curing (*https://blog.yellowpages-uae.com/methods-of-curing-concrete/***)**

- Advantages
  1. As the water is applied continuously, concrete never dries.
  2. This method can be used on all types of surfaces.
- Disadvantages
  1. This method requires huge amount of water.

1.2.2 Ponding Method

It is a popular and a widely used curing technique. In this method concrete is cured by storing water on a horizontal surface. In this method, a canvas is used to cover the exposed surface of concrete after the concrete is placed. This canvas is removed after 24 hours and clay or sand is used to create small ponds for the purpose of storing water. These ponds are then further divided into rectangles and then the water is filled in the ponds. Ponds are refilled with water thrice or twice in a day.

- Advantages
  1. Better than other methods under most curing conditions.

2. Horizontal surfaces can be easily cured by using this method

- Disadvantages

  1. Cannot be used for vertical surfaces.
  2. Requires high amounts of water.
  3. Difficult to clean after curing is finished.

Fig 1.2: Curing by Ponding method (*https://www.quora.com/What-is-the-meaning-of-curing-in-civil-engineering* **)**

1.2.3 Membrane curing

In this method to prevent the water from evaporating a waterproof member is used to cover the concrete surface. This type of curing takes about a week. Plastic sheet, bitumen emulsion, water resistant bitumen paper and wax emulsion etc. can be used as membrane in this method. Concrete strength gain in this method is less as compared to other concrete moisturizing methods.

- Advantages

  1. Reduced evaporation.
  2. Can be easily adopted for horizontal surfaces.
  3. Weathering of concrete is prevented.

- Disadvantages

1. Strength of concrete is reduced.
2. Cost is high as wax emulsion, bitumen emulsion etc. are used.

Fig 1.3: Membrane curing (*https://www.tradeindia.com/fp2329434/Concrete-Curing-Membrane-For-Road-Base.html* **)**

1.2.4 Steam curing

In this method, due to high curing temperatures strength gain of concrete is very rapid. This type of curing is generally used in precast concrete works. In this technique curing is done above 22°C temperature. Temperature is generally kept below 75°C as a proper humidity level is required to prevent the concrete from drying. Temperature can be raised up to 100degrees in case of hot water curing.

- Advantages
    1. It requires less curing time as compared to other techniques.
    2. It is a better curing method in cold weather.
    3. This method is advantageous in precast concrete, as high early strength can be achieved.
- Disadvantages
    1. This method cannot be used in case of large surfaces.
    2. It is a costly method as it involves curing at temperatures above 22°C.

Fig 1.4: Steam curing (*https://www.shutterstock.com/video/clip-4155103-stock-footage-surgut-july-washing-hot-steam-curing-of-the-plastic-barrels-for-reuse-july-in.html* **)**

1.2.5 Sealed curing

This type of curing is generally done to prevent evaporation of water from concrete and contain the moisture. Curing membrane, plastic sheeting and waterproof paper are most widely used for sealed curing. The major advantage of using this curing technique is that it can be used for any shape and size of concrete structures.

Fig 1.5: Sealed curing (*http://civilengineersforum.com/concrete-curing-methods-advantages-limitations/***)**

- Advantages
    1. Weathering of the concrete surface is prevented.
    2. Prevents evaporation of water from concrete surface.
- Disadvantages
    1. This method is rarely used.
    2. Very costly as water resistant paper, plastic sheets etc. are required.

1.3 ACCELERATED CARBONATION CURING

Precast concrete contributes to 20-30% of the total concrete industry *(Glass et al., 2001).* Steam curing is generally used in the precast concrete industry in order to achieve high strengths in comparatively lesser time. In steam curing an atmosphere of high temperature (40-70°C) and humidity (95%) is created to allow for the rapid hydration of cement. Even though the rate of strength gain is improved in this process, other unwanted effects can appear at the later ages. Also, this process requires high amount of energy. Therefore carbonation curing has been studied in the recent past as an alternative of steam curing to lower the energy consumption and CO_2 emission.

The use of CO_2 in the building industry is not new. In the ancient Rome, CO_2 present in the atmosphere use to improve the binding properties of mortar prepared with water, sand and lime by slowly reacting with it. This effect was also used in the Great Wall of China. Portland cement (PC) was introduced in the building material industry in the nineteenth century. PC, after mixing with water, produce a paste which solidifies and binds aggregates (fine and coarse) together to produce a hard durable mass called concrete. Unlike ancient past, extended exposure of CO_2 is harmful for the concrete because it gradually decomposes the chemical products that form during the reaction of the concrete. It is also found that calcium silicate hydrate (C-S-H) decalcifies, which is the primary binding constituent of the cement, when subjected to CO_2 over a long durations. Carbonation can also reduce the pH of the concrete pore solution which increases the vulnerability of the reinforcing steel to corrosion. The deteriorating effects of CO_2 on the concrete and mortars are generally termed as ‘weathering carbonation’.

But as opposite to the weathering carbonation, carbonation of freshly cast concrete is found to increase the early age strength and durability properties of concrete. The idea of carbonation curing was first introduced in 1970s and was not widely discussed until recently. This method was generally neglected due to high production cost of pure carbon dioxide and the deteriorating effects caused by the weathering carbonation. But the increase in greenhouse emissions has reignited the interest of researchers in this process.

From the studies it has been found that, binder like consolidation is attained when minerals e.g. monocalcium silicates, dicalcium silicates, which generally exhibit no hydraulic reactivity, are carbonated. There are certain industrial wastes which exhibit similar mineral composition. Therefore their use as a supplementary material can be explored in the carbonation cured concrete. Unlike the weathering carbonation, where CO_2 causes deterioration of the hydration products, CO_2 reacts directly with the anhydrous binder materials to form binder matrix in early age carbonation. The time of this type of curing is generally kept between few hours to few days.

1.3.1 Chemical reactions during accelerated carbonation curing

More than 60% of hydrated PC consists of calcium silicates and their hydrated products. Engineering properties of concrete are majorly caused by these compounds. Anhydrous mineral alite ($3CaO{\cdot}SiO_2$, or C_3S) and belite ($2CaO{\cdot}SiO_2$, or C_2S) react with water H_2O in the following manner.

$$2C_3S + 6\,H_2O \rightarrow C_3S_2H_3 + 3Ca(OH)_2 \text{ ………………..(1.1)}$$

$$2C_2S + 4\,H_2O \rightarrow C_3S_2H_3 + Ca(OH)_2 \text{ …………………(1.2)}$$

$Ca(OH)_2$ formed during the above reactions is not a desirable product since it is soluble in water and gets leached out of concrete while making it porous and hence decreasing its durability. $Ca(OH)_2$ also react with sulphate present in soil or water to form $CaSO_4$ which further reacts with C_3A and forms calcium sulphoaluminate (ettringite) which causes volume expansion such that expanded volume is 227% of the volume of the original aluminates, thus resulting in crack and subsequent disruption. The only advantage of $Ca(OH)_2$ is that being alkaline in nature it maintain pH = 13 in concrete which resist corrosion of reinforcement.

When the concrete is cured with the help of CO_2 the following reactions occur

$$3(3CaO{\cdot}SiO_2) + (3-x)CO_2 + yH_2O \rightarrow xCaO{\cdot}SiO_2{\cdot}yH_2O + (3-x)CaCO_3 \text{ …....(1.3)}$$

$$2(2CaO{\cdot}SiO_2) + (2-x)CO_2 + yH_2O \rightarrow xCaO{\cdot}SiO_2{\cdot}yH_2O + (2-x)CaCO_3 \text{ ……...(1.4)}$$

Calcium silicates ($CaO.SiO_2$) react with carbon dioxide (CO_2) in aqueous conditions to generate calcium silicate hydrate ($xCaO{\cdot}SiO_2{\cdot}yH_2O$) and calcium carbonate ($CaCO_3$). As opposite to $Ca(OH)_2$, $CaCO_3$ is insoluble in water and exists in hardened form, thus increases the durability properties of concrete.

1.4 LABORATORY PROCESS OF CARBONATION CURING:

The following three phase process is generally followed in the accelerated carbonation of concrete.

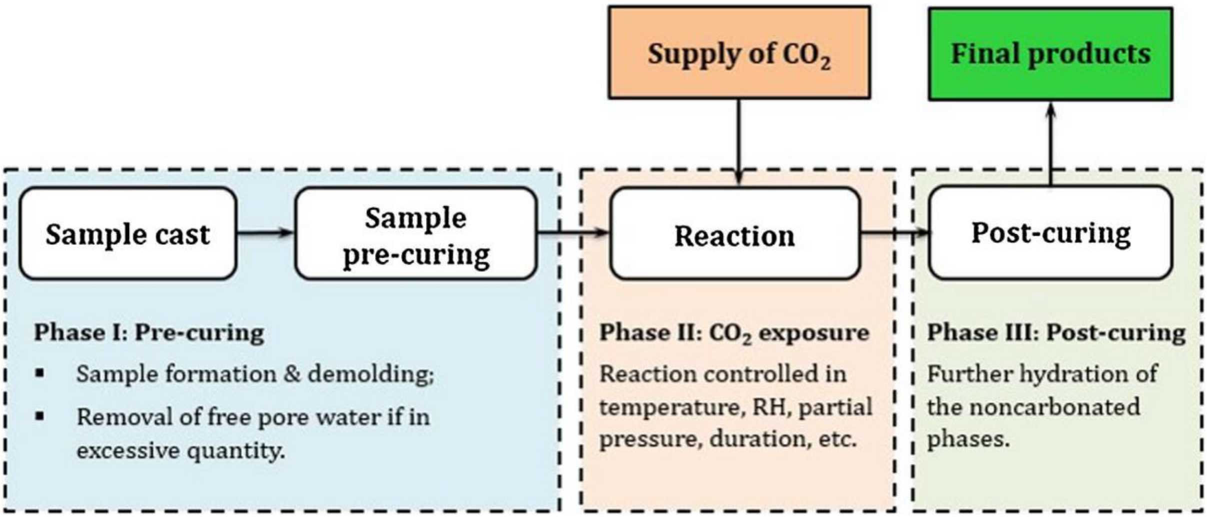


Fig 1.6: Laboratory process of carbonation curing (*Zhang et al., (2017)*)

1.4.1 Phase I: Pre curing

This process involves the controlled removal of water from the surface of the specimen after it has been demoulded. This is an important step for the effective carbonation to occur as majority of the reaction takes place in the presence of water and presence of optimum amount of water needs to be ensured for the effective carbonation. Presence of excess water can cause blocking of reactants from CO2 while water depletion can result in incomplete reaction.

1.4.2 Phase II: CO_2 exposure

CO_2 curing can be done under two systems: enclosed and flowable. Enclosed systems are generally used for the process as they have higher reaction efficiencies and can store CO_2 under elevated partial pressures. To speed up the diffusion process pure CO_2 is generally used. The carbonation curing of Portland cement based materials is usually done at a temperature of 20-25°C. Relative humidity (RH) is generally adopted in the range of 60-70%.

1.4.2 Phase III: post-curing

Post curing is done to ensure the progression of hydration reaction. For the post curing any of curing process mentioned in 1.2 can be adopted. The depletion of water due to pre-curing and carbonation curing should be recompensed to ensure the proper hydration of the concrete at the subsequent ages.

1.5 GROUND GRANULATED BLAST FURNACE SLAG (GGBS)

The cost of concrete is proportional to the cost of its ingredients i.e. cement, fine aggregates and coarse aggregates which are scarce and expansive, this leads to the use of economical alternative materials in its production.

Ground Granulated Blast furnace Slag (GGBS) can provide for an effective replacement to rapidly depleting building materials and also being a byproduct its use in concrete is an eco-friendly way of utilizing it instead of dumping it in the ground. It has also been observed that the strength of concrete doesn't degrade much with the use of GGBS ***(Suresh et al. (2015)).***

GGBS is a byproduct from the blast furnace process which is used in the production of iron.

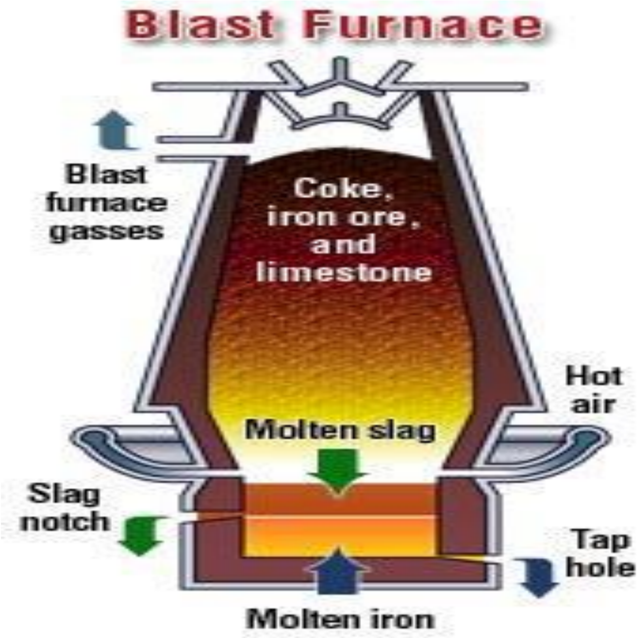


Fig 1.7: Iron manufacturing process ***(Suresh et al. (2015))***

The furnaces are operated at a temperature of 1500°C and are fed with a mixture of iron, coke and limestone. Iron is obtained from the iron slag and the remaining material forms a slag and floats on the top of on the top of iron. This slag is periodically removed from the top and if it is to be used in the production of GGBS, it needs to be rapidly quenched in large volumes of water. The quenching optimizes the cementitious properties and coarse sand like granules are produced at the end of this process. GGBS is the obtained by grinding this granular slag to a fine powder.

1.5.1 Chemical composition of GGBS

The chemical composition of GGBS can vary depending on the raw material used in the iron production process. In pig iron production, GGBS generally consist of mixture of limestone and forsterite or dolomite in some cases. The typical chemical composition of GGBS is given in Table 1.1

Table 1.1: Chemical composition of GGBS

Constituent	Constituent %
SiO_2	35
Al_2O_3	13
CaO	40
MgO	8

The glass content of the slag, which largely depends on the cooling method and temperature, varies between 90-100%, which is suitable for blending with the Portland cement. Generally GGBS is highly cementitious in nature and when ground to cement fineness, it hydration behavior is similar to that of cement.

The typical physical properties of GGBS are given in Table 1.2

Table 1.2: Physical properties of GGBS

Property	Value
Specific gravity	2.9
Bulk density	1200 kg/m^3
Fineness	350 m^2/kg
Colour	Off white

1.5.2 Applications and uses of GGBS

GGBS is used in making durable concrete structures in combination with OPC and other pozzolanic materials. It has been increasingly used in Europe and in the United states and in Asia (mostly in Japan and Singapore) as its use makes concrete more durable.

GGBS is majorly used in the production of quality-improved slag cement, called Portland Blast Furnace Cement (PBFC) and high slag blast furnace cement (HSBFC), in which GGBS content can range from 30-70%, and to produce ready mixed or site bleached concrete.

Depending on the replacement levels, GGBS concrete sets more slowly as compared to concrete made with OPC but it also continuous to gain strength at the later stages. Therefore in GGBS concrete heat of hydration and temperature rise is less as compared to the normal concrete.

The major advantages of using GGBS in concrete are listed as below:

- It gives better workability, which makes placing and compaction easier.
- Temperature rise is low, which reduces the risk of thermal cracking.
- It has higher resistance to chloride penetration, which reduces the risk of reinforcement corrosion.
- It has higher resistance to attack by sulphate and other chemicals.

GGBS is generally used as a direct replacement of PC. Replacement levels can vary from 30% to up to 85%. In most instances 40% to 50% is used. Replacement is kept up to 30% in case of ground concrete structures where high early age strength is required. For the underground structures where moderate strength is required, replacement ratio is kept between 30% and 50%. For special concrete structures which have high durability requirement i.e. corrosion resistance in marine structures, sewerage treatment plants etc., and the replacement ratio is taken from 50% to 70%.

1.6 OBJECTIVE OF THE PRESENT WORK

The main objective of this study is to study the effect of carbonation curing on the properties of concrete containing GGBS. The present work focuses on utilizing industrial waste in concrete and using an innovative technique to enhance the performance of concrete. The effect of CO_2 curing and water curing on various parameters has been studied and compared.

1.7 ORIENTATION OF THE THESIS

Chapter 1 gives the introduction of this study, in this chapter various types of curing techniques with their advantages and disadvantages have been discussed. This chapter gives a brief introduction about carbonation curing and use of GGBS in building construction materials. Chapter 2 discusses about the research papers published regarding CO_2 curing and GGBS, which shows the path to new study and also helps as a reference. Chapter 3 explains in detail the experiments performed in the present study, it also gives information about the materials used in the study and gives the properties of these materials. Chapter 4 gives the results obtained from the experiments performed in this study and also gives explanations of these results. Chapter 5 gives the conclusions drawn from the results and discussions during the present work.

CHAPTER 2: LITERATURE REVIEW

2.1 GENERAL

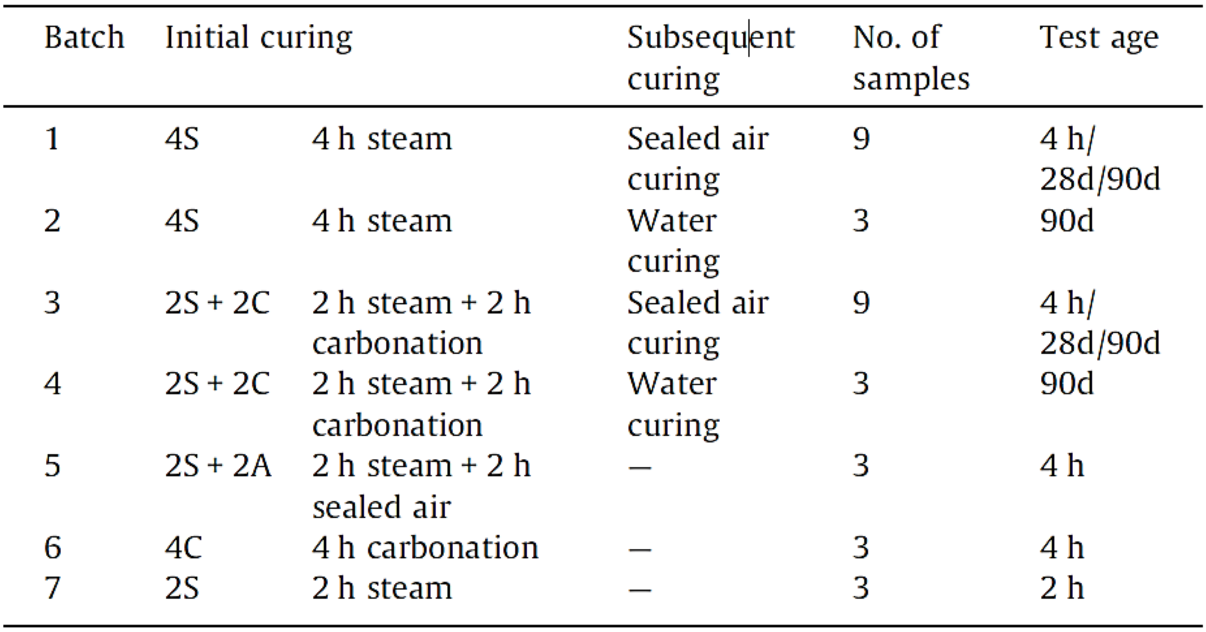
This study focuses on utilization of industrial waste and using an innovative technique to enhance the durability of concrete. In this chapter various carbonation techniques adopted by different researchers have been discussed and then the effect of accelerated carbonation curing on the properties of concrete has been studied. Various researches done on the effect of GGBS addition as partial replacement of cement on the properties of concrete have also been discussed.

2.2 CARBONATION CURING TECHNIQUES

Rostami et al. (2011) studied the strength and durability properties of carbonated concrete blocks. Strength property include compressive strength and durability properties included carbon uptake, strength gain, pH, content of calcium hydroxide, chloride permeability, sorptivity and sulfate and acid attack.

They used different techniques of carbonation curing as mentioned in the Table 2.1 below.

Table 2.1: Curing schemes of concrete samples (*Rostami et al. (2011)*)



Batch	Initial curing		Subsequent curing	No. of samples	Test age
1	4S	4 h steam	Sealed air curing	9	4 h/ 28d/90d
2	4S	4 h steam	Water curing	3	90d
3	2S + 2C	2 h steam + 2 h carbonation	Sealed air curing	9	4 h/ 28d/90d
4	2S + 2C	2 h steam + 2 h carbonation	Water curing	3	90d
5	2S + 2A	2 h steam + 2 h sealed air	–	3	4 h
6	4C	4 h carbonation	–	3	4 h
7	2S	2 h steam	–	3	2 h

The temperature was increased at a rate of 40˚C/h up to 63˚C in the steam curing. After steam curing the temperature was dropped with the help of a cooling chamber. The specimens were shifted to the carbonation chamber after 2h steam curing for combined steam and carbonation curing. Purity of CO_2 used was 99.5% and pressure used was 1.5 bar. Relative humidity was kept at CO_2 uptake was measured using a digital balance. Subsequent curing was done in a sealed bag or in water till 28 and 98 days to study the effect of carbonation on compressive strength at later ages. The CO_2 uptake was measured using mass curve and mass gain method. Compressive strength was measured by conducting compression tests on specimens having cross-section of 127mm x 40mm and strength was measured at the ages of 4 h, 28 days and 90 days.

The pH measurements were carried out on 5 mm thick slices which were also used in XRD phase analysis. Fig 2.1 shows the carbonation process set up.

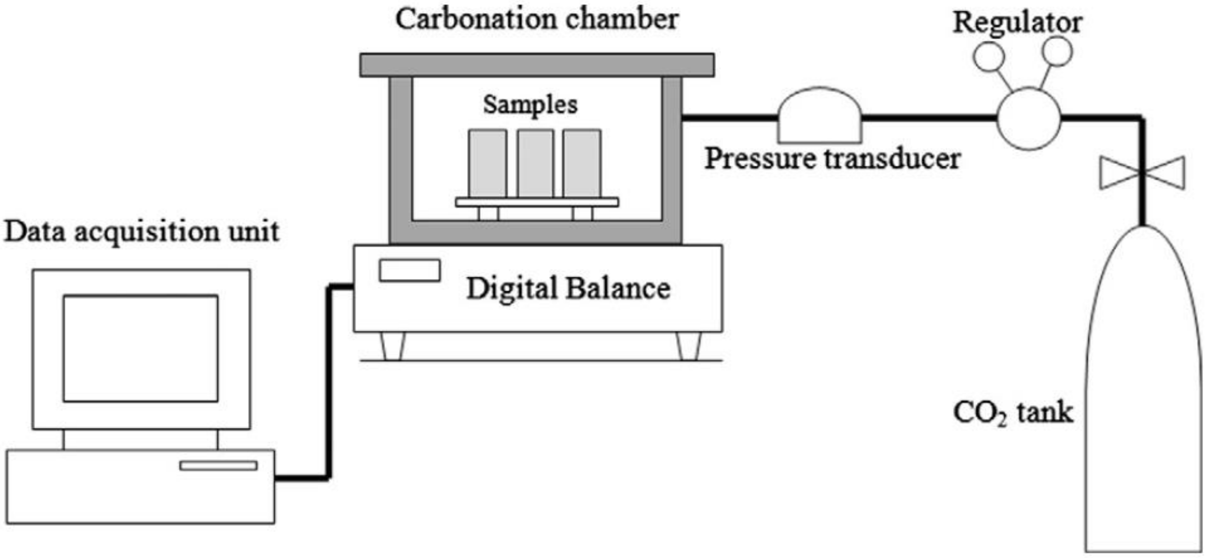


Fig 2.1: Carbonation process set up (*Rostami et al. (2011)*)

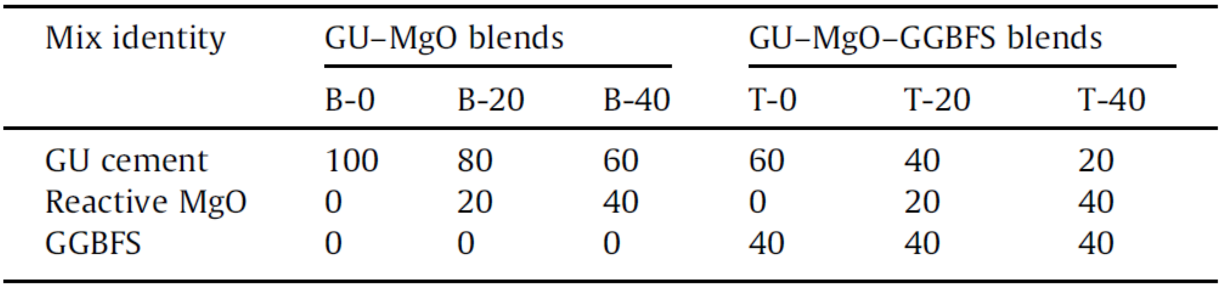
To quantify calcium hydroxide at different ages and depths of the samples subjected to carbonation treatment XRD analysis was used. 5 mm thick slices were crushed and passed through a 38µ sieve. To conduct Rapid Chloride Permeability Test (RCPT) disk samples of 100 mm diameter and 50 mm thick were tested according to ASTM C 1202. Sorptivity test was conducted in accordance with ASTM C 1585. Samples were tested for sulphuric acid resistance in accordance with the guidelines provided in ASTM C 267. The specimens were immersed in a sulphuric acid solution having a pH between 1 and 2 and the corresponding mass loss was checked on weekly basis.

Hassan et al. (2013), in this paper the effect of carbonation curing con concrete masonry units (CMU) was studied. The period of initial curing was taken as 4 to 18h. The relative humidity, temperature and pressure were kept at 50%, 25°C and 1 bar respectively. Mass gain and mass curve method was used to estimate the carbon uptake. To simulate the typical web of a hollow CMU 38 mm (1.5 inch) rectangular slab samples were casted and carbonation curing parameters were studied on theses samples. Then the optimized parameters were applied on the 200 mm (8 inch) thick CMU units. Steam cured samples were taken as reference samples for the carbonation cured samples. Carbonation cured samples without initial curing were also used as reference. In this paper instead of steam curing air curing was used as initial curing.

Carbonation procedure was similar to the one shown earlier. Mass curve, mass gain and thermal decomposition analysis methods were used to estimate the carbon uptake. XRD analysis of CMU units was also performed

Mo et al. (2013), in this paper the effect of carbonation curing was studied on binary and ternary reactive MgO mortar was studied. Experiments were conducted on mortar samples comprised of general use (GU) cement, ground granulated blast furnace slag (GGBFS),and reactive MgO which was used as cement replacement. Binary (GU-MgO) and ternary (GU-GGBFS-MgO) blends were exposed to atmospheric curing (0.038% CO_2) and carbonation curing (99.9% CO_2). CO_2 curing was done at 25°C, RH of 50% and a pressure of 0.1 bar. The proportions of the cementitious binder are shown in Table 2.2

Table 2.2: Mix proportions of cement used in mortars(wt.%) (*Mo et al. (2013))*



Mix identity	GU–MgO blends			GU–MgO–GGBFS blends		
	B-0	B-20	B-40	T-0	T-20	T-40
GU cement	100	80	60	60	40	20
Reactive MgO	0	20	40	0	20	40
GGBFS	0	0	0	40	40	40

1% phenolphthalein solution was sprayed on the fresh split surface were used to determine the carbonation front of CO_2 cured samples.

The compressive strength of specimens was tested at the ages of 7d, 28 d and 56 days. XRD analysis of the samples was also performed.

Hassan et al. (2015) studied the effect of carbonation curing on the mechanical properties and microstructure of concrete masonry units (CMU) with Portland limestone cement (PLC) as binder. The time of initial curing was taken as 4 to 18 h. RH, temperature and pressure were taken as 50%, 25°C and 1 bar respectively. After the initial curing carbonation curing was done for 4h at 0.1 bar pressure. CO_2 used was 99.9% pure

To simulate a typical web of a 200-mm PLC CMU, rectangular concrete samples 127 mm long, 76 mm wide, and 38 mm thick were cast. Carbonation procedure used was same as discussed earlier. Mass gain and mass curve methods were used to determine CO_2 uptake. The carbonation results of PLC cements were then compared with the OPC cement.

Chabannes et al. (2016), in this paper the properties of rice husk and hemp based building material cured under natural and accelerated carbonation curing were studied. The specimens were cured for 10 months either in climate-controlled room or exposed outdoors to simulate natural carbonation. The binder used was 50/50 wt. % combination of natural hydraulic lime.

The binder used in this study was a 50/50 wt. % combination of natural hydraulic lime. Rice husk concretes (LRC) and Hemp concretes (LHC) were manufactured by means of manual compaction process in cylindrical moulds. RH mostly ranged between 45% and 75% during the outdoor exposure curing. CO2 curing set up is shown in Fig2.2.

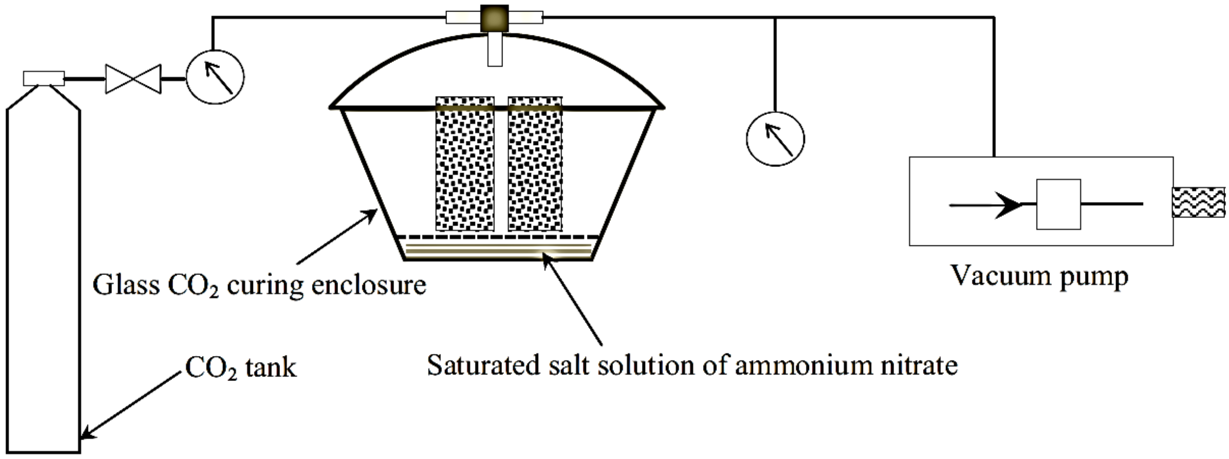


Fig 2.2: Illustration of CO_2 curing system of concrete specimens *(Chabannes et al. (2016))*

The RH was kept at 65% and the temperature was kept at 20°C. The carbonation chamber was refilled 42 times and the mass of CO_2 consumed was measured after each refilling.

Mechanical properties in compression were studied after 1–2–4–10 months of setting and hardening under natural conditions and after ACC (40 days of initial conditioning and 1 month of CO_2 curing). Carbonation depth was measured by phenolphthalein spray.

Junior et al. (2016), in this paper the effect of early age carbonation on the mechanical and porosity related properties of high strength sulphate resistant Portland cement (HS SR PC) was studied. These properties were then compared with the non-carbonated references. The duration of carbonation curing was taken as 1h and 24h. The mechanical properties studied were compressive strength, tensile strength, elastic modulus and Poisson's coefficient. Table 2.3 summarizes the conditions of carbonation treatment.

Table 2.3: Conditions of carbonation treatment *(Junior et al. (2016))*

Specimens	Age of initial carbonation (h)	Carbonation time (h)	Temperature (°C)	Relative humidity (%)	CO_2 concentration (%)
P_{ref}	-	-	25	100	-
P_{c1h}	6	1	25	60	20
P_{c24h}	6	24	25	60	20

Shao et al. (2016), in this paper the effect of carbonation curing was studied on precast flyash concrete. The replacement levels of flyash were taken as 20% and 50%. The precast units were subjected to initial hydration curing before carbonation, as carbonation curing right after demoulding is not possible as the precast concrete has high slump. After the preconditioning the samples were placed inside the chamber at a pressure of 5 bars for 2, 12 and 24 h durations. The purity of CO_2 used was 99.8%. After CO_2 curing, the specimens were placed in a moisture room for 360 days for subsequent hydration. The hydrated reference samples were also prepared.

Zhang et al.(2016), in this paper the effect of weathering carbonation and early age carbonation on chloride penetration of the flyash concrete was studied. The flow chart of the experimental process is shown in Fig 2.4.

2.3 EFFECT OF ACCELERATED CARBONATION CURING ON THE PROPERTIES OF CONCRETE

2.3.1 Carbon dioxide uptake

Experiments conducted by *Rostami et al. (2011)* showed that the carbon uptake more than 40% of the carbon uptake occurred in the first 10 min after that it was slowed down and the final uptake was around 9% after 2h carbonation. The graph is shown in Fig 2.4

The reason for increased rate of carbonation could be that, at the high temperature in steam curing free water at the surface got vaporised and created voids for CO_2 penetration. This phenomenon is presented in Fig 2.5 where the loss in mass of water with time in steamed sample is displayed. Fig 2.4 shows change of carbon uptake with time.

Carbon uptake results of CMU units by *Hassan et al. (2013)* summarized in Table 2.4. It was observed that after 28 days CO_2 uptake of the specimens was similar as of 1 day, which confirms the permanent sequestration of CO_2.

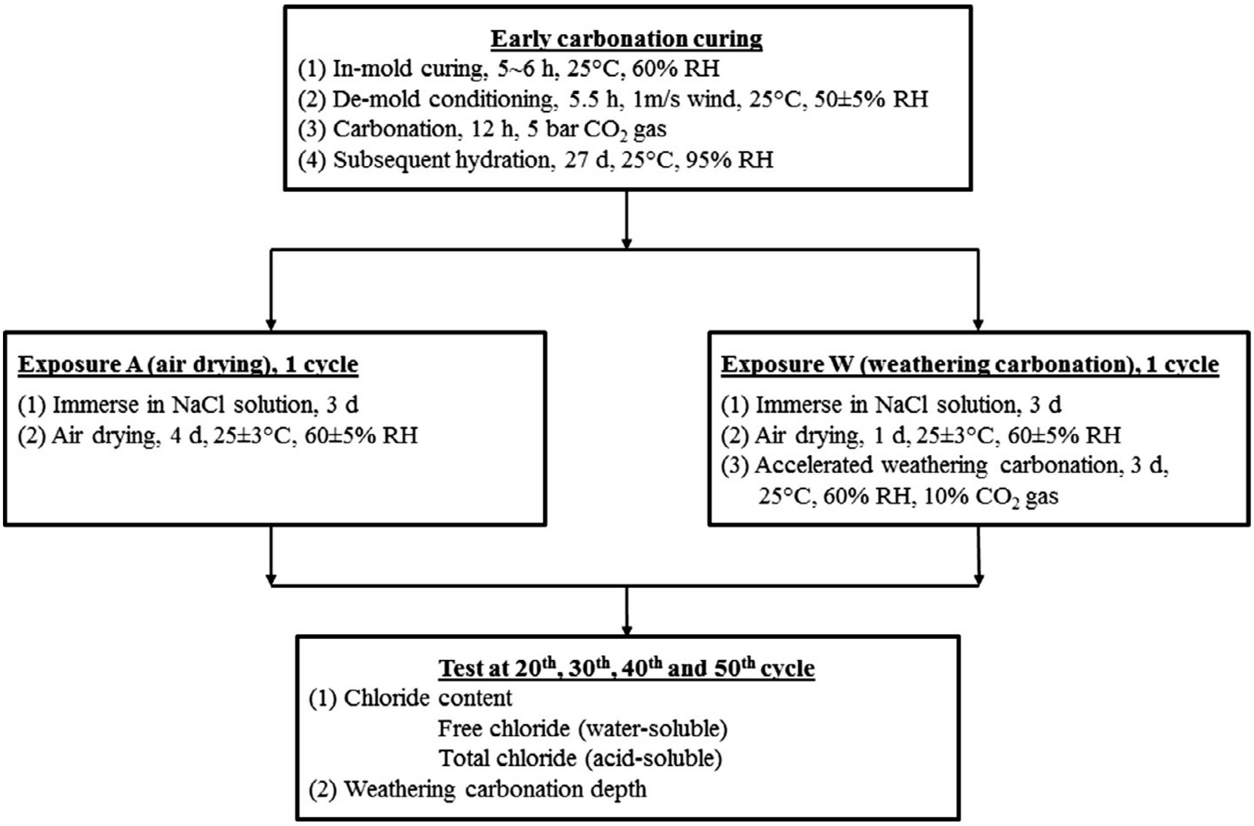


Fig 2.3: Experiment flow chart *(Zhang et al. (2016))*

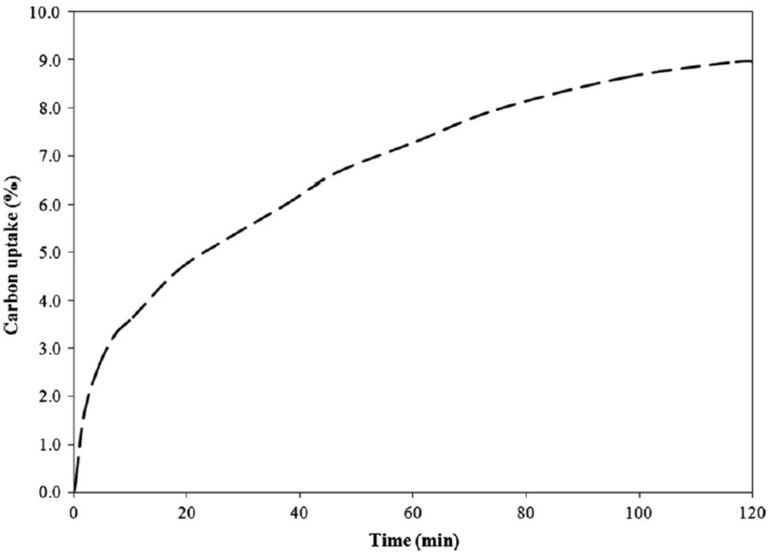


Fig 2.4: Graph of carbon uptake % v/s time (*Rostami et al. (2011)*)

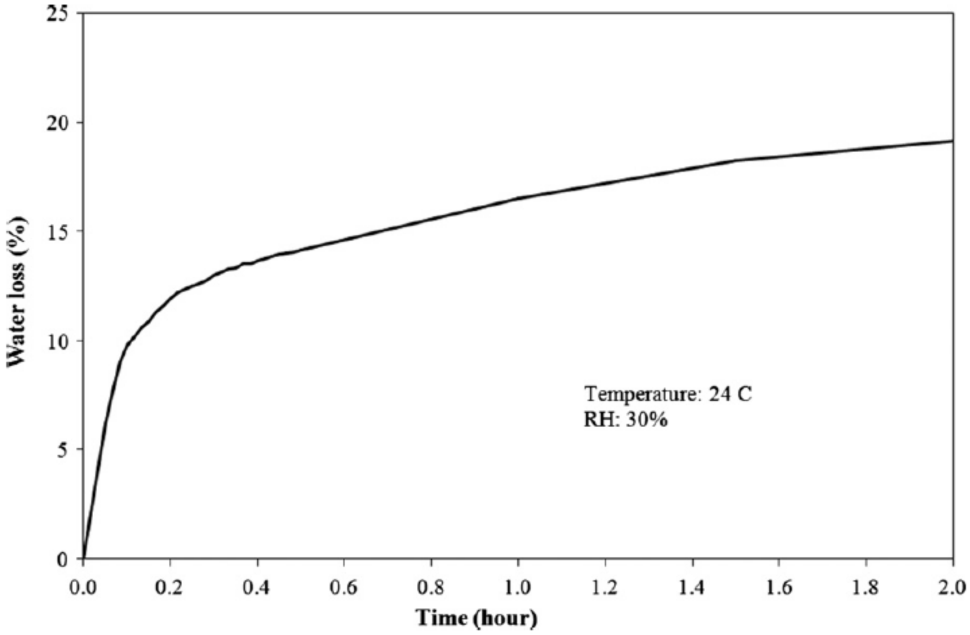
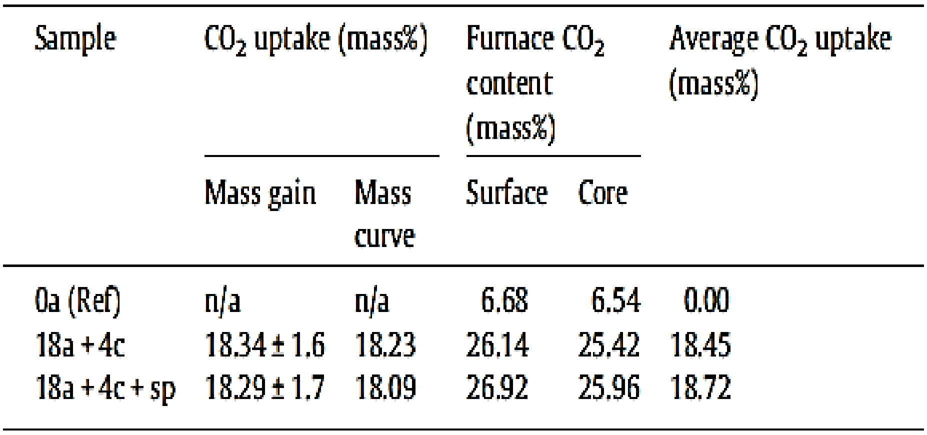


Fig 2.5: Graph of water loss% v/s time (*Rostami et al. (2011)*)

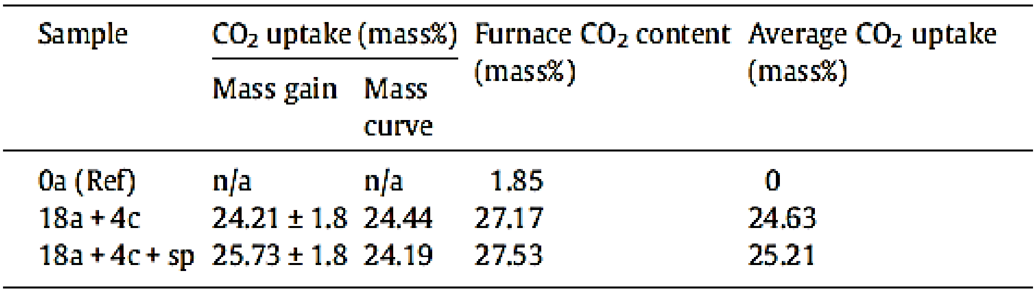
Table 2.4: CO_2 content and uptake in PLC concretes (*Hassan et al. (2013)*)



Sample	CO_2 uptake (mass%)		Furnace CO_2 content (mass%)		Average CO_2 uptake (mass%)
	Mass gain	Mass curve	Surface	Core	
0a (Ref)	n/a	n/a	6.68	6.54	0.00
18a + 4c	18.34 ± 1.6	18.23	26.14	25.42	18.45
18a + 4c + sp	18.29 ± 1.7	18.09	26.92	25.96	18.72

The carbon dioxide uptake of carbonated OPC concrete is shown in Table 2.5. Carbonated OPC concrete showed an uptake of 24.6 %, which was 6% more than PLC. The 15% cement replacement with limestone reduced the amount of reactants, C_3S and C_2S, and which subsequently reduced the reaction rate.

Table 2.5: CO_2 uptake of carbonated OPC (*Hassan et al. (2013)*)



Sample	CO_2 uptake (mass%)		Furnace CO_2 content (mass%)	Average CO_2 uptake (mass%)
	Mass gain	Mass curve		
0a (Ref)	n/a	n/a	1.85	0
18a + 4c	24.21 ± 1.8	24.44	27.17	24.63
18a + 4c + sp	25.73 ± 1.8	24.19	27.53	25.21

Mo et al. (2013) calculated values of the carbonation fronts by using 1% phenolphthalein solution. The results of which are shown in Fig 2.6

An obvious red colour was observed on the entire surface of B-0 specimen, which showed that there was a large amount of calcium hydroxide present in the sample. The carbonation front was unclear in the B-0, B-20 and B-40 samples. Whereas a clear carbonation front was observed in the T-0 samples with a carbonation depth of 4mm by the age of 56 days.

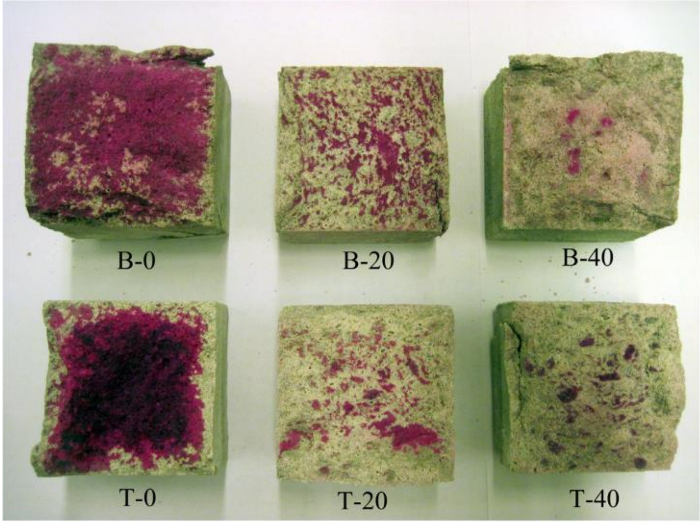


Fig 2.6: Split surfaces of cement mortar specimens after phenolphthalein solution spray after 56 days of CO_2 curing (*Mo et al. (2013)*)

CO_2 consumption tests results conducted by *Chabannes et al. (2016)* are represented in Fig 2.7

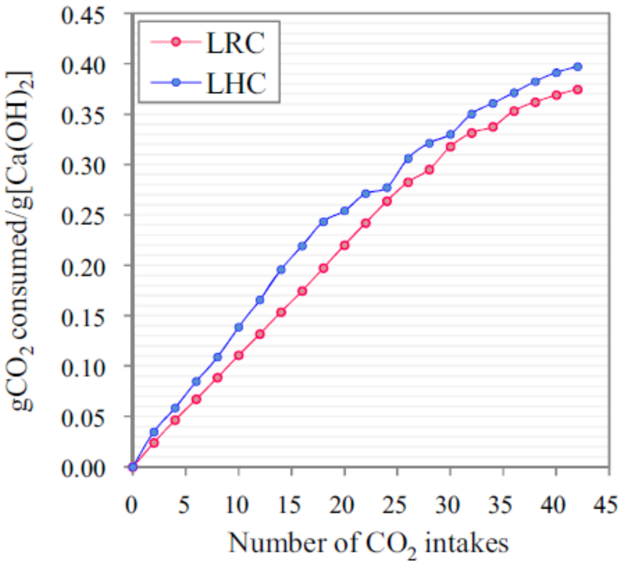


Fig 2.7: Relation of $Ca(OH)_2$ with CO_2 intake *(Chabannes et al. (2016))*

Profiles of the specimens obtained by Phenolphthalein spray test done by *Chabannes et al. (2016)* are shown in Fig 2.8. The amount of CO_2 consumed decreased slightly after the 20 intakes in both the concretes. The decrease in consumption could be due to the high amount of released during the curing process.

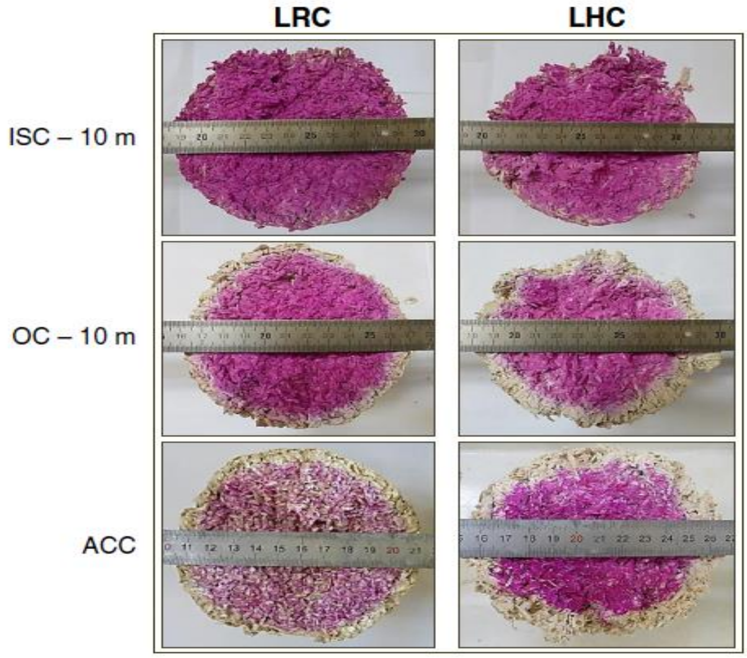


Fig 2.8: Cross-sections of the specimens after compression failure after phenolphthalein spray (*Chabannes et al.(2016)*)

2.3.2 Compressive strength

Experiments conducted by *Rostami et al. (2011)* showed that the strength 2 hour steam + 2 hour CO_2 curing was 90% of the reference sample and this value was very close to 2-h steam + 2-h air curing specimens. Subsequently the strength of CO_2 cured (2S + 2C) and air cured (2S + 2A) concretes was found to be 10% and 8% more, respectively, when compared to the 2 hour steam (2S) curing samples. The strength gain in 4 hour CO_2 cured specimens without steam curing was only 3.6 MPa. Compressive strengths results produced by accelerated curing are presented in Fig 2.9. The 4 hour steam curing batch was taken as the reference.

The results of compressive strength at the age of 28 and 90 days are shown in Fig 2.10 where it was observed that the further hydration took place in the carbonated samples. But the compressive strength of carbonated samples was found to be lower than the reference air cured sample at the age of 28 and 90 days.

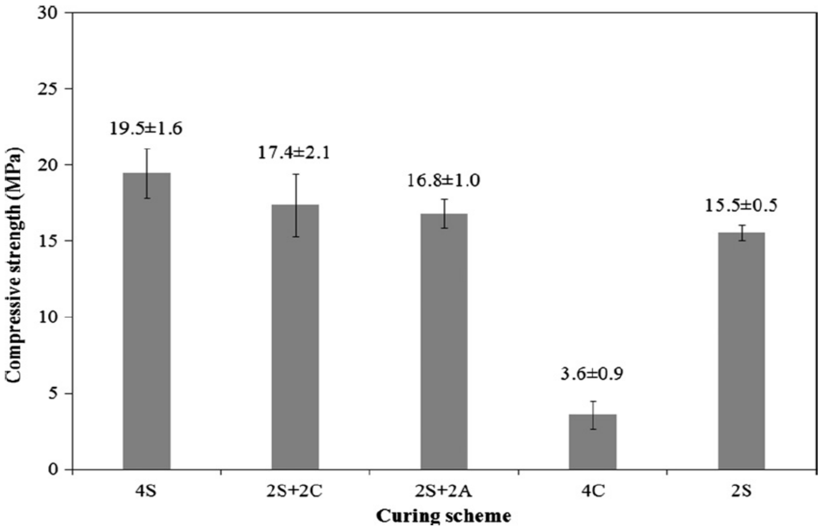


Fig 2.9: Early strength of CO_2 cured and steam cured specimens (*Rostami et al. (2011))*

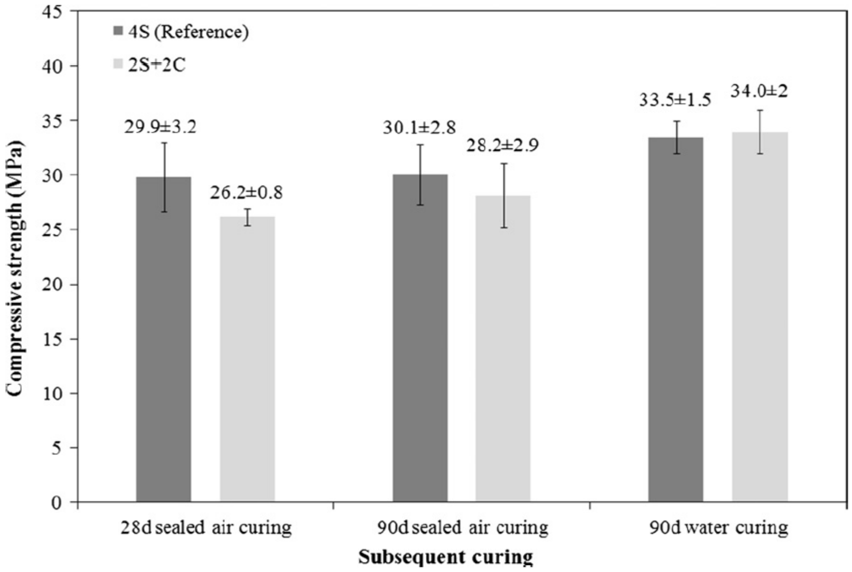


Fig 2.10: Late strength of Early strength of CO_2 cured and steam cured specimens and steam hydrated concretes after subsequent curing (*Rostami et al. (2011))*

The compressive strength test results conducted by *Hassan et al. (2013)* at the age of 4 hours after casting and without initial curing are shown in Fig 2.11. Early strength was increased significantly in both steam cured and carbonation cured samples.

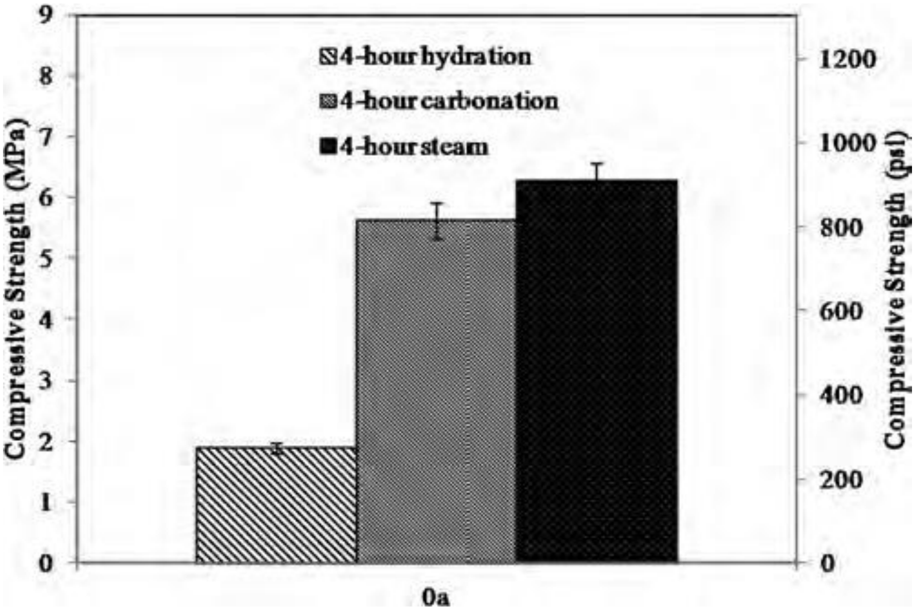


Fig 2.11: Compressive strength after 4 hours (*Hassan et al. (2013)*)

Fig 2.12 shows the effect of carbonation duration with a fixed initial curing of 18 hours.

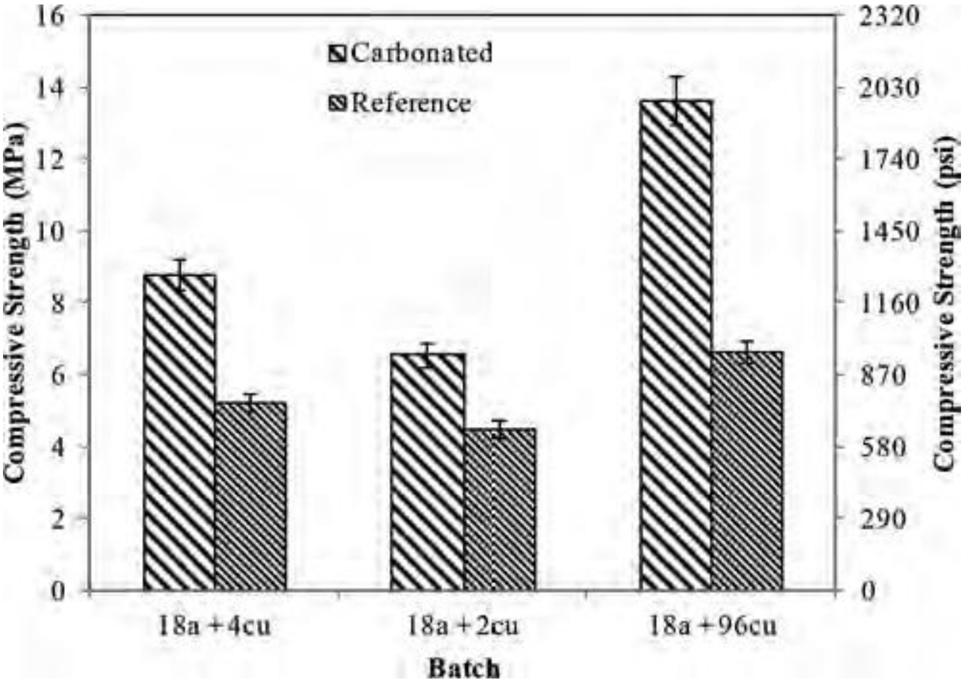


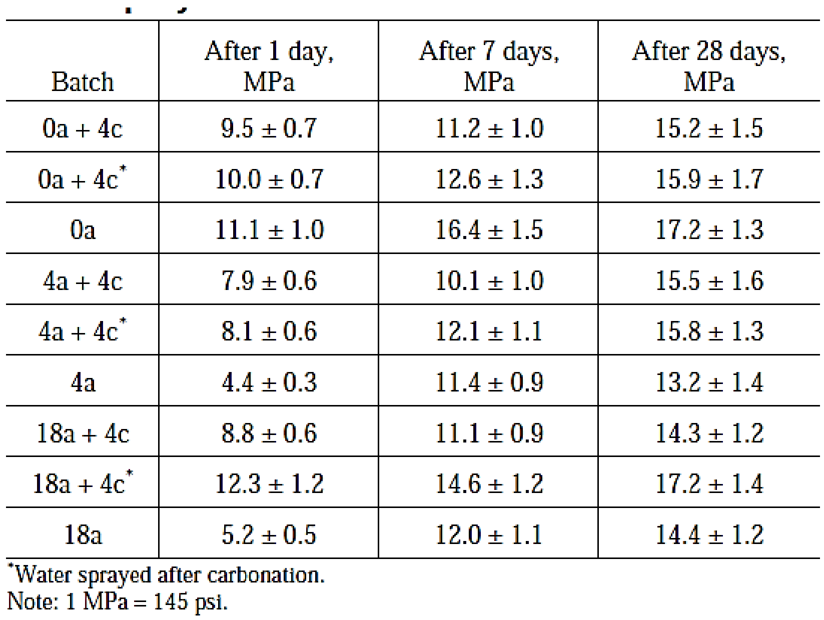
Fig 2.12: Compressive strength with varied carbonation duration *(Hassan et al. (2013))*

Longer was the carbonation time more was the strength produced. The results of compressive strength after the application of water spray are shown in Table 2.5. It could be observed from the table that compressive strength was improved after the application of water spray. This shows that water application is beneficial to the compressive strength. it can also be observed that subsequent hydration was not hindered by the carbonation curing. With the application of water it the compressive strength results were comparable to the hydration reference.

From the tests performed it was found out that 18h initial curing followed by 4h carbonation produced the best results when compared to the hydration reference and reached a carbon uptake of 24%.

The compressive strength of 1- and 28-day CMUs is presented in Fig 2.13. The strength gain in carbonated CMU units was twice as compared to the hydration reference. After the age of 28 days the CO_2 cured samples (18a + 4c) produced lower strength when compared to the hydrated samples due to the water loss in early air curing. Thus it was observed that, to restore the water loss water spray was essential.

Table 2.6: Compressive strength of concrete specimens with water spray (*Hassan et al. (2013)*)



Batch	After 1 day, MPa	After 7 days, MPa	After 28 days, MPa
0a + 4c	9.5 ± 0.7	11.2 ± 1.0	15.2 ± 1.5
0a + 4c*	10.0 ± 0.7	12.6 ± 1.3	15.9 ± 1.7
0a	11.1 ± 1.0	16.4 ± 1.5	17.2 ± 1.3
4a + 4c	7.9 ± 0.6	10.1 ± 1.0	15.5 ± 1.6
4a + 4c*	8.1 ± 0.6	12.1 ± 1.1	15.8 ± 1.3
4a	4.4 ± 0.3	11.4 ± 0.9	13.2 ± 1.4
18a + 4c	8.8 ± 0.6	11.1 ± 0.9	14.3 ± 1.2
18a + 4c*	12.3 ± 1.2	14.6 ± 1.2	17.2 ± 1.4
18a	5.2 ± 0.5	12.0 ± 1.1	14.4 ± 1.2

*Water sprayed after carbonation.
Note: 1 MPa = 145 psi.

The results of the compressive strength tests on OPC concretes conducted by *Hassan et al. (2015)* are shown in Fig 2.14. Here also due to the loss of water in early air curing the 28 day compressive strength came out to be lower than the hydrated reference.

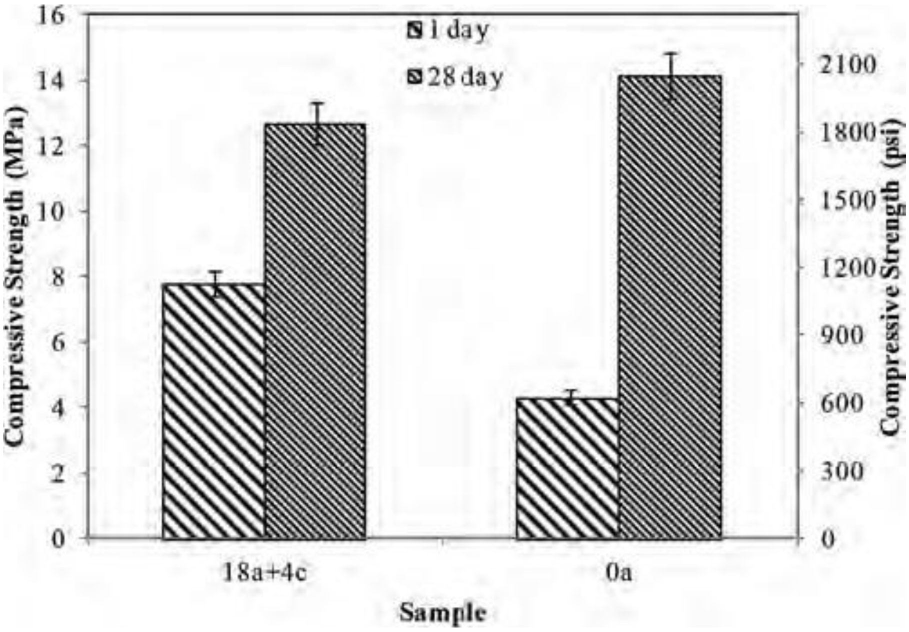


Fig 2.13: Compressive strength of CMU (*Hassan et al. (2013)*)

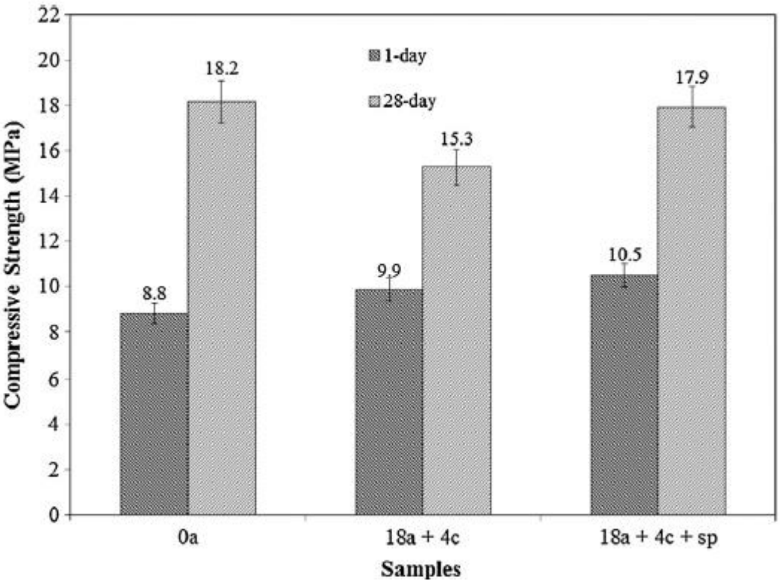


Fig 2.14: Compressive strength OPC concrete at the age of 1 and 28 days (*Hassan et al. (2015)*)

The results of compressive strength tests by *Chabannes et al. (2016)* after initial curing of 40 days and accelerated CO_2 curing of one month are reported in Fig 2.15. These results were compared with the reference samples cured under natural conditions for 2 months and 12 months. From the results it was observed that compressive strength after accelerated carbonation curing was comparable to the compressive strength of the samples cured in outdoor exposure for 10 months.

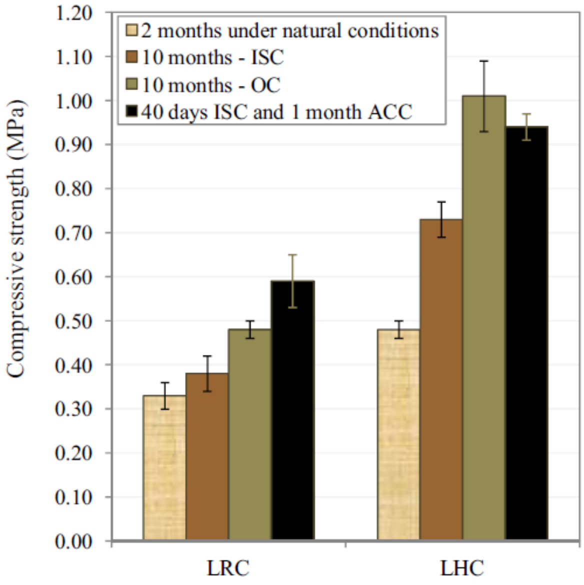


Fig 2.15: Compressive strength results of LRC and LHC samples after ACC compared to natural conditions (*Chabannes et al. (2016)*)

Junior et al.(2015) found that that the strength of the P_{C1h} specimens was greater than the P_{REF} and P_{C24h} specimens. It was observed that the CO_2 of 1 hour affected the matrix of concrete mix in such a way that it promoted a slight gain in compressive strength.

The compressive strength test results of carbonated FA-OPC conducted by *Shao et al.(2016)* are compared in Fig 2.16

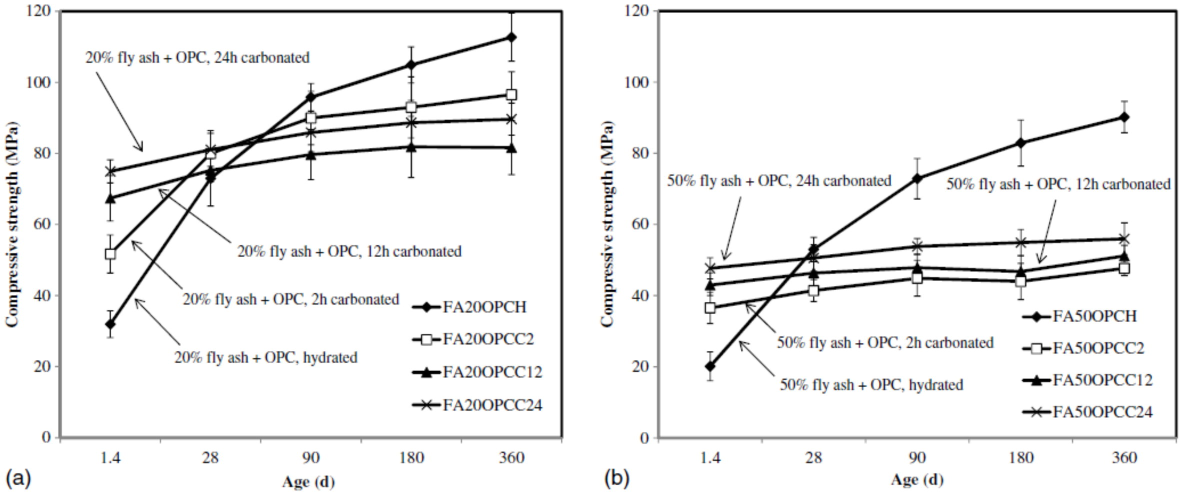


Fig 2.16: Compressive strength test results of carbonation cured FA-OPC pastes: (a) fly ash/binder =20%; (b) fly ash/binder = 50% *(Shao et al.(2016))*

From the Fig 2.16 it was observed that the early strength was improved by CO_2 curing but the gain in strength was slower at the age of 28 days in carbonated pastes. This indicates that the pozzolanic reaction was hindered by early carbonation.

Zhang et al. (2016) concluded that the carbonation curing produced high early strength. At 28 days carbonated samples still showed higher strength but difference in strength was not much when compared to the reference samples.

2.3.3 XRD analysis

Rostami et al. (2011), XRD analysis before and after carbonation is presented in Fig 2.18 where it was observed that $Ca(OH)_2$ phase was significantly reduced while the $CaCO_3$ phase was considerably increased after carbonation.

Fig 2.17 also shows that the $CaCO_3$ was not produced solely due to the consumption of $Ca(OH)_2$, as the amount of non-hydrated phases (like C_2S and C_3S) also showed a significant decrease.

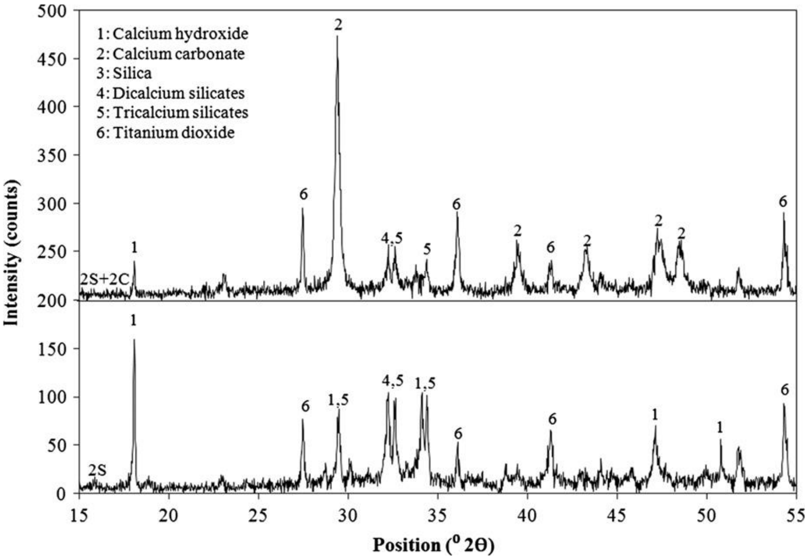


Fig 2.17: XRD analysis of cement paste before and after carbonation curing (*Rostami et al. (2011)*)

Figs 2.18 and 2.19 show the XRD patterns acquired from 5-mm layers of the carbonated and reference specimens at ages of 4 h and 28 days. It can be observed that $Ca(OH)_2$ peaks were lesser at the surface and slowly increased while moving towards the core.

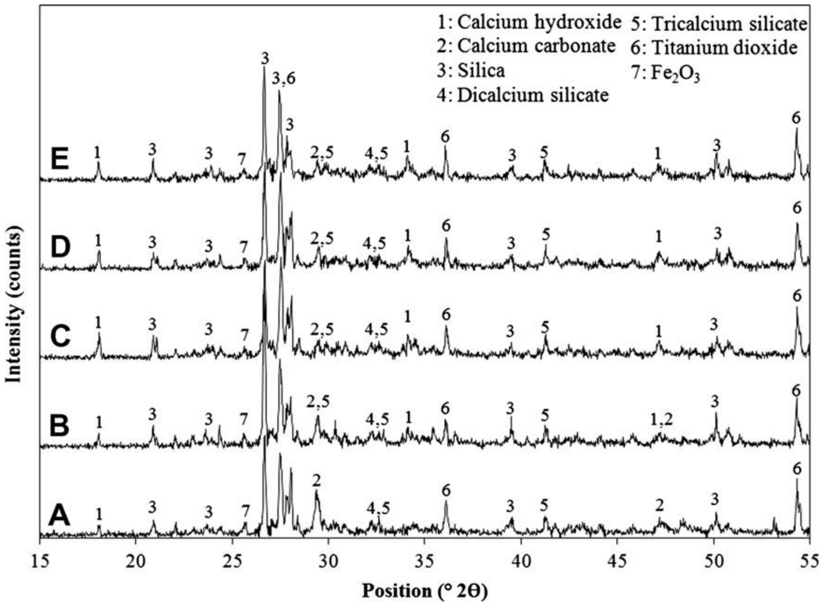


Fig 2.18: XRD patterns of concrete at 4 h: (A) 2S + 2C, 0–5 mm, (B) 2S + 2C, 5–10 mm, (C) 2S + 2C, 10–15 mm, (D) 2S + 2C, 15–20 mm, (E) 4S (Reference) (*Rostami et al. (2011)*)

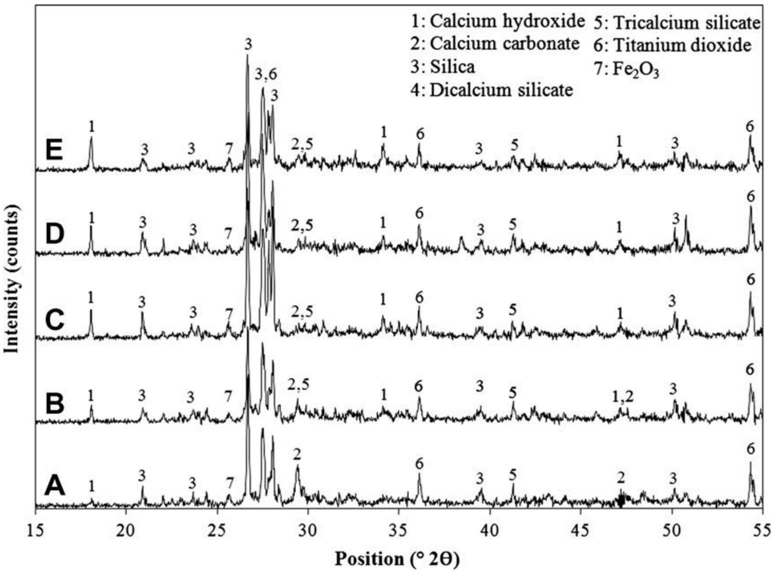


Fig 2.19: XRD patterns of concrete at 28 days: (A) 2S + 2C, 0–5 mm, (B) 2S + 2C, 5–10 mm, (C) 2S + 2C, 10–15 mm, (D) 2S + 2C, 15–20 mm, (E) 4S (Reference*).(Rostami et al.(2011))*

After 28 days, the carbonated and hydrated block samples were analyzed using XRD by *Hassan et al. (2013)* and the results are presented in Fig 2.20

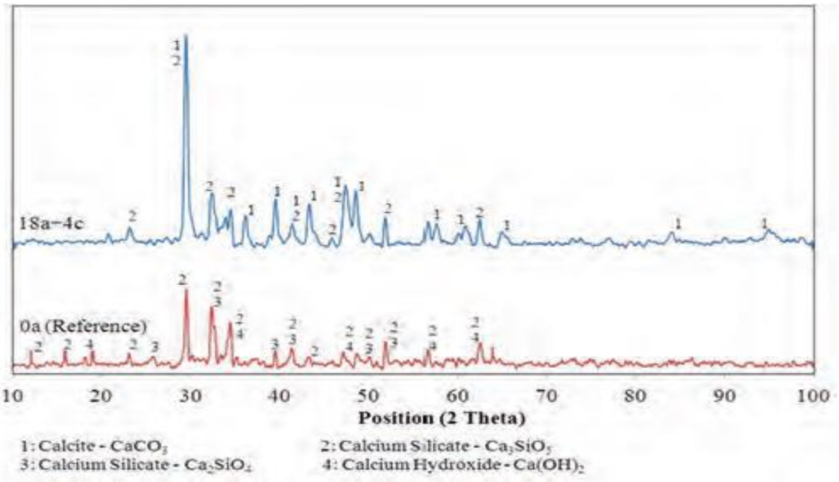


Fig 2.20: XRD patterns of CMU blocks *(Hassan et al. (2013))*

Calcite and tricalcium silicate were the two most prominent compounds found in the carbonated samples. Dicalcium silicate was also found but in lesser amount. In the hydrated reference calcium hydroxide, dicalcium silicate and tricalcium silicates were found. It is is clear from the graph that calcium hydroxide was eliminated in carbonated specimens.

Results of Microstructure analysis of PLC concrete at 1 and 28 days by *Hassan et al.(2015)* are shown in Fig 2.21 and 2.22

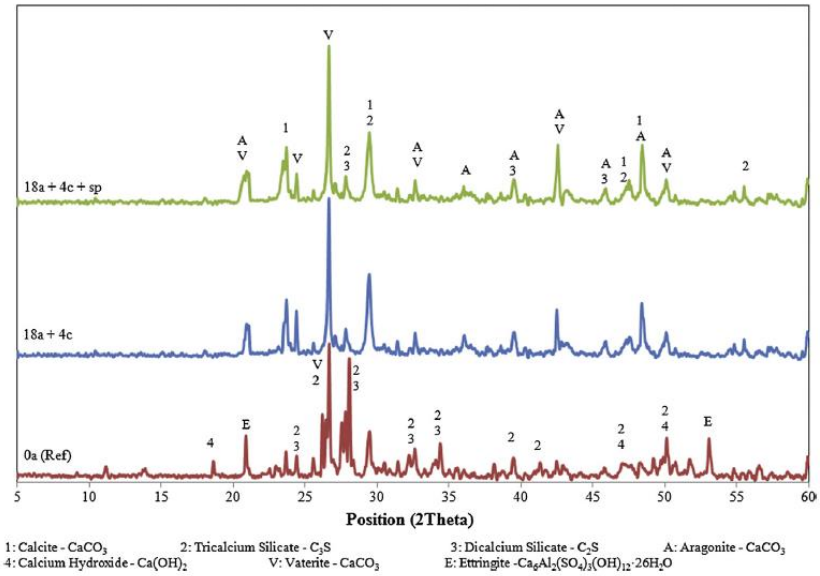


Fig. 3. XRD patterns of PLC concretes after 1 day.

Fig 2.21: XRD patterns concretes after 1 day (*Hassan et al.(2015)*)

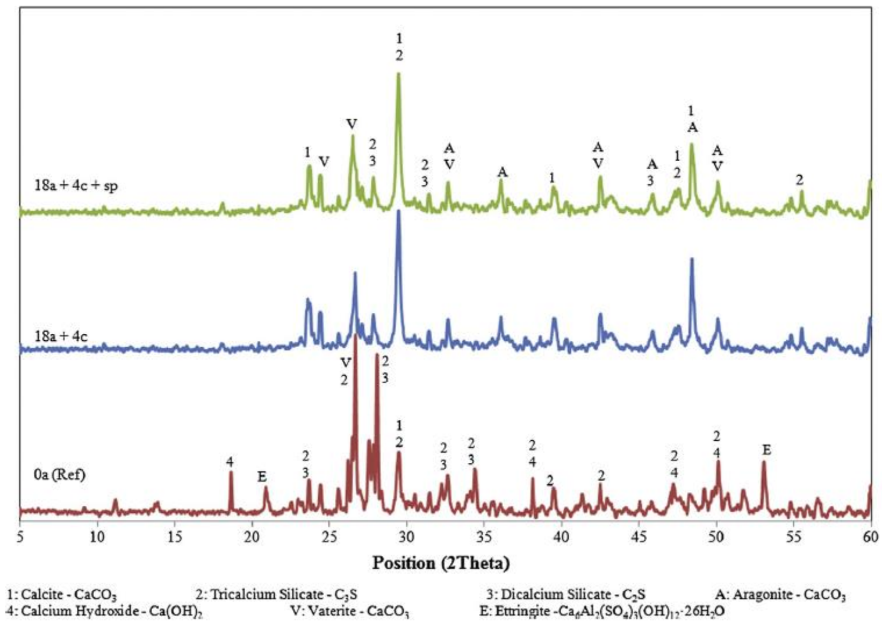


Fig 2.22: XRD patterns of PLC concrete after 28 days. (*Hassan et al. (2015)*)

Vaterite and aragonite peaks, observed at 21.5° and 43°, decreased when compared to the results at one day. While aragonite formed during (18a + 4a) curing, varite formed during the accelerated carbonation reaction. The hydrated sample did not show much difference between 1 and 28 days, other than more $Ca(OH)_2$ peaks were observed at the age of 27 days.

The microstructure changes of OPC cement after 1 day are presented in Fig 2.23. The patterns for carbonated concretes showed formation of vaterite, aragonite, and calcium carbonate as carbonation products with the elimination of $Ca(OH)_2$.

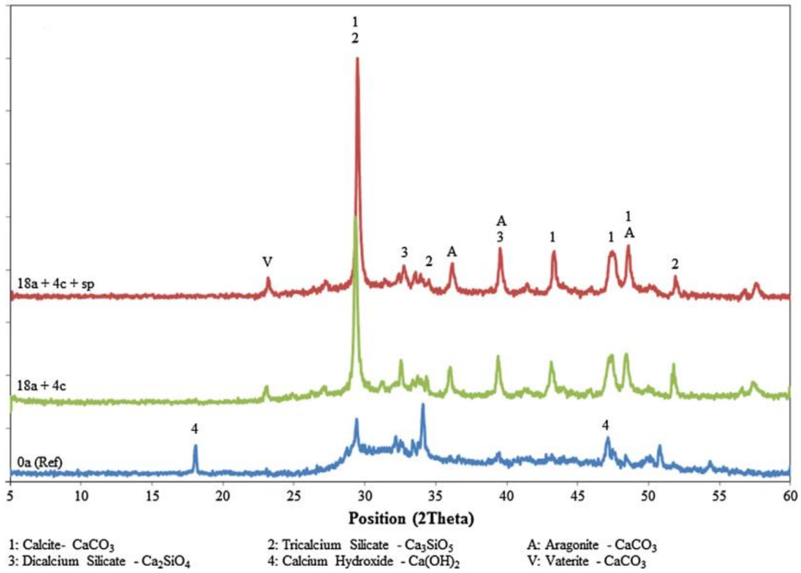


Fig 2.23: XRD patterns of OPC concretes after 1 day. (*Hassan et al.(2015)*)

The XRD patterns of atmosphere cured and carbonation cured samples by *Liwu Mo et al.(2013)* at the age of 56 days are shown in Fig 2.24. Fig 2.24a represents the XRD patterns of specimens containing GU and MgO as partial replacement of cement and Fig 2.24b represents the XRD patterns of samples containing 40% GGBFS as partial replacement of cement and 40% reactive MgO.

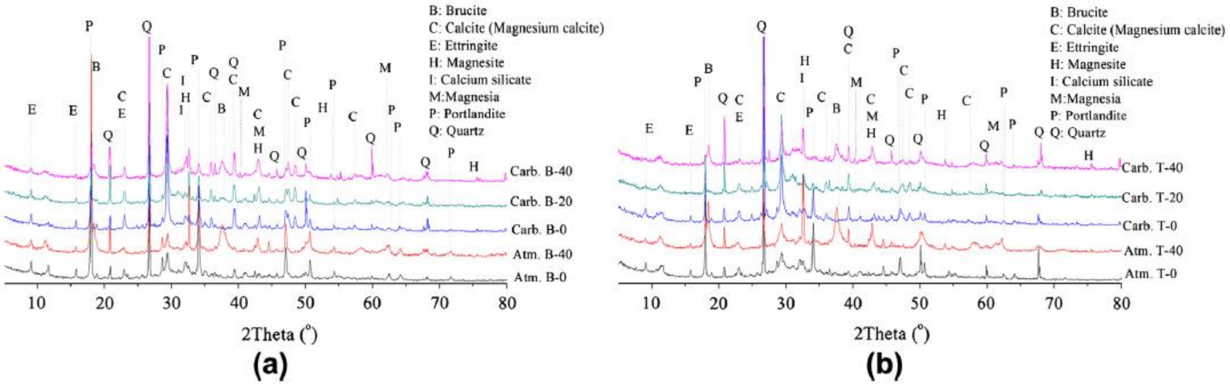


Fig 2.24: XRD analysis of samples from atmosphere-cured and carbonation-cured samples at the age of 56 days: (a) GU-reactive MgO blends and (b) GU-GGBFS- MgO blends (*Liwu Mo et al.(2013)*)

For the CO_2 cured specimens, clear peaks of calcite ($CaCO_3$) were seen, in all the cases peaks of $Ca(OH)_2$ and ettringite were observed even after 56 days of curing.

2.3.4 SEM analysis

Fig 2.25 shows the microstructure of hydrated concrete at the age of 28 d *(Hassan et al. (2015)*. Presence of ettringite was observed along with CSH gel.

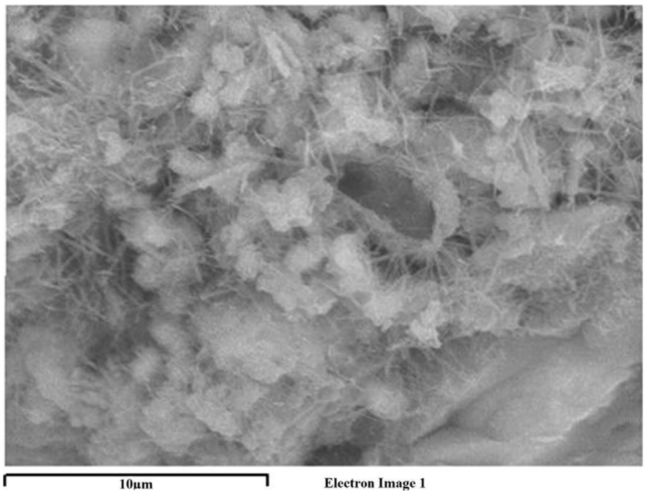


Fig 2.25: : SEM analysis of water cured PLC specimens (0a) at the age of 28 days. *(Hassan et al. (2015))*

The microstructure of CO_2 cured specimens (18a + 4c) is shown in Fig 2.26, where it was found that ball like crystals were created with the dimensions of 1µm and 5µm.

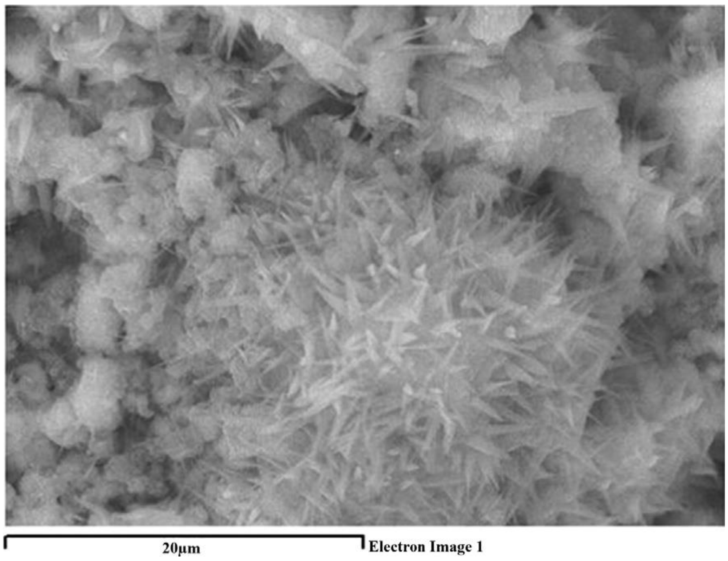


Fig 2.26: SEM analysis of carbonation cured (18a + 4c) specimens at the 28 days.*(Hassan et al. (2015))*

Fig 2.27 shows the microstructure of water compensated carbonated samples (18a + 4c + sp). Here the dense microstructure was observed when dense and closely packed crystals.

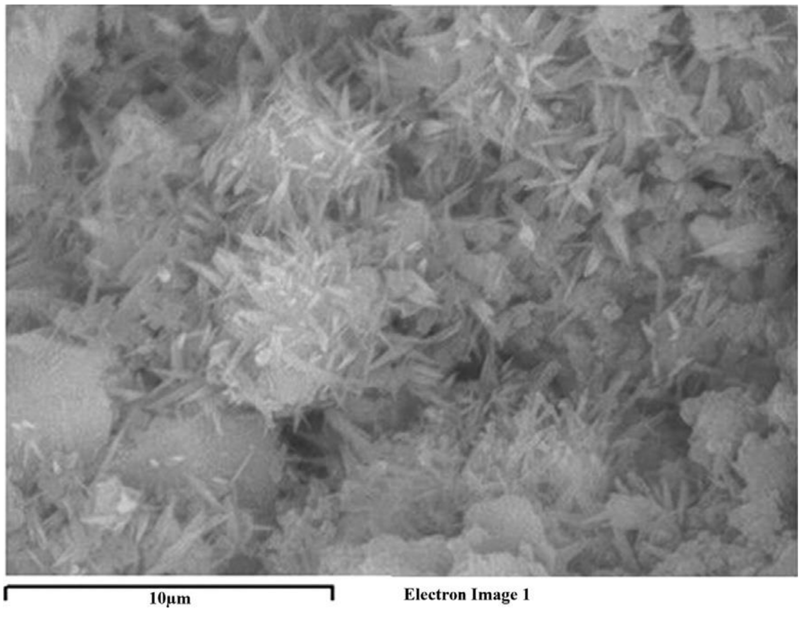


Fig 2.27: SEM analysis of carbonation cured (18a + 4c + sp) PLC specimens at the age of 28 days (Hassan et al. (2015))

2.3.5 Chloride penetration

Rostami et al. (2011) found that chloride penetration was found to be almost half for the carbonated samples as compared to the steam cued samples. Fig 2.28 shows the coulomb passing of carbonation cured and hydrated concrete at 2 d and 28 d. The 28 d results of chloride permeability test on steam cured samples and steam-CO_2 cured samples are also shown in this Fig 2.28

There was linear increase in total charge passed, which suggest that the linear conductance remained same during the test and upto its end. The 28 days results also showed the same pattern.

Results of the chloride penetration tests conducted on OPC concrete by *Zhang et al. (2016)* are shown in Fig 2.29. It can be clearly observed in Fig. 2.29a that lesser chloride content was observed in all layers in CO_2 cured concrete than in hydrated specimens. The occurrence was more considerable in the 50th cycle presented in Fig. 2.29b.

Results of the chloride penetration tests conducted on flyash-OPC concrete by *Zhang et al. (2016)* are shown in Fig 2.30.

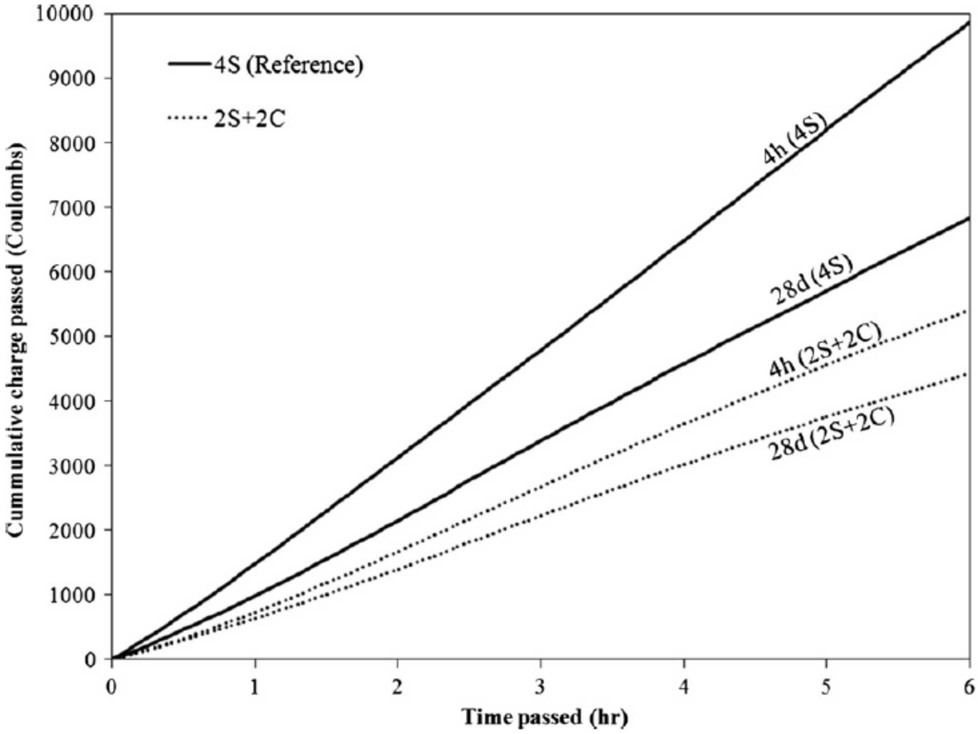
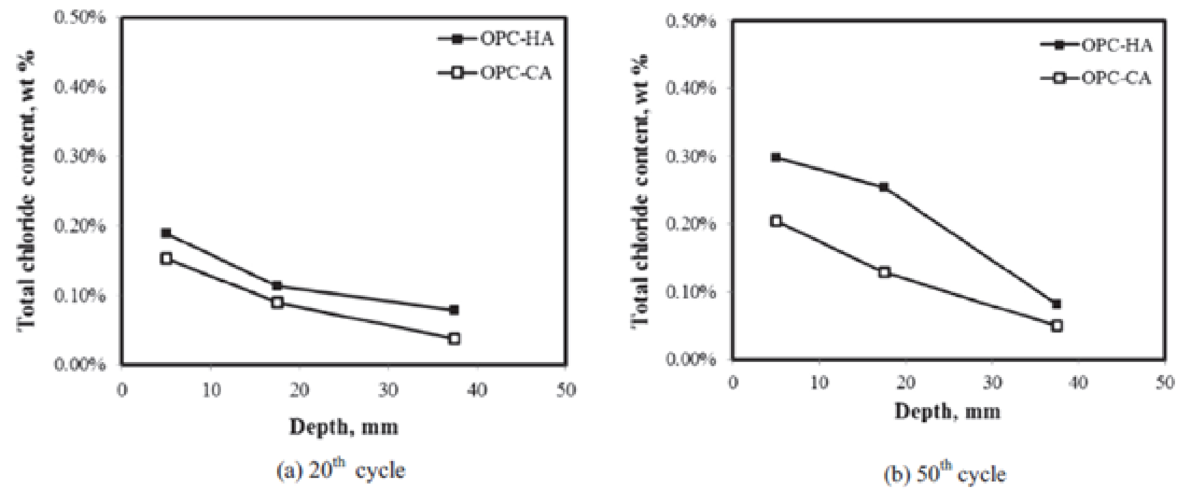


Fig 2.28: Coulomb passing of carbonation cured and water cured samples at the age of 2 and 28 days (*Rostami et al. (2011)*)

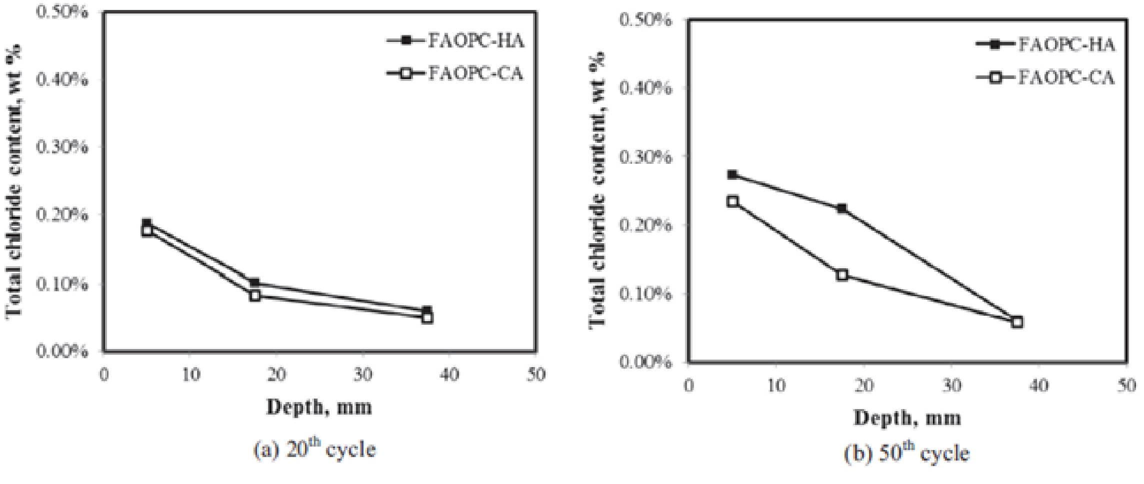


(a) 20th cycle

(b) 50th cycle

Fig 2.29: Chloride penetration of carbonation cured OPC concrete exposed to chloride immersion and air drying cycles (*Zhang et al. (2016)*

At 20th cycle shown in Fig. 2.30a chloride distribution along the depth of the specimen was quite similar between hydrated reference (FAOPC-HA) and carbonation cured (FAOPC-CA) samples. More noticeable difference was observed after 50th cycle in Fig 2.30b



(a) 20th cycle

(b) 50th cycle

Fig 2.30: Chloride penetration of carbonation cured Flyash-OPC concrete exposed to chloride immersion and air drying cycles (*Zhang et al. (2016))*

2.3.6 Acid attack

Acid resistance of steam cured and carbonation cured samples *(Rostami et al. (2011)* is shown in Fig 2.31. from the graph it could be observed that both the steam cured and CO_2

cured specimens showed similar weight loss trend. Therefore, it is clear that the CO_2 cured specimens are not more susceptible to sulphuric acid attack than the hydrated specimens.

2.4 EFFECT OF GGBS REPLACEMENT ON THE PROPERTIES OF CONCRETE

Hwang and lin (1986), this paper studied the effect of GGBS replacement on the compressive strength of the cement mortars Fig 2.32 shows the variation of compressive strength with the change in slag content. From the figure it can be seen that the maximum strength was obtained at a particular GGBS replacement and at a particular age. Thus, it can be concluded that strength of GGBS concrete depends both on percentage of GGBS and the age of concrete.

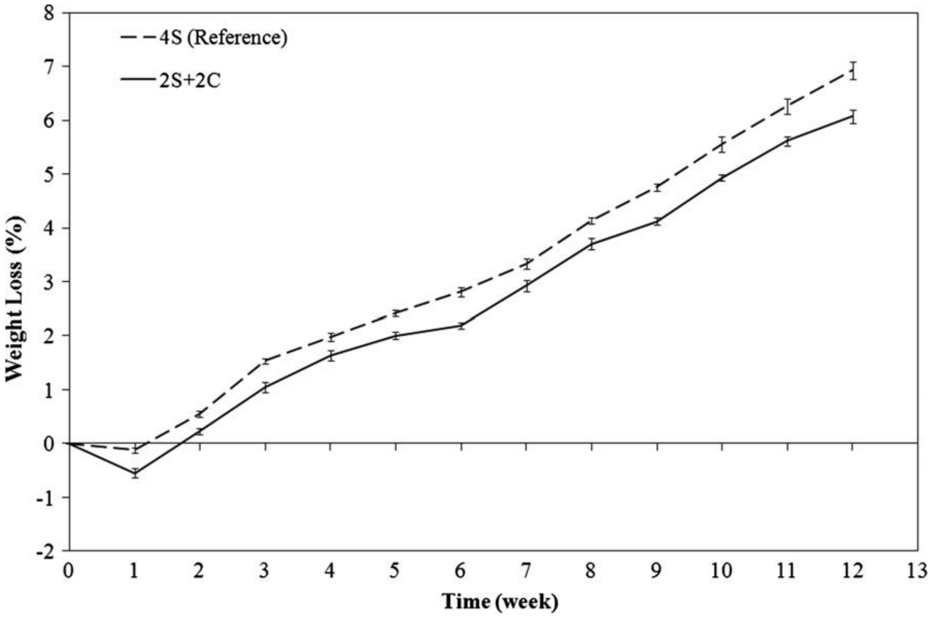


Fig 2.31: Weight loss of concretes in sulfuric acid solution (1 < pH < 2) ***(Rostami et al. (2011))***

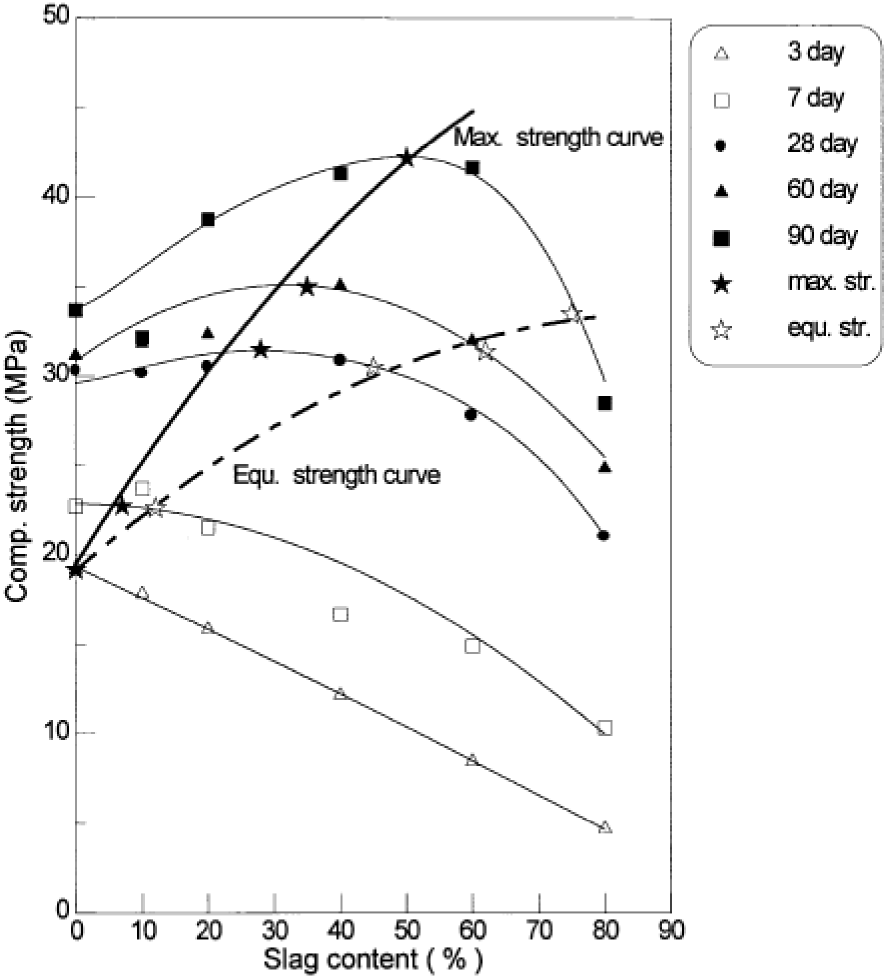


Fig 2.32: Effect of slag content on the strength development in cement mortars *(Hwang and Lin (1986))*

Law et al. (2009), studied the compressive strength and sorptivity of the alkali-activated slag and flyash based geopolymer concrete containing varying percentages of GGBS as a partial replacement of concrete. Replacement levels of GGBS were taken as 0%, 30%, 50% and 70%. Table 2.7 gives the mix proportions of the concrete mixes used in this study.

Table 2.7: Mix proportions *(Law et al. (2009))*

Mix	Binder		Aggregate			water
	OPC	GGBS	sand	7mm	10mm	
CTL	428	-	784	346	693	222
S30	296	127	784	346	693	220
S50	210	210	784	346	693	219
S70	125	293	784	346	693	217

Fig 2.33 shows the compressive strength test results of the various concrete mixes. From the figure it was found that the strength development in GGBS concrete was slow and strength decreased as the percentage of the GGBS increased. Strength was similar to the control mix

up to 50% replacement and reduced when replacement reached 70% at the age of 28 days. The strength of GGBS concrete increased till 50% replacement and decreased when replacement reached 70%. The early strength of GGBS concrete low but it shows higher strength at the later ages. This is due to the reason that calcium hydroxide from cement hydration is required for slag hydration therefore the slag hydration will not start until the cement hydration has taken place. Due to this the early strength of the GGBS concrete is lower.

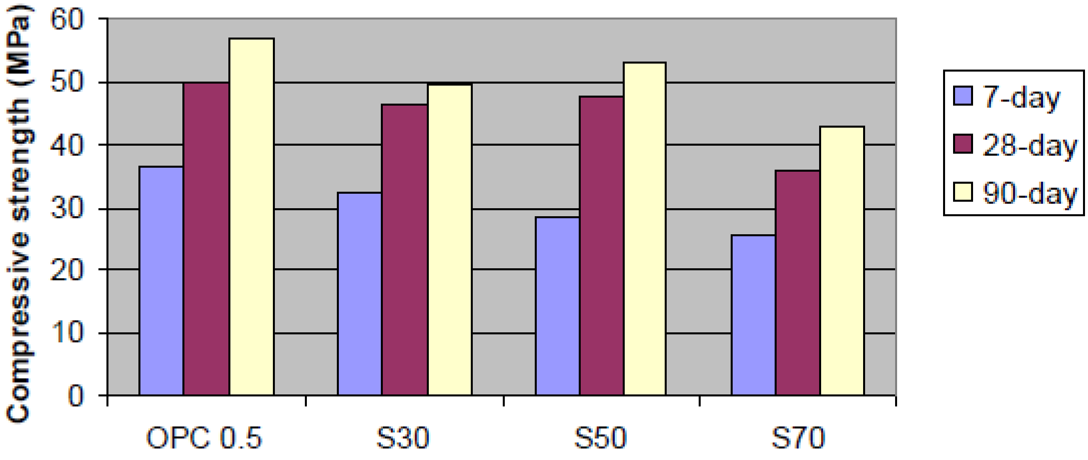


Fig 2.33: Compressive strength of the concrete mixes *(Law et al. (2009))*

Sorptivity test results of various concrete mixes are shown in Fig 2.34. From the figure it can be observed that the value of sorptivity decreased as the percentage of GGBS increased.

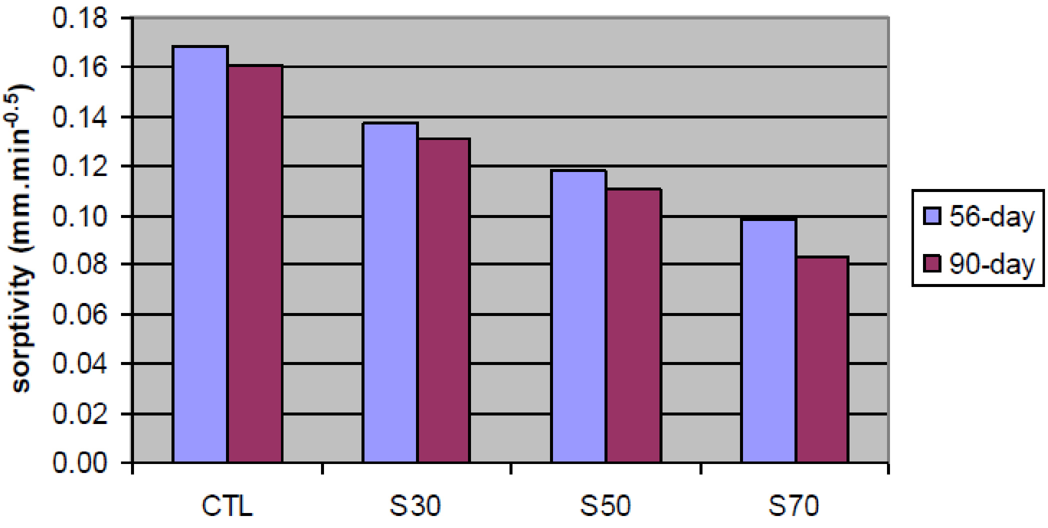


Fig 2.34: Sorptivity test results *(Law et al. (2009))*

Ling et al. (2014) studied the compressive strength, water absorption and acid resistance of architectural mortar made with 100% recycled glass aggregates containing metakaolin and varying percentages of GGBS as a partial replacement of cement. The replacement levels were taken as 15%, 30%, 45%, 60% and 75%. Table 2.8 shows the mix proportions of different mixes. Fig 2.35 shows the results of the compressive strength of the specimens at the age of 1, 7, 28 and 90 days.

Table 2.8: Mix proportions of the different mixes *(Ling et al. (2014))*

Notation	*w/b*	Water	Cementitious materials		
		(kg/m^3)	WC (kg/m^3)	MK (kg/m^3)	GGBS (kg/m^3)
Control	0.4	283	706	0	0
MK15	0.4	283	600	106	0
GGBS15	0.4	283	660	0	106
GGBS30	0.4	283	494	0	212
GGBS45	0.4	283	388	0	318
GGBS60	0.4	283	282	0	424
GGBS75	0.4	283	106	0	600

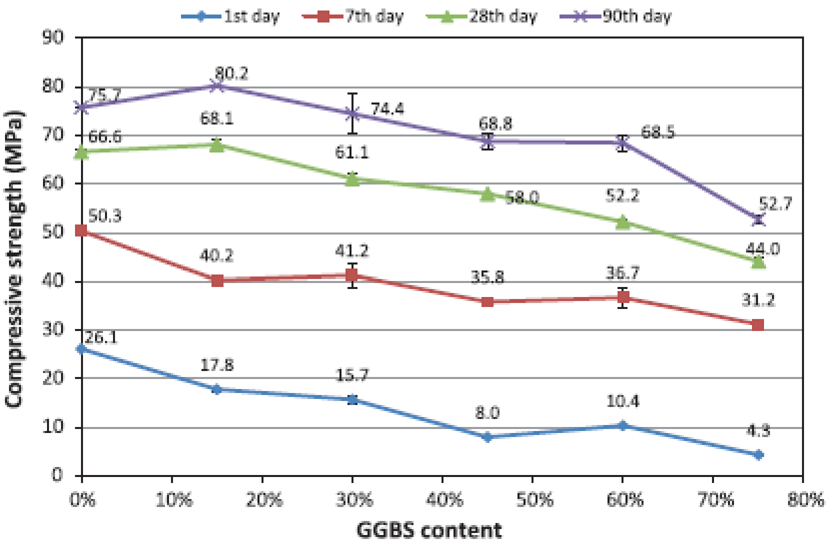


Fig 2.35: Compressive strength of the specimens at the ages of 1, 7, 28 and 90 days *(Ling et al. (2014))*

From Fig 2.35 it was found that early strength of all the samples containing GGBS was lower than the control mix. At the ages of 28 and 90 days it was found that the strength of concrete samples containing 15% GGBS was slightly higher than the control mix. Therefore it was concluded that the slower rate of pozzolanic reaction decreases the early strength of the concrete. Thus, GGBS addition could not compensate for the strength loss due to reduction in cement content. A denser C-S-H gel microstructure was observed in the GGBS concrete due to the consumption of calcium hydroxide.

Fig 2.36 shows the permeable voids and water absorption of the concrete mixes, containing metakaolin and GGBS, at the age of 90 days. It was found that the water absorption and the amount of permeable voids reduced with the addition of GGBS. At the 60% replacement the permeable voids were reduced by 7.9% as compared the control mix. But as the replacement level reached 75%, the value of the water absorption and permeable voids became more than the control mix. This could be due to the reason that as the cement content was reduced formation of the primary hydration products was lesser which resulted in the higher value of the water absorption and permeable voids.

The percentage mass loss of the concrete samples v/s the time of acid exposure is plotted in Fig 2.37. From the Fig 2.37 it can be observed that control mix and GGBS15 mix mass reduced with the time of exposure. There was an initial mass gain followed by the loss in mass in the GGBS30 and GGBS45 mix. At the age of 8 weeks the GGBS30 mix suffered a higher mass loss than the control mix but the mass loss of GGBS40 mix was similar to that of the control mix. The samples containing high volumes of GGBS i.e. 60% and 75% showed a steady mass gain with exposure time up to 8 weeks. This could be due to the low amount of calcium hydroxide present in these samples.

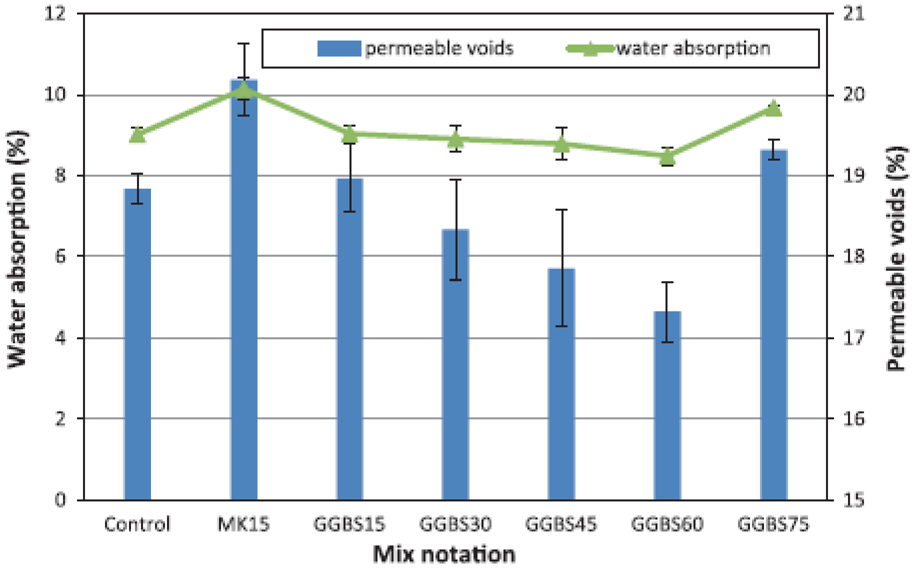


Fig 2.36: Permeable voids and water absorption of the concrete mixes at the age of 90 days *(Ling et al. (2014))*

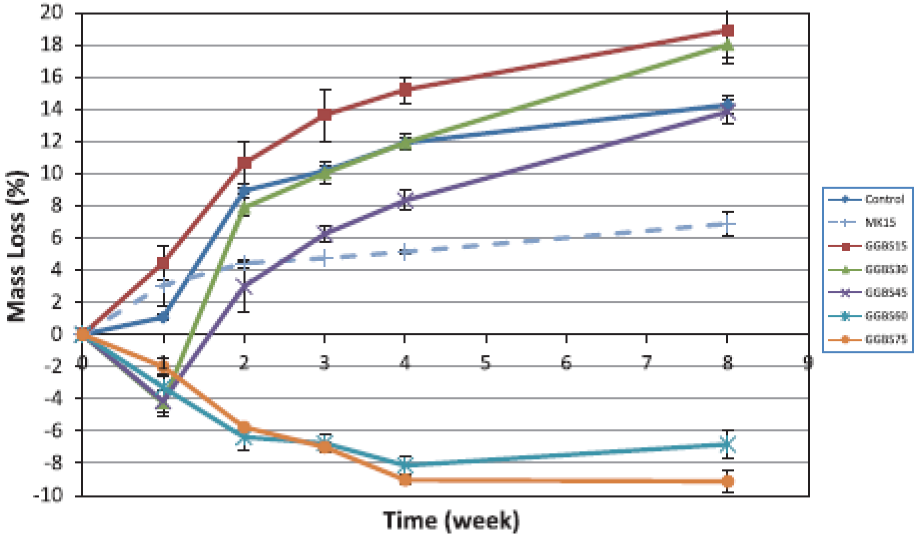


Fig 2.37: Percentage mass loss of the concrete specimens versus the acid exposure time *(Ling et al. (2014))*

Nath et al. (2014) studied the effect of GGBS addition as a partial replacement of cement on the early strength properties of flyash geopolymer concrete. The results of compressive strength of concrete and mortar mixes are shown in Fig 2.38(a) and 2.8(b)

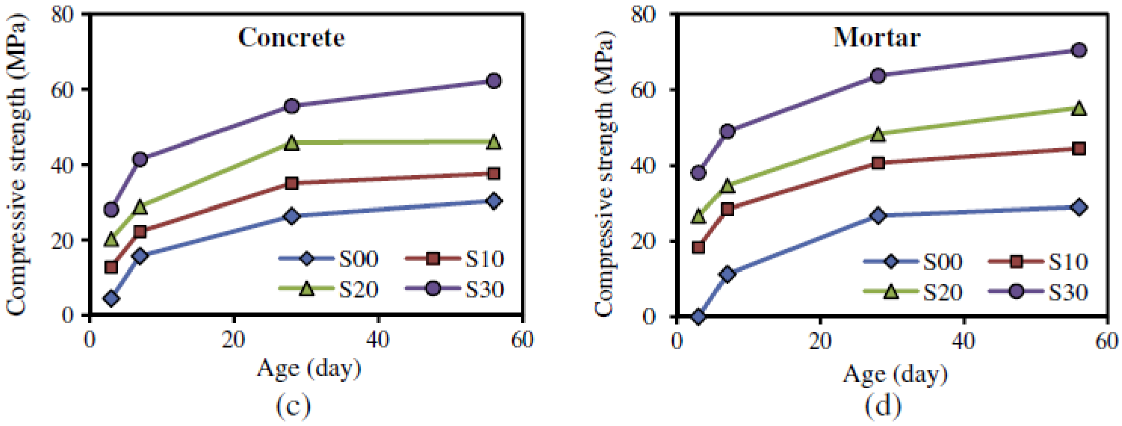
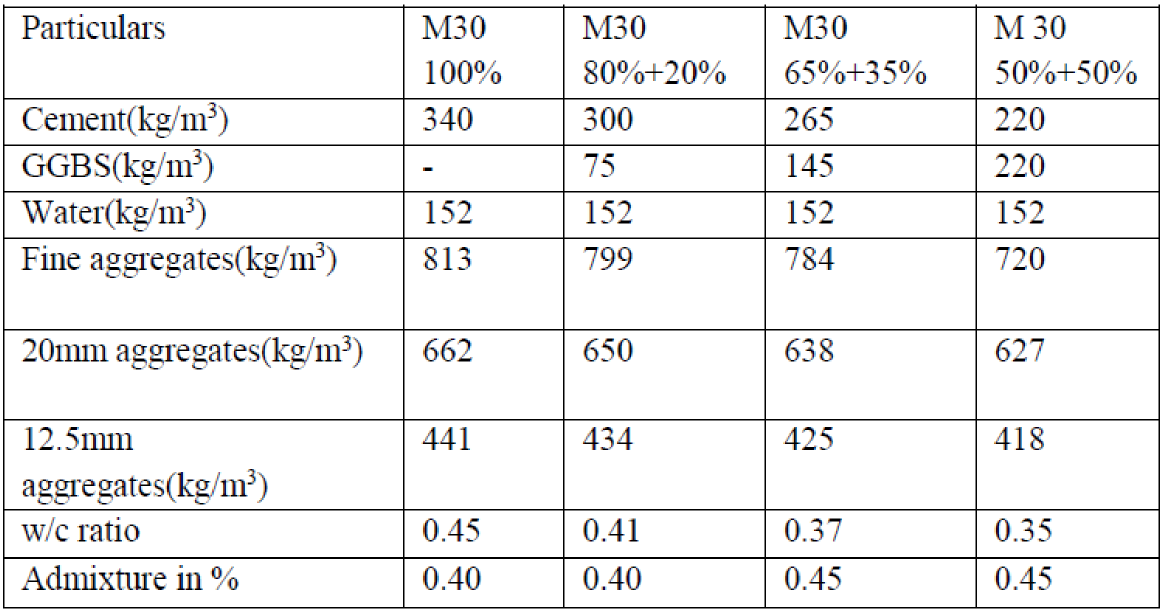


Fig 2.38: Compressive strength results of concrete and mortar mixes *(Nath et al. (2014))*

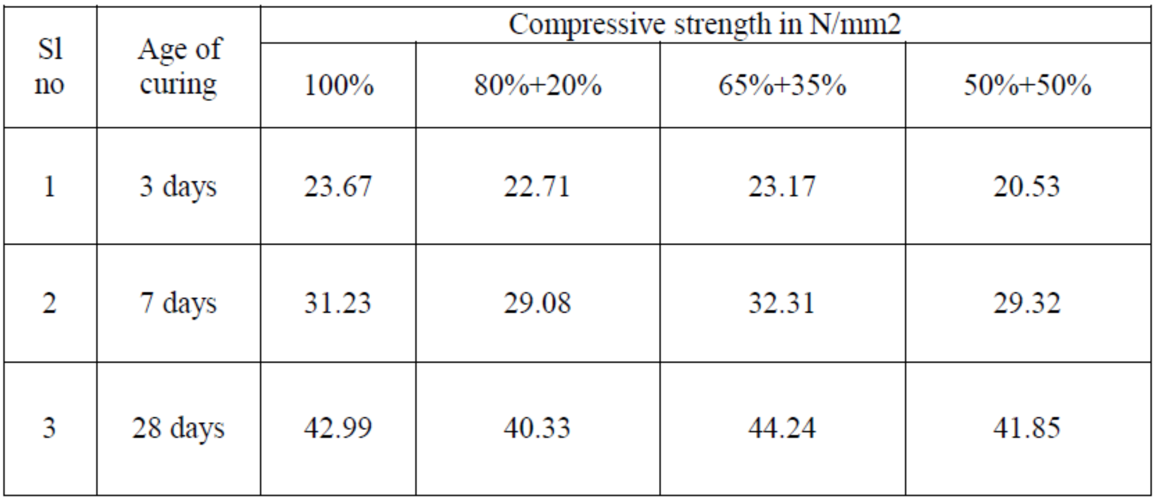
From the figure it can be observed that when GGBS was added in the mix the compressive strength increased significantly from the age of 3 days. At the age of 28 days the concrete mixes containing 10%, 20% and 30% GGBS showed 34%, 73% and 110% higher strength than the control mix. Therefore it was observed that the strength increased by 10Mpa for every 10% increase in GGBS content. The strength gain in mortar samples was greater as compared to the strength gain in concrete samples. At the age of 28 days mortar specimens containing 10%, 20% and 30% gained 52%, 81% and 137% strength respectively. However similar strength gain was observed at the age 56 days in both the mixtures.

Table 2.9: Mix proportions of the various concrete mixes *(Nandini et al. (2017))*



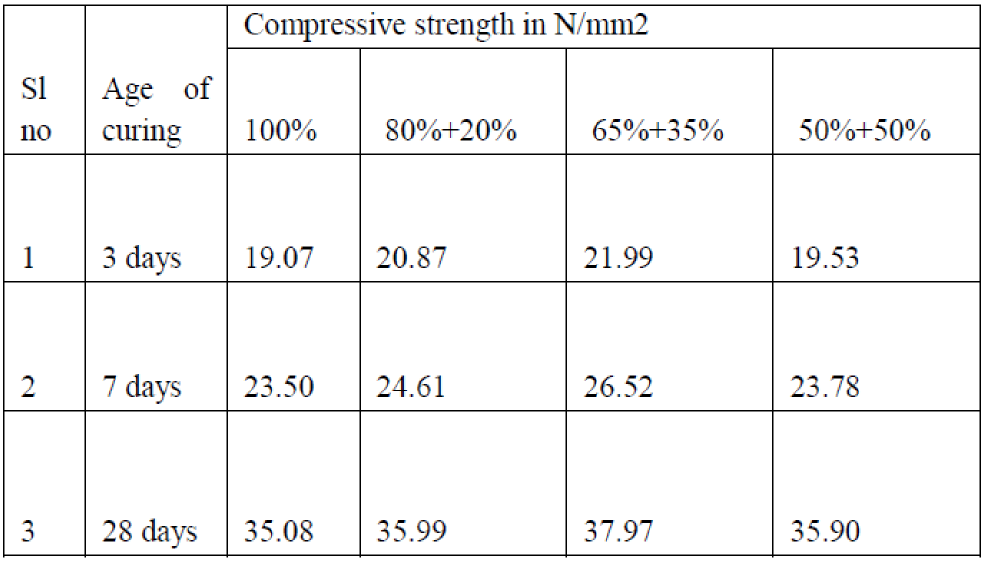
Particulars	M30 100%	M30 80%+20%	M30 65%+35%	M 30 50%+50%
Cement(kg/m^3)	340	300	265	220
GGBS(kg/m^3)	-	75	145	220
Water(kg/m^3)	152	152	152	152
Fine aggregates(kg/m^3)	813	799	784	720
20mm aggregates(kg/m^3)	662	650	638	627
12.5mm aggregates(kg/m^3)	441	434	425	418
w/c ratio	0.45	0.41	0.37	0.35
Admixture in %	0.40	0.40	0.45	0.45

Table 2.10: Compressive strength test results of various concrete mixes *(Nandini et al. (2017))*



Sl no	Age of curing	Compressive strength in N/mm2			
		100%	80%+20%	65%+35%	50%+50%
1	3 days	23.67	22.71	23.17	20.53
2	7 days	31.23	29.08	32.31	29.32
3	28 days	42.99	40.33	44.24	41.85

Table 2.11: Compressive strength of cubes cured in acid solution *(Nandini et al. (2017))*



Sl no	Age of curing	Compressive strength in N/mm2			
		100%	80%+20%	65%+35%	50%+50%
1	3 days	19.07	20.87	21.99	19.53
2	7 days	23.50	24.61	26.52	23.78
3	28 days	35.08	35.99	37.97	35.90

Nandini et al. (2017), studied the compressive strength and acid resistance of the concrete mixes containing varying amount of GGBS as partial replacement of cement. The replacement levels were taken as 20%, 35% and 60%. Table 2.9 gives the mix proportions of the various concrete mixes.

Table 2.10 shows the compressive strength test results of the various concrete mixes. From the Table 2.10 it was found that the 35% GGBS mix showed the highest strength. Therefore it was concluded that 35% was the optimum replacement level. Compressive strength test results of the cubes cured in acid solution are shown in Table 2.11. Here also the maximum compressive strength was found at 35% replacement level.

2.5 CONCLUDING REMARKS

- Accelerated carbonation curing provides better early age strength and a denser microstructure. In ACC procedure hydrated and unhydrated products from the hydration reaction are converted into CSH gel and calcium carbonate.
- The replacement of cement with GGBS provides better strength and durability to the concrete mixes. The strength gain in GGBS is caused by the pozzolanic action of constituents of GGBS.
- Most of the studies on ACC have been emphasized on mortars. Effect of ACC on concrete mixes made with GGBS has not been studied.

CHAPTER 3

EXPERIMENTAL PROGRAM

3.1 GENERAL

This chapter describes in detail the experimental procedure followed for the measurement of strength properties (compressive strength) and durability properties such as water absorption, sorptivity, and rapid chloride permeability of concrete mixes made with varying percentages of GGBS as partial replacement of cement. It also describes the methods used to study the microstructure of various concrete mixes.

3.2 MATERIALS

3.2.1 Cement

In this study Ordinary Portland cement (OPC) of 43 grade was used. The physical and chemical properties of cement were tested in accordance with Indian Standard specifications (BIS-1489 part 1:1991) and are shown in Table 3.1 and Table 3.2 respectively

Table 3.1: Physical properties of ordinary Portland cement (OPC)

Physical properties	Obtained values	Standard Values
Standard consistency (%)	23	-
Initial setting time (min)	123	Not less than 30 minutes
Final setting time (min)	270	Not more than 600 minutes
Specific gravity	3.1	-
Compressive strength (28 days) (Mpa)	44.5	43

Table 3.2: Chemical properties of Ordinary Portland cement (OPC)

Constituent	% in OPC
SiO_2	21.25
Al_2O_3	4.74
Fe_2O_3	4.30
CaO	63.49
MgO	1.02

K_2O	0.78
Na_2O	0.30
SO_3	2.93
TiO_2	0.36

3.2.2 Fine aggregates

Natural sand with maximum aggregate size of 4.75mm was used as fine aggregate. Measurement of physical properties and sieve size analysis was done in accordance with IS 383-1970 and are shown in Table 3.3 and 3.4 respectively.

Table 3.3: Sieve analysis of fine aggregates

Sieve size	Mass Retained (g)	%age mass retained	%age passing	Cumulative %age mass retained
4.75 (mm)	31	3.1	96.9	3.1
2.36 (mm)	137	13.7	86.3	16.8
1.18 (mm)	238	23.8	76.2	40.6
600 microns	168	16.8	83.2	57.4
300 microns	316	31.6	68.4	89
150 microns	65	6.5	93.5	95.5
Pan	45	4.5	95.5	100
			∑ %age retained =302.4	
Fineness modulus = 302.4/100 = 3.02				

Table 3.4: Physical properties of fine aggregates

Properties	Observed values
Specific gravity	2.64
Water absorption (%)	0.87
Fineness modulus	3.02

3.2.3 Coarse aggregates

Crushed stone with maximum aggregate size of 10mm was used as coarse aggregate. Measurement of physical properties and sieve size analysis was done in accordance with IS 383-1970 and are shown in table 3.5 and 3.6 respectively.

Table 3.5: Physical properties of coarse aggregates

Properties	Observed values
Maximum size	10mm
Specific gravity	3.06
Water absorption (%)	2.04

Table 3.6: Sieve size analysis of coarse aggregates

Sieve size (mm)	Mass Retained (g)	%age mass retained	%age passing	Cumulative %age mass retained
10	3.65	36.5	63.5	36.5
4.75	5.13	51.3	48.7	87.8
Pan	1.16	11.6	-	-
			$\sum$ %age retained =124.3	
Fineness modulus = $\frac{500+\sum \text{\%age retained}}{100}$ = 6.24				

3.2.4 Ground granulated blast furnace slag (GGBS)

GGBS used in this study was obtained from Ultracon Infrachem Pvt. Ltd. Its physical properties and chemical composition are shown in Table 3.7 and 3.8 respectively.

Table 3.7: Physical properties of GGBS

Test	Value
Specific gravity	3.1
Fineness	12000 cm^2/g
Particle size distribution d_{10}	1.5 microns
d_{50}	4.2 microns
d_{90}	9.0 microns
Bulk density	680 kg/m^3
Marsh cone flow	27 secs

Table 3.8: Chemical composition of GGBS

Constituent	% in GGBS
SiO_2	33.2
Al_2O_3	22.7
Fe_2O_3	1.0
CaO	33.8
SO_3	0.13
MgO	6.6

3.3 CONCRETE MIX DESIGN

The strength and quality of the concrete is generally associated with its compressive strength. The mix proportions were calculated to in accordance with the guidelines specified in BIS 10262-2009 to design M20 mix.

Mix composition

After deciding the mix proportions four type of concrete mixes were prepared by partially replacing cement with 0%, 20%, 40% and 60% GGBS by weight of cement. Table 3.8 gives the mix proportions of different concrete mixes used in this study.

Table 3.9: Mix proportions of different concrete mixes

Type of mix	Binder (kg/m^3)		Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water (kg/m^3)
	cement	GGBS			
0% GGBS	403.5	0	688.75	1200.38	181.58
20% GGBS	322.8	80.7	688.75	1200.38	181.58
40% GGBS	242.1	161.4	688.75	1200.38	181.58
60% GGBS	161.4	242.1	688.75	1200.38	181.58

3.4 CASTING AND CURING

Four different types of concrete mixes were casted and then these mixes were cured under two different types of curing conditions. The nomenclature was in a manner such that the first two alphabets represent the curing condition and the numerals in the subscript represent the replacement level of GGBS as a partial replacement of cement by its weight. Table 3.9 shows the concrete mixes and curing schemes adopted for this study. De-moulding of all the specimens was done after 12 hours of casting and then the specimens were subjected to subsequent curing. For the comparative study, the specimens were divided into two sets. The first set was cured through the conventional water curing while the second set was cured through the carbonation curing. Water curing was done by placing the specimens in water at temperature of 27±2˚C till the testing age. Before the carbonation curing the initial pre-conditioning for 2 hours was done to remove excessive pore water, thus ensuring easy penetration of CO_2.

Figure 3.1 and 3.2 shows the basic carbonation curing set up and the carbonation chamber used in this study. An airtight vacuum chamber was used and it was vacuumed before the injection of CO_2 gas. Pressure gauge and safety valve were installed with the CO_2 cylinder and the CO_2 gas used was 99% pure. Pressure gauge was used to maintain the pressure at the CO_2 cylinder and the curing chamber. The pressure at the time of injection was kept at 10psi. Silica gel was kept at the bottom of the chamber to remove evaporated water from the specimens. The specimens were kept inside the chamber for 12 hours for the curing purpose and after that they were placed in water for the subsequent water curing for 3 days. Once the

3 day water curing was finished, the samples were kept in the sealed plastic bags till the testing age.

Table 3.10: Concrete mixes and the curing schemes

Curing scheme	Stages of curing (after de-moulding of specimen at 12 hours of casting)		Post conditioning	Batch designation
	Pre-conditioning	Curing		
Water curing (WC)	-	Water curing 27±2°C temperature and 100% RH	-	WC_0, WC_{20}, WC_{40}, WC_{60}
Carbonation curing (CC)	Air drying for 2 hours after de-moulding	Carbonation curing for 12 h and subsequent water curing for 3 days	Sealed in plastic bag	CC_0, CC_{20}, CC_{40}, CC_{60}

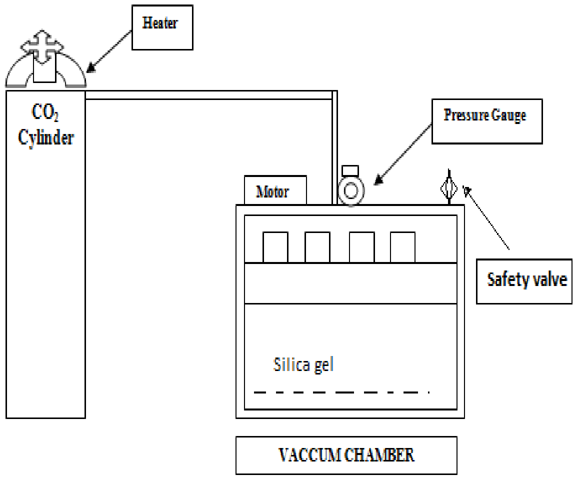


Fig 3.1: Set up for carbonation curing chamber

Fig 3.2: Carbonation chamber

3.5 TESTING PROCEDURE FOR CONCRETE

Table 3.10 shows the list of tests performed and the codes that were followed while doing the tests.

Table 3.11: Tests and codes

Test	Code
Compressive strength	BIS 516-1959
Water absorption	ASTM C642-2006
Rapid chloride permeability test	ASTM C1202-2010
Sorptivity	ASTM C1585-2004
Acid attack	ASTM C267-2006
X-Ray Diffraction (XRD)	
Scanning electron microscopy (SEM)	

3.5.1 Compressive strength

The ability of a material or a structure to withstand a directly applied axial pushing force is termed as its compressive strength. Material gets crushed when the limit of its compressive strength is reached.

To measure the compressive strength of concrete mixes cubes of dimensions 100 x 100 x 100mm were casted and tested at the ages of 1, 3, 28 and 56 days. The testing age was calculated from the time when water was added to the dry ingredients. The Automatic Compression Testing Machine (ACTM) used for testing was of 500 tons capacity. To remove the surface moisture the specimens were surface dried after being taken out of the curing tank and were kept outside at room temperature for half an hour. As per the procedure specified in BIS 516-1959 the cubes were placed in such a manner that the load was applied at right angle to the face of the cube. The pace of the load was kept at 2.4 MPa per second. Fig 3.3 shows the testing of cube under ACTM.

Fig 3.3: Compression testing of cubes

3.5.2 Rapid Chloride Permeability Test

A concrete is called durable if it performs well under the anticipated exposure conditions during its life span. Chloride ingression is one of the main characteristics affecting the durability of concrete. Presence of chloride is harmful to the concrete as well as to the reinforcement. As compared to water penetration swelling of concrete can be 2 to 2.5 times larger in case of chloride penetration. This test method determines the electrical conductance of concrete and correlates it with the resistance of concrete to chloride ion penetration. The relationship between the charge passed and chloride permeability is shown in Table 3.11. The chloride penetration of the samples was tested at the ages of 7 and 28 days in accordance with ASTM 1202. In this test method the electric current is passed through a 50mm in length and

100mm diameter sample for a 6 h period. A potential difference of 60V is maintained at the ends of the sample. One end of the sample remains in contact with the sodium chloride solution while the other end remains I contact with the sodium hydroxide solution. The total charge passed is related to the chloride penetration of the sample. Fig 3.4 shows the test set up for Rapid Chloride permeability test.

Table 3.12: Chloride ion permeability based on charge passed (ASTM 1202)

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

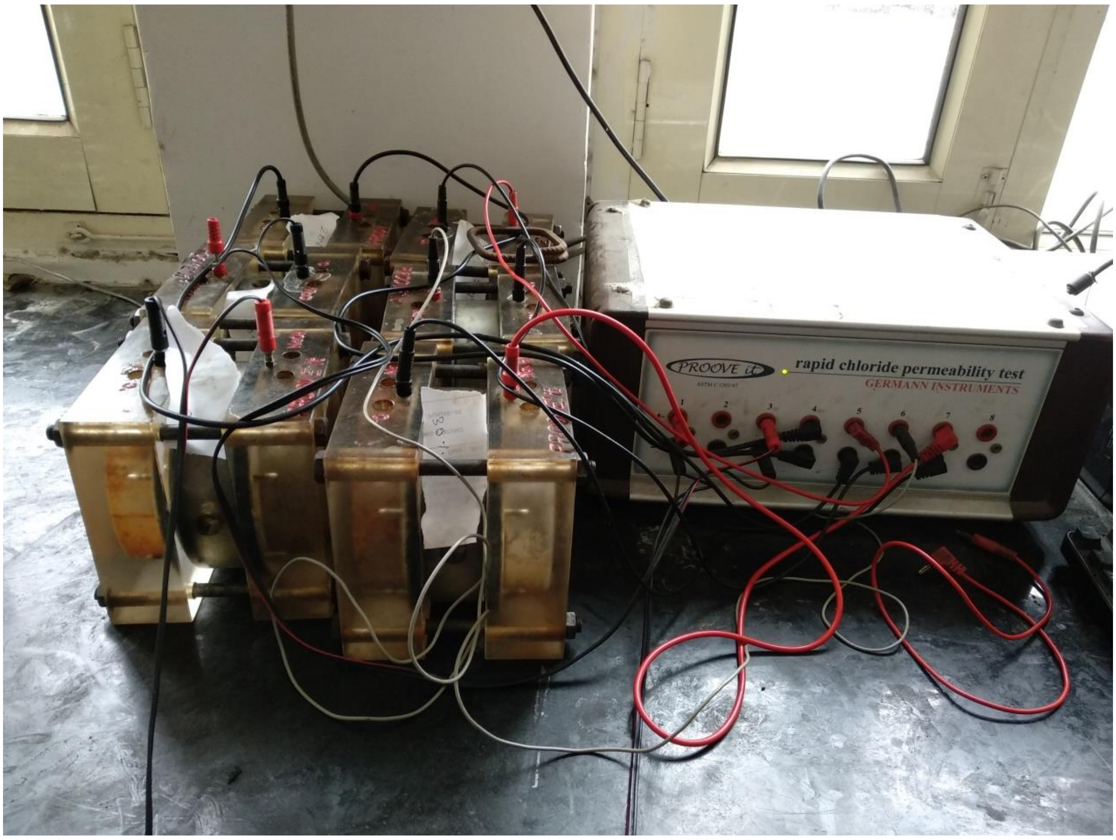


Fig 3.4: Rapid chloride permeability test

Preparation of samples

Cylindrical specimens of 100mm diameter and 200mm length were casted and cured in water for 7 and 56 days. Concrete of M20 grade was designed and cement was partially replaced with 0%, 20%, 40% and 60% GGBS by its weight.

Conditioning and testing of samples

Samples were placed in a vacuum desiccator bowl, in which vacuum was maintained for 3 hours. The bowl was filled with distilled water such that the water covered the samples completely and no air was allowed to enter. After the period of 3 hours samples were left to soak in the desiccator for another 18 hours. After that specimens were removed from the desiccator bowl and were placed on a gasket to dry. The liquid solutions of 3% NaCl and 0.3N NaOH were prepared and filled in two cells. Values of current passes, in coulombs, were recorded after the completion of the test i.e. after the period of 6 hours.

3.5.3 Water Absorption

The water absorption test was performed in accordance with the guidelines specified in ASTM C642. Cubes of dimensions 100 x 100 x 100mm were casted. Water absorption of the specimens was tested at the ages of 1, 3 and 28 days. After the completion of curing period the specimens were placed inside the oven at 110°C for 24 h and their dry weights were recorded. Then the specimens were taken out of the oven and immersed in water at approximately 21°C for a period of 48 h and their saturated weights were recorded. Then the water absorption of the specimens was calculated as per the following equation:

$$\text{Water absorption \%} = \frac{B-A}{A} * 100$$

Where: A = mass of oven dried sample in grams

B = mass of the sample after immersion in water for 48 h

3.5.4 Sorptivity

Sorptivity is a measure of force exerted through the capillary action by the pore structure of a material which causes fluids to be drawn into the body of the material. Sorptivity test was performed on the concrete specimens at the ages of 7 and 28 days as per the guidelines specified in ASTM C 1585-04. Cylindrical specimens of length 50mm and diameter 100mm were casted to perform this test. Three specimens for each concrete mix were prepared. Specimens were preconditioned by drying in the oven at 50°C for 4 days and they were allowed to cool inside a sealed container for 3 days. As per the codal provisions the sides the specimens were coated with epoxy resin so that flow of fluid cannot occur from the sides. The top of the specimen was covered with a loosely attached plastic sheet to prevent the evaporation of water from the top surface. The initial mass of the sample was taken and then the specimens were placed on the water surface with the help of a supporting device. The level of water was kept at 2-3mm above the supporting device. After that, as per codal provisions the weight of the samples were measured at selected times i.e. at 1, 5, 10, 20, 30, 60, 120…up to 360 mins for initial absorption and at every 24 hours for 7 days for secondary absorption. While taking the weights of the samples, excess water on the bottom surface was removed with the damp paper towel and then the weight was taken and then sample was again placed in water for the selected time period. Then the graph was plotted between the mass gain per unit area over the water density and the square root of time. The slope of the line which was the best fit which was taken as sorptivity value. The following formula was used while calculating the absorption coefficient.

$$I = \frac{mt}{a/d}$$

Where I = absorption coefficient in mm

mt = gain in mass of the sample in g at the time t

a = exposed area of the specimen in mm^2

d = density of water in g/mm^3

The initial rate of absorption ($mm/s^{1/2}$) is the slope of the best fit line in a I vs square root of time plot. The slope is obtained by using least squares, linear regression analysis of this plot. For the regression analysis, all the points from 1 min to 6 h were used.

Initial absorption:

I = Si = t + b (points up to 6 h are used)

The secondary rate of water absorption ($mm/s^{1/2}$) was measured by finding the slope of the best fit line in a I vs square root of time plot by taking all the points from 1 d up to 7 d. slope was found out by using least square linear regression.

Secondary absorption:

I = Ss = t + b (points after first day are used)

Fig 3.5: Sorptivity testing

3.5.5 Acid Attack

Concrete structures are sometimes required to face chemically aggressive environments. This condition particularly arises when the concrete is exposed to biological processes for example in waste water systems. In the sewage collection systems biogenic degradation generally occurs, which significantly reduces the service life of the structure. In the environments in which there is high Hydrogen Sulphide (H_2S) concentration, moisture and oxygen is present, biogenic sulphuric acid corrosion occurs, which is one of the major causes of concrete degradation.

To test the resistance of concrete to sulphuric acid resistance acid attack test was conducted. Cubes of dimensions 100 x 100 x 100mm of different concrete mixes were casted. After 10 days of respective curing, these cubes were immersed in a 2% sulphuric acid solution. The pH of the solution was maintained at 1± 0.1. The pH of the solution was monitored with the help of a pH meter and the solution was replaced with a fresh solution once in every two weeks. The compressive strength of the samples was measured at the ages of 28 and 56 days and was compared with unexposed specimens to calculate the loss in strength. In Fig 3.6 (a) and 3.6 (b) shows the specimen after immersion in acid solution after 28 and 56 days respectively

(a) (b)

Fig 3.6: Acid attack specimens at the ages of 28 and 56 days

3.6 MICROSTRUCTURE ANALYSIS

Microstructure Analysis of the concrete specimens was done through scanning electron microscopy (SEM) and X-ray diffraction studies (XRD).

3.6.1 SEM analysis

To analyze the complex microstructure cement and concrete scanning electron microscopy (SEM) has been developed. This technique helps in understanding the mechanisms predicted by compressive strength results. A SEM is basically a high magnification microscope, in which a focused scanned beam is used to produce the image of the object. After the ages of 1, 3 and 28 days, the broken concrete samples were taken from the inner part of the concrete matrix after the compressive strength test. For the removal of moisture before SEM analysis, the sample was placed in desiccator for a period of 24h. The broken samples were placed on a brass stub using carbon tape and gold coating. Then the microscopic structure was analyzed by scanning electron microscope (JOEL JSM 6510 LV, USA) at 15kV.

Fig 3.7: Scanning electron microscope (SEM)

3.6.2 XRD analysis

XRD analysis is a non-destructive method to determine the elements present in a particular substance. X-Ray powder diffraction technique is the most widely used technique to determine the structure of a material in bulk and thin film forms. X’Pert PRO (PANanlytical) diffractometer was used to obtain the XRD spectra with a Cu anode (40 kV and 30 mA) with scanning angle of 10° to 70°. The samples were crushed and ground and then they were mounted on a glass fiber filter with the help of a tubular aerosol suspension chamber (TASC). The components of the sample were determined by comparison with standards established by International Center for Diffraction Data (ICDD). X-Ray diffraction is based on the principal that the diffraction peaks are proportional to the substances producing them. The samples for the XRD analysis were taken in the powdered form. The samples were taken from the inner core of the concrete matrix after the compression test.

CHAPTER 4

RESULTS AND DISCUSSION

The aim of this study is to compare the effect of accelerated carbonation curing with the normal water curing on the concrete prepared with varying percentages of GGBS as partial replacement of cement. In this chapter the results of various tests conducted i.e. compressive strength, water absorption, RCPT, sorptivity, acid attack, SEM and XRD analysis have been discussed.

4.1 COMPRESSIVE STRENGTH

4.1.1 Effect of water curing on the compressive strength of concrete mixes

The values of the compressive strength of water cured samples of all the concrete mixes at the ages of 1,3, 28 and 56 days are shown in Table 4.1. The positive sign shows the gain in strength while the negative sign shows the loss in strength.

Table 4.1: Effect of water curing on compressive strength different concrete mixes containing GGBS

Testing age (days) → % of GGBS ↓		1	3	28	56
0	CS (MPa)	19	20.2	32.9	39.65
	% change	-	-	-	-
20	CS (MPa)	20.2	23.5	35.5	41.6
	% change	+6.31	+16.33	+7.9	+4.91
40	CS (MPa)	24.6	30.1	42.8	50.36
	% change	+29.47	+49	+30.09	+27.01
60	CS (MPa)	19.5	21.5	35	40.2
	% change	+2.63	+6.43	+6.38	+1.38

Fig 4.1 and 4.2 show the effect of water curing on compressive strength of concrete mixes containing varying percentages of GGBS at the ages of 1, 3, 28 and 56 days. It can be seen from the graph that all the concrete mixes containing GGBS showed greater strength than the control mix but the mix containing 40% GGBS showed the highest strength at all curing ages.

It can also be observed that even at early ages GGBS concrete mixes showed higher strength than the control mix. This can be attributed to the finer particle size of the blast furnace slag. **Wan et al. (2004)** concluded that the characteristics of GGBS like particle size distribution, shape etc. has a significant effect on the properties of concrete. It was found out that the concrete containing GGBS processsed by ball mill gave high early strength, whereas long term strength of the mix was lower. It was concluded that GGBS mortars containing finer particles (<3μm) gave high early strength whereas GGBS mortars containing particles in the range of 3μm-20μm gave high long term strength. In this case the both the strengths i.e. early strength and long term strength of GGBS incorporated mixes are coming out to be higher than the control mix but the 3 day strength showed more increase i.e. 49% as compared to 28 and 56 days strength which showed increase of 30% and 27% respectively. This could be attributed the fact that GGBS used in this study was processed through ball mill and its average particle size was 4.2μm. Therefore, it could be due to the presence of finer particles that early strength gain of GGBS concrete mixes was more than later strength gain when compared to the control mix. It could also be observed that the concrete containing 60% GGBS also showed higher strength than the control mix but the gain in strength was not significant.

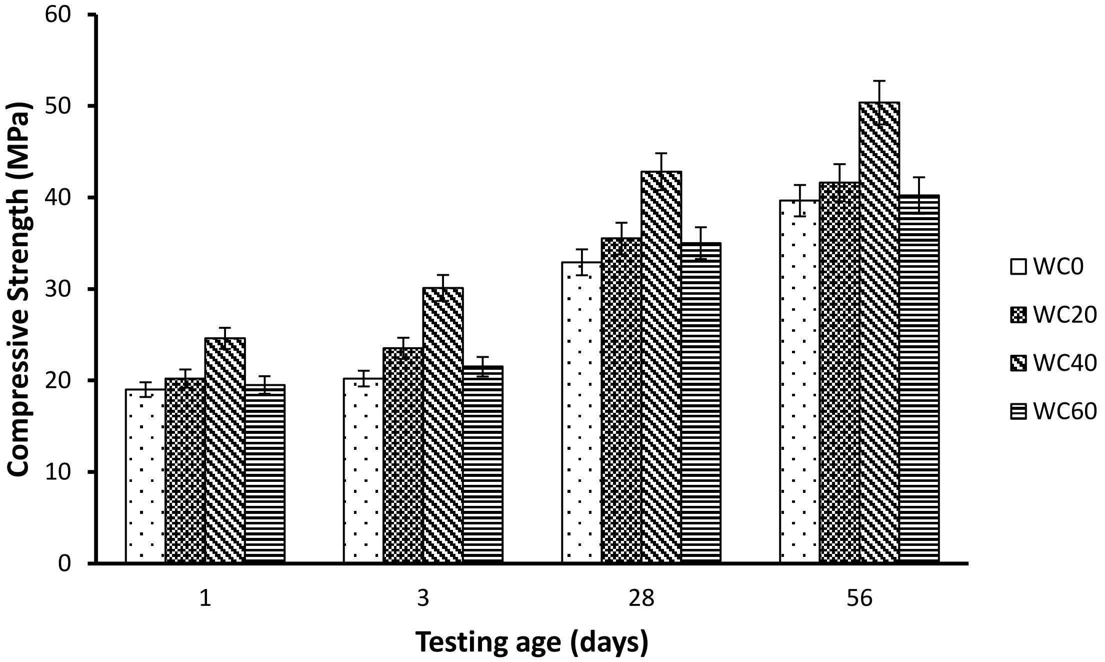


Fig 4.1: Variation of compressive strength on addition of GGBS at different ages (water curing)

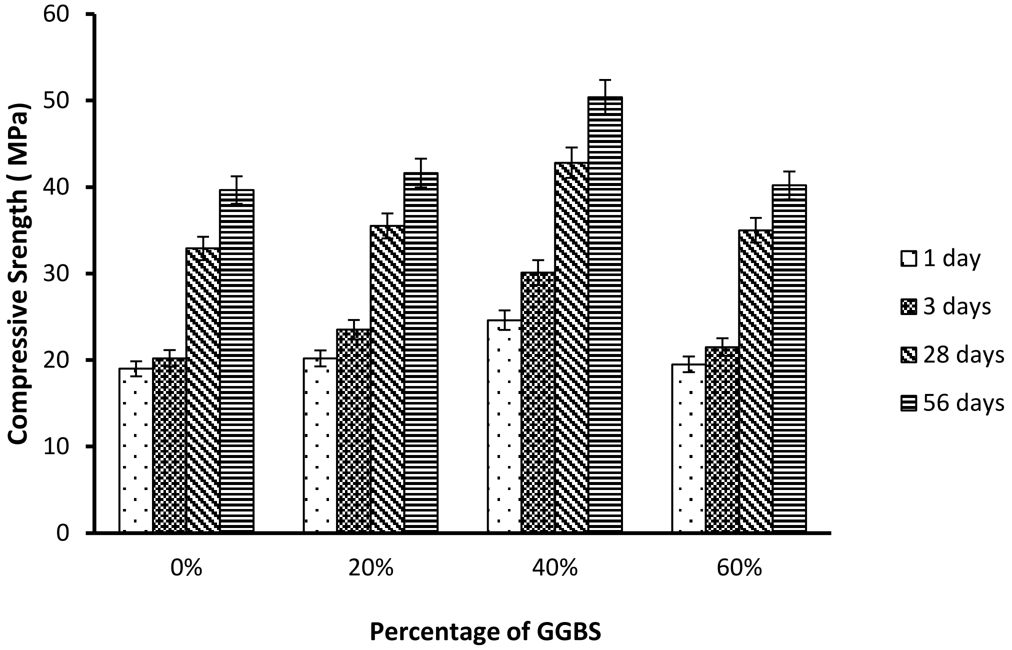


Fig 4.2: Effect of change of Percentage of GGBS on compressive strength at different ages (water curing)

4.1.2 Effect of accelerated carbonation curing on the compressive strength of concrete mixes

The values of the compressive strength (CS) of carbonation cured samples are shown in table 4.2 along with the percentage increase or decrease in from the strength of reference control mix. The positive sign shows the gain in strength while the negative sign shows the loss in strength.

Fig 4.3 and Fig 4.4 shows the effect of carbonation curing on compressive strength concrete mixes containing varying percentages of GGBS at the ages of 1, 2, 28 and 56 days. In case of carbonation curing also a similar trend was observed as in water curing i.e. all the concrete mixes containing GGBS showed higher strengths than the control mix and the concrete mix containing 40% GGBS showed the highest strength at all ages. The concrete mix containing 60% GGBS still showed higher strength than the control mix but the increase in strength was not significant.

Table 4.2: Effect of accelerated carbonation curing on compressive strength different concrete mixes containing GGBS

Testing age (days) → % of GGBS ↓		1	3	28	56
0	CS (MPa)	19.5	22.6	33.4	35.4
	% change	-	-	-	-
20	CS (MPa)	21.5	27.56	36.1	39.5
	% change	+10.25	+21.94	+8.08	+11.58
40	CS (MPa)	25.5	31.8	43.8	44.5
	% change	+30.76	+40.70	+31.14	+25.7
60	CS (MPa)	20.1	24.6	35.6	37.6
	% change	+3.07	+8.84	+6.58	+6.21

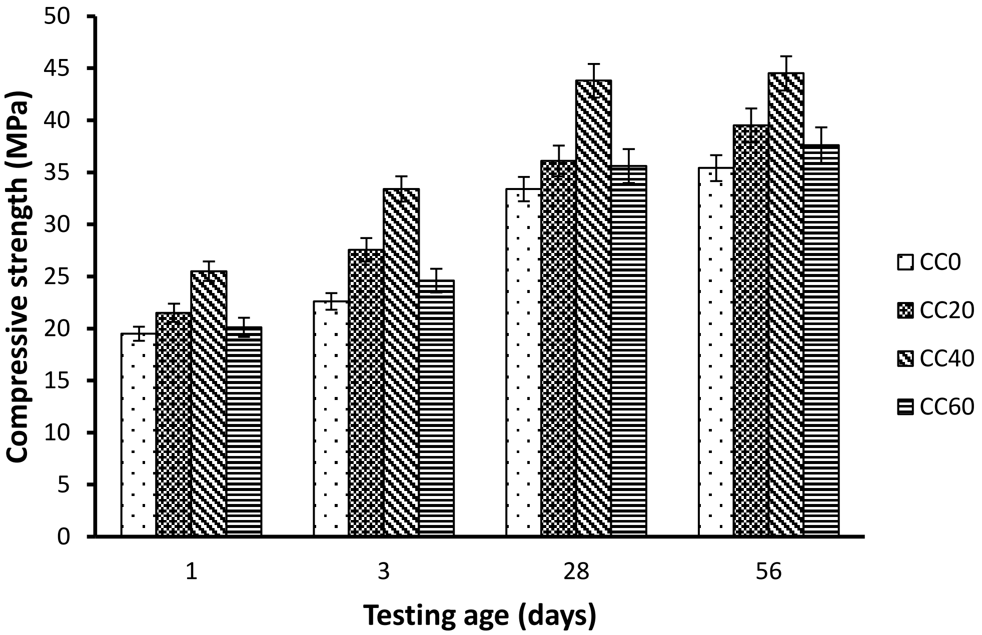


Fig 4.3: Variation of compressive strength on addition of GGBS at different ages (carbonation curing)

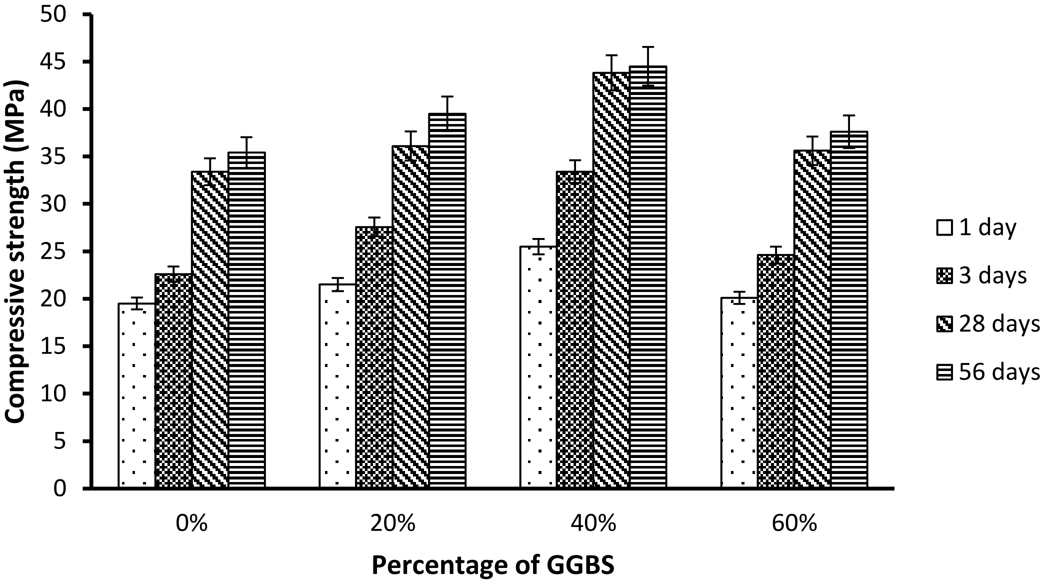


Fig 4.4: Effect of percentage of GGBS on compressive strength of carbonation cured concrete (carbonation curing)

4.1.3 Comparison of effect of water curing and carbonation curing on compressive strength of concrete mixes

The effect of carbonation curing and water curing on strength of concrete mixes at the ages of 1, 3, 28 and 56 days is shown in Fig 4.5, 4.6, 4.7 and 4.8 respectively. The carbonated specimens showed higher strength than the water cured specimens at all the curing ages except at 56 days. It can also be observed the gain in strength after the age of 1 day is much less as compared to strength gain at the age of 3 day. This suggests that the carbonation curing improved the early strength but more strength can be achieved by providing the subsequent hydration. At the age of 28 days, the carbonated samples still showed higher strength but the difference in strength was not much when compared with the strength at 3 days. This shows that the strength gain in carbonated samples was slow as compared to the water cured samples due to the non-availability of sufficient water. Similar observations were made by *Sharma et al.(2018).* All the concrete mixes showed similar strength gain at a particular age which shows that carbonation curing had a similar effect on all the concrete mixes. The gain in strength can be attributed to the fact that, on passing the CO_2 the hydrated and unhydrated components of the concrete mix undergo carbonation reaction to form CSH gel and calcium carbonate in place of calcium hydroxide ($Ca(OH)_2$) which is chemically unstable. $Ca(OH)_2$ is not a desirable product in concrete as it is soluble in water and gets leached out making the concrete porous while $CaCO_3$ is insoluble in water and has a solid structure, thus it fills the pores in concrete providing it more strength and a denser microstructure. It was also observed that while all the carbonated specimens showed higher strength than the water cured specimens till the age of 28 days, their strength was slightly lower at the age 56 days. This could be due to the reason that the hydration reaction in water cured samples continued till the later ages as the sufficient water was available but the hydration reaction in carbonation cured sample remained incomplete due to the non-availability of water.

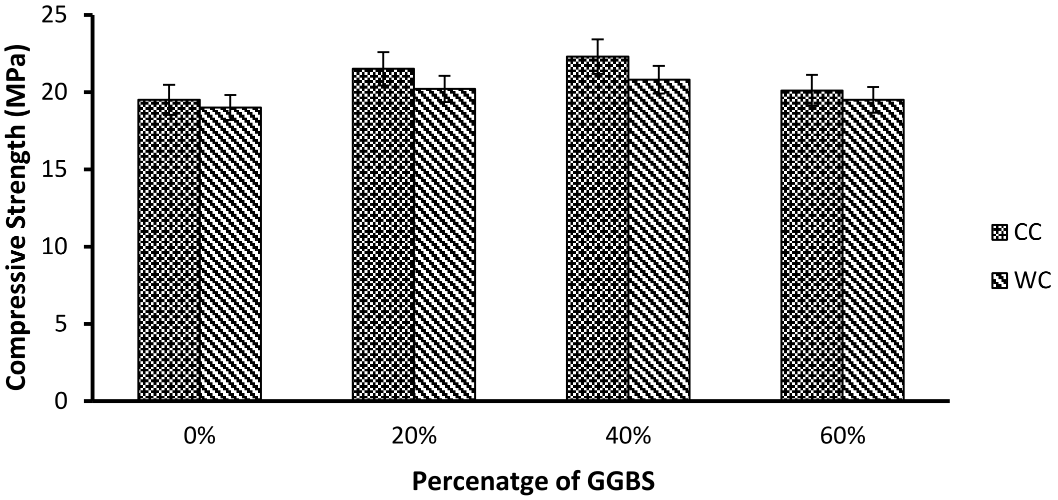


Fig 4.5: Effect of carbonation curing and water curing on 1 day compressive strength of concrete

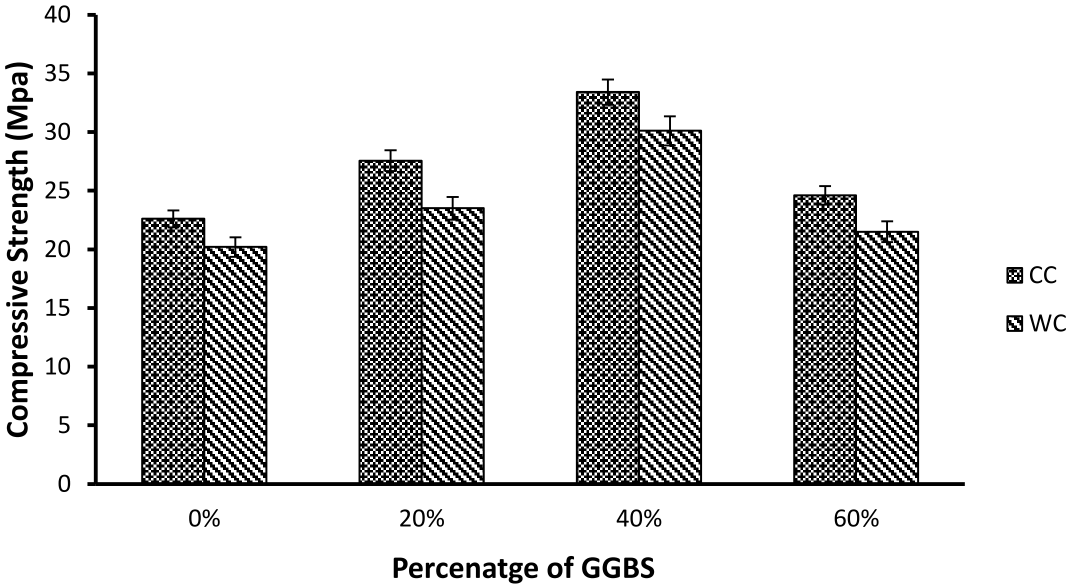


Fig 4.6: Effect of carbonation curing and water curing on 3 day compressive strength of concrete

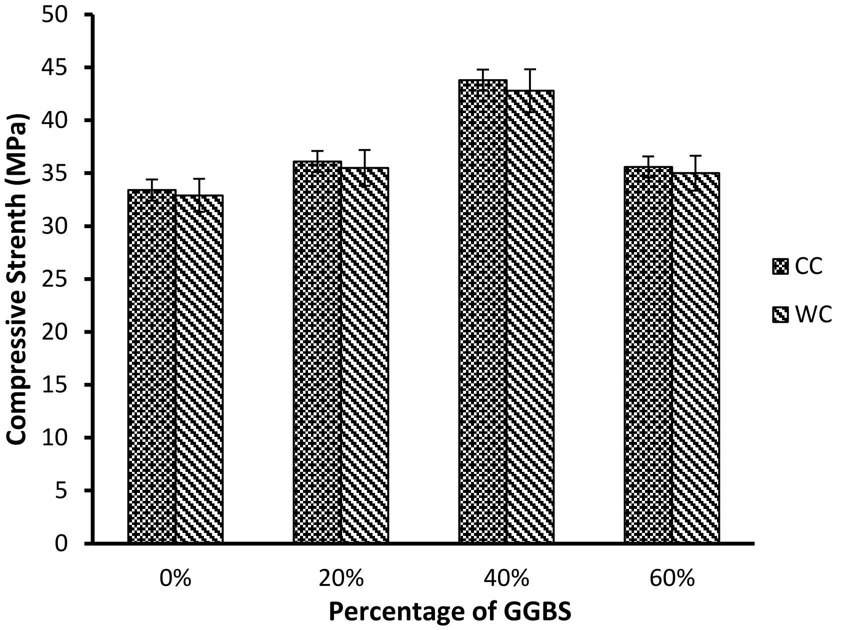


Fig 4.7: Effect of carbonation curing and water curing on 28 day compressive strength of concrete

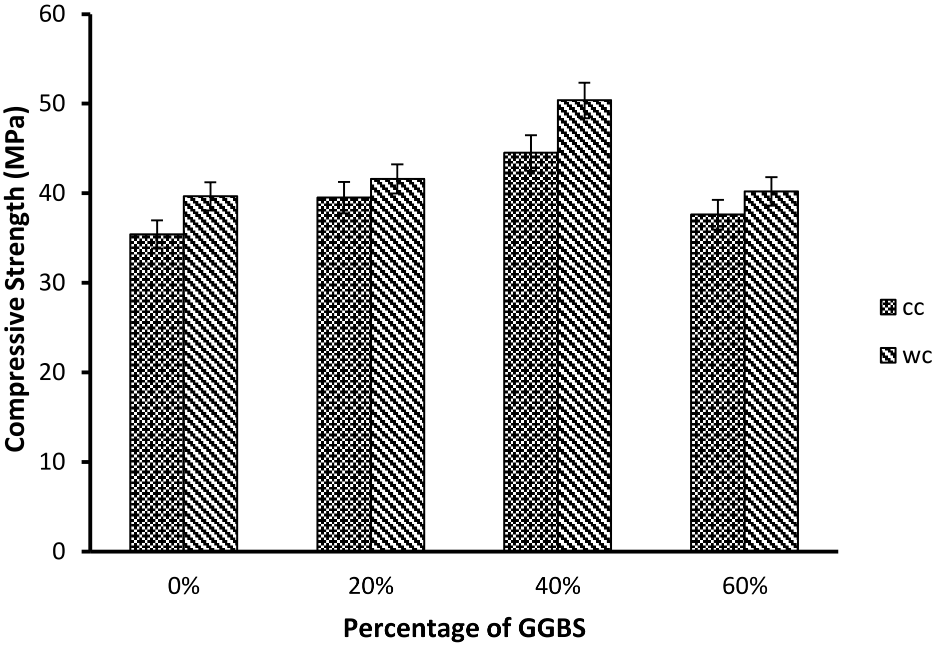


Fig 4.8: Effect of carbonation curing and water curing on 56 day compressive strength of concrete

4.2 WATER ABSORPTION

4.2.1 Effect of water curing on the water absorption of concrete mixes

The values of the water absorption (WA) of water cured samples are shown in table 4.3 along with the percentage increase or decrease from the water absorption of reference control mix. The positive sign shows the gain in absorption while the negative sign shows the loss in absorption.

Table 4.3: Effect of water curing on water absorption different concrete mixes containing GGBS

Testing age (days) → % of GGBS ↓		1	3	28
0	WA (%)	6.21	4.23	2.54
	% change	-	-	-
20	WA (%)	5.34	3.36	1.82
	% change	-14	-20.56	-28.34
40	WA (%)	4.96	3.2	1.46
	% change	-20.12	-24.34	-42.51
60	WA (%)	6.56	4.54	3.8
	% change	+5.63	+7.33	+49.6

Fig 4.9 shows the effect of water curing on water absorption concrete mixes containing varying percentages of GGBS at the ages of 1, 2 and 28. It can be observed that water absorption decreased with the increase in GGBS till the replacement level of 40% and increased sharply at 60% replacement. Decrease in water absorption could be due to the reason that GGBS decreased the pore size of the concrete mixes due to its finer particle size. The average particle size (D_{50}) of GGBS is 4.2µ which is much finer than cement. But when the replacement reached 60% the cement content in the concrete mix reduced which resulted in lesser formation of CSH gel which could have increased the water absorption of the specimen. Water absorption for 40% concrete mix at the age 1, 3 and 28 days was 20.12%, 24.34% and 42.51% less than the control mix respectively. This shows that the durability of concrete containing GGBS improved with the curing age. Same trend was observed at the other replacements also except for 60% replacement. Concrete specimens containing 40% showed the lowest absorption .Therefore it could be said that 40% is the optimum

replacement level of GGBS for concrete. **Gao et al. (2005)** concluded that the moisture transport of GGBS mixes is less due to the dense microstructure of the aggregate/binder transition zone of GGBS, which is generally not present in other composites. GGBS decreased the content and the size of $Ca(OH)_2$ crystals in the cement aggregate paste, which makes the microstructure of concrete dense and strong.

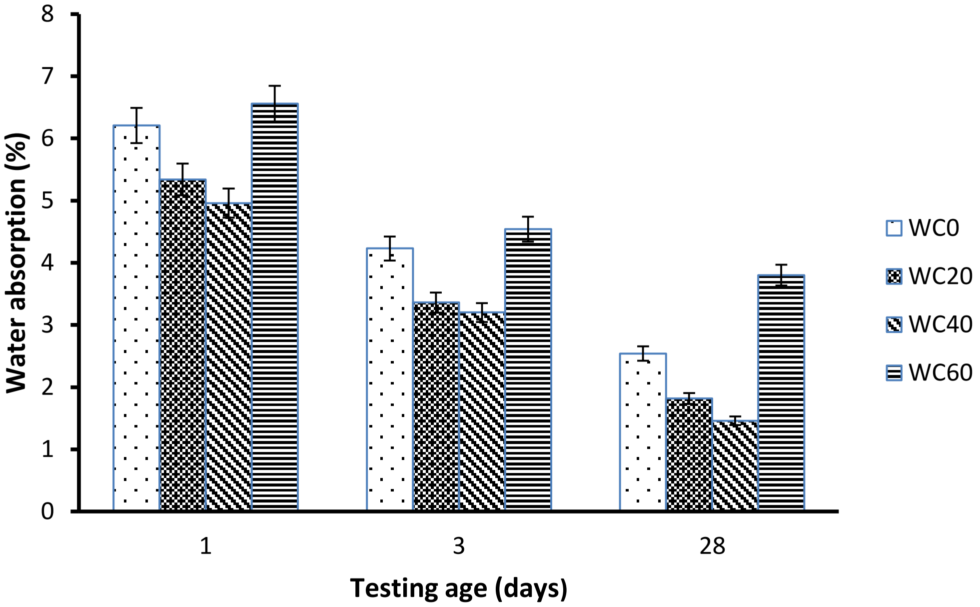


Fig 4.9: Variation of water absorption on addition of GGBS at different ages (water curing)

4.2.2 Effect of carbonation curing on the water absorption of concrete mixes

The values of the water absorption (WA) of all the carbonation cured samples are shown in Table 4.3 along with the percentage increase or decrease from the water absorption of reference control mix. The positive sign shows the gain in absorption while the negative sign shows the loss in absorption.

Fig 4.10 shows the effect of carbonation curing on water absorption concrete mixes containing varying percentages of GGBS at the ages of 1, 2 and 28. The water absorption decreased with the increase in GGBS content till 40% and then increased when the replacement level was 60%. The same trend was observed in water cured samples also. Here also CC_{40} mix showed the minimum absorption. Thus, water absorption of GGBS incorporated mixes decreases with the increase in amount of GGBS, irrespective of the curing regime.

Table 4.4: Effect of carbonation curing on water absorption of different concrete mixes containing GGBS

Testing age (days) → Percentage of GGBS ↓		1	3	28
0	WA (%)	5.92	3.94	2.32
	% change	-	-	-
20	WA (%)	5.84	3.1	1.61
	% change	-1.35	-21.31	-30.60
40	WA (%)	4.56	2.58	1.13
	% change	-22.97	-34.51	-51.3
60	WA (%)	6.1	4.45	3.56
	% change	+3.04	+12.94	+53.44

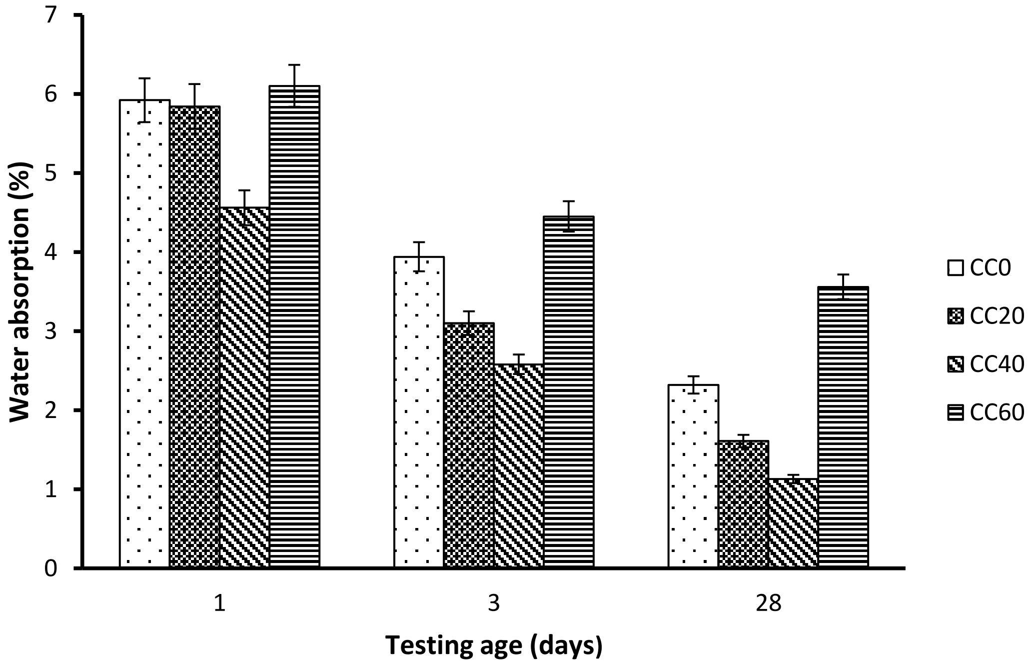


Fig 4.10: Variation of water absorption on addition of GGBS at different ages (carbonation curing)

4.2.3 Comparison of effect of water curing and carbonation curing on water absorption of concrete

The effect of carbonation curing and water curing on 1 day, 3 day and 28 day water absorption of concrete mixes is shown in Fig 4.11, 4.12 and 4.13 respectively.

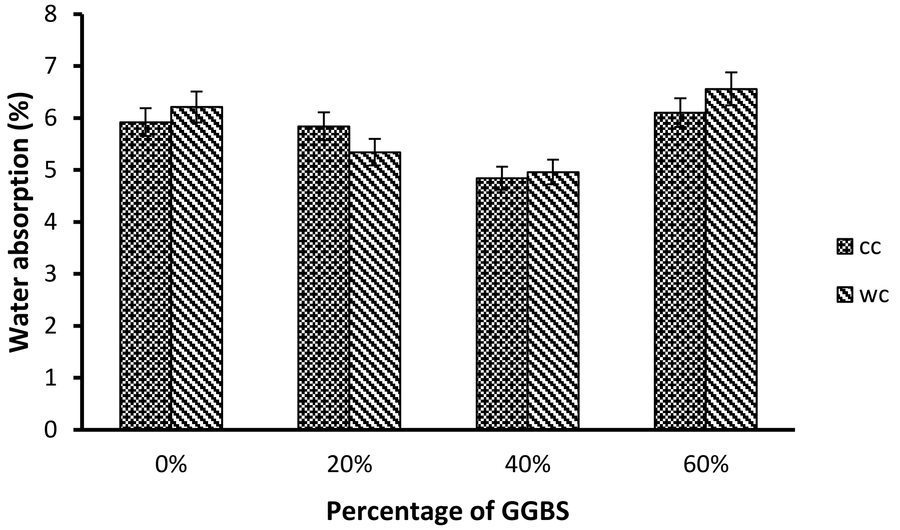


Fig 4.11: Effect of carbonation curing and water curing on 1 day water absorption of concrete

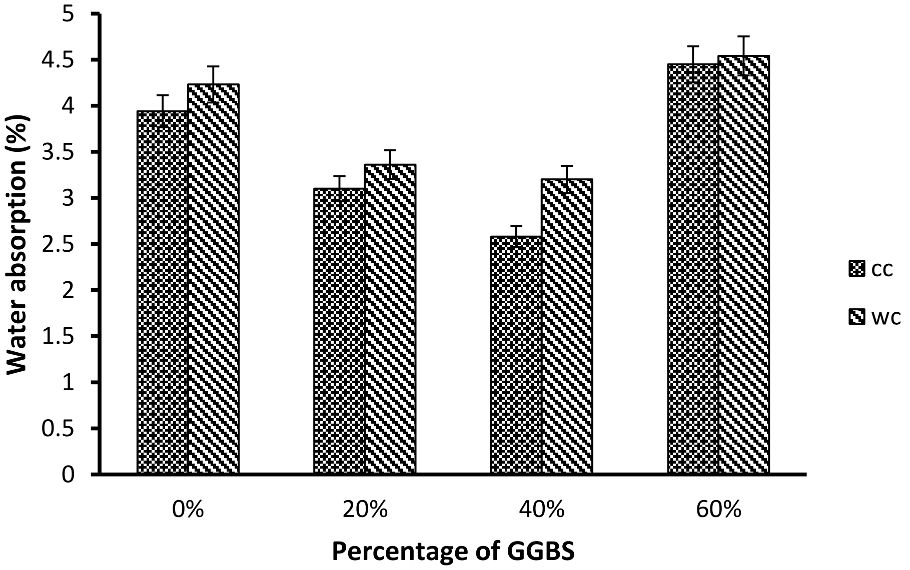


Fig 4.12: Effect of carbonation curing and water curing on 3 day water absorption of concrete

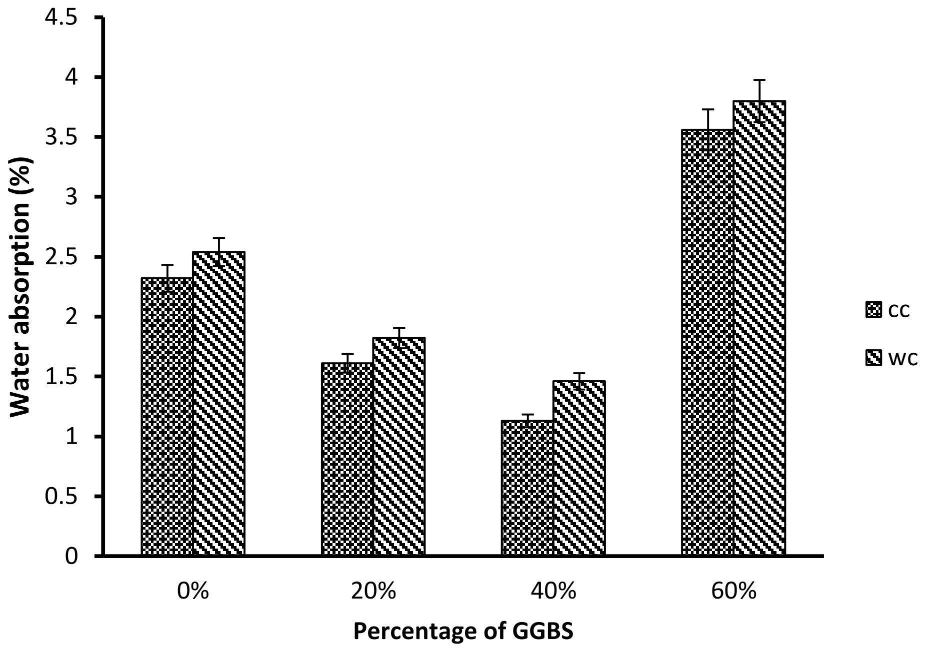


Fig 4.13: Effect of carbonation curing and water curing on 28 day water absorption of concrete

From the figures it can be observed that the water absorption of the carbonation cured samples was less as compared to the water cured samples at all the ages. This could be due to the reason that the voids in carbonation cured samples were occupied by the formation of calcium carbonate ($CaCO_3$). This leads to a denser microstructure and an impermeable surface which made penetration of water difficult.

4.3 CHLORIDE PERMEABILITY

Table 4.5 shows the coulomb passing of the concrete specimens at the ages of 3 and 28 days.

Table 4.5: Coulomb passing of different concrete mixes at the ages of 3 and 28 days

Curing age	3 days		28 days	
	Coulomb passing		Coulomb passing	
Percentage of GGBS	CC	WC	CC	WC
0	2498	3278.5	2021	2233
20	1362	1893	1232	1380
40	782	1013	490	550
60	476	735	313	343

The change of coulomb passing in different concrete mixes cured under two different curing conditions at the ages of 3 and 28 days is shown in Fig 4.14 and 4.15.

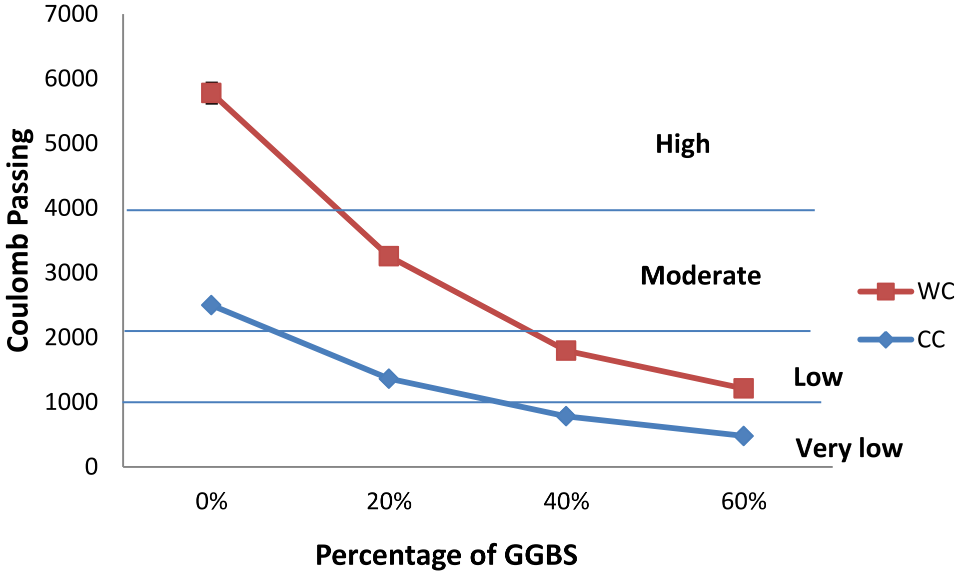


Fig 4.14: Coulomb passing of water cured and carbonation cured concrete at 3 days

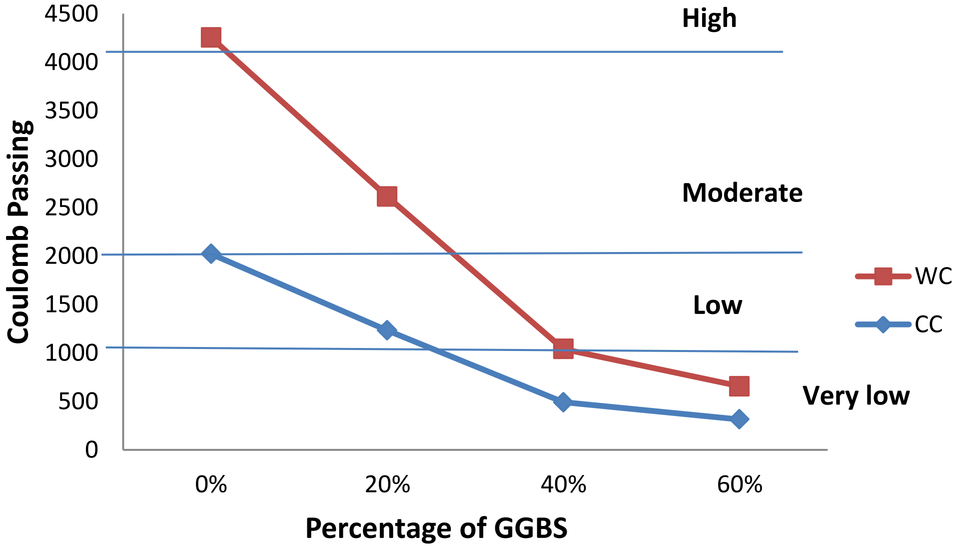


Fig 4.15: Coulomb passing of water cured and carbonation cured concrete at 28 days

4.3.1 Effect of GGBS replacement on chloride permeability

It can be observed that as the chloride permeability decreases as the percentages of GGBS increases. As the percentage of GGBS was increased from 0 to 60% the chloride penetration was reduced be more than 75%. This shows that addition of GGBS improved the resistance to concrete to chloride penetration. The decrease in chloride penetration in GGBS concrete could be due to the denser pore structure of concrete caused by the finer particles of GGBS. **Lee et al. (2016)** reported similar results where addition of GGBS increased the resistance of concrete to chloride penetration and cement less slag concrete showed minimum chloride permeability. **Oteino et al. (2013)** conducted experiments on three types of slag namely Fe Mn arc-furnace (GGAS), Corex (GGCS) and blast furnace (GGBS) slags and concluded that at a given water to binder ratio chloride conductivity and porosity reduced with the increase in slag content, regardless of slag type used. **Higashiyama et al.** (2014) conducted chloride ion penetration test on CWA (ceramic waste aggregate) mortars containing GGBS and concluded that the chloride ion penetration of mortars containing GGBS was significantly lower than the mortars without GGBS.

4.3.2 Effect of type of curing on chloride permeability

The chloride permeability of the water cured samples was more than that of the carbonation cured samples at both the curing ages i.e. at 3 and 28 days. From the figures it could be observed that while coulomb passing of the carbonation cured samples was significantly lower than the water cured samples at the age of 3 days, this difference reduced at the age of 28 days. Which shows that the early age carbonation improved the resistance of concrete to chloride penetration but due to the lack of subsequent hydration the chloride permeability did not improved much at the later ages. **Rostami et al. (2011)** reported similar results where rapid chloride permeability test was conducted on the concrete specimens cured under steam curing and carbonation curing and found that the carbonated samples showed lower chloride permeability than the steam cured samples.

4.4 SORPTIVITY

The sorptivity values of different concrete mixes at the ages of 3 and 28 days are shown in Table 4.6.

Table 4.6: Sorptivity of concrete mixes at the ages of 3 and 28 days

Curing age	3 days		28 days	
	Sorptivity (mm-sec$^{-0.5}$)		Sorptivity (mm-sec$^{-0.5}$)	
Replacement (%)	CC	WC	CC	WC
0	0.0192	0.0213	0.0178	0.0183
20	0.0165	0.0179	0.0162	0.0168
40	0.0147	0.0154	0.0156	0.0163
60	0.009	0.0117	0.008	0.01

Fig 4.16 and 4.17 shows the change in sorptivity value with the change in percentage of GGBS of the water cured and carbonation cured samples at the ages of 3 and 28 days respectively.

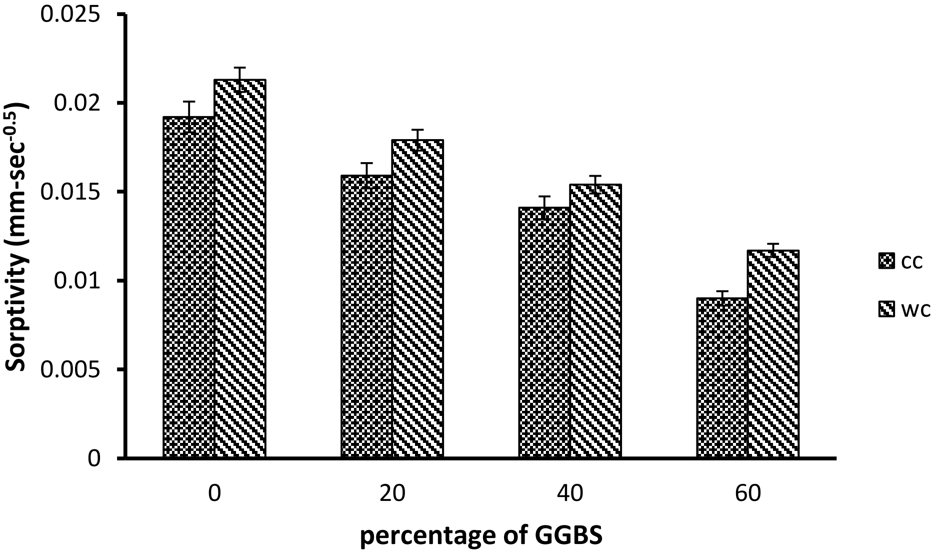


Fig 4.16: Change in sorptivity value with the GGBS percentage at the age of 3 days

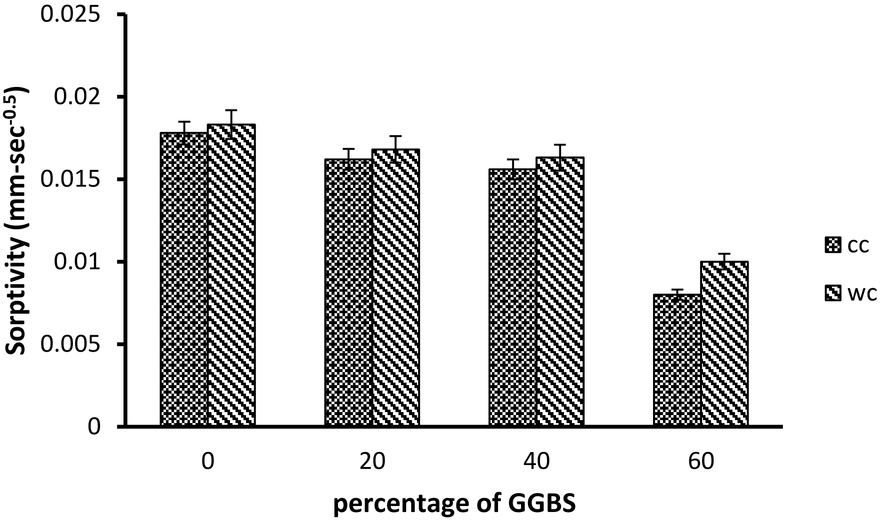


Fig 4.17: Change in sorptivity value with the GGBS percentage at the age of 28 days

4.4.1 Effect of GGBS replacement on sorptivity of concrete

From Fig 4.16 and 4.17 it can be observed that at both the curing ages the value of the sorptivity decreased with the increase in percentage of GGBS and the minimum value was obtained at 60 % replacement. The decrease in sorptivity value with the increase in GGBS percentage could be attributed to the fact that due to its finer particle size distribution GGBS improved the pore structure of the concrete. GGBS reduced the amount and size of pores in concrete thus reducing their capillary action which resulted in lesser sorptivity value. Similar observations were made by **Law et al. (2016)** where sorptivity test was conducted was conducted on concrete mixes containing varying amount of GGBS and it was found out that sorptivity decreased with the increase in GGBS percentage and minimum value was observed at 70% replacement.

4.4.2 Effect of curing type on sorptivity of concrete.

From Fig 4.16 and 4.17 it can be observed that the value of sorptivity of carbonation cured samples was lower than the water cured samples at all the replacement levels. This could be due to the reason that carbonation of concrete improved the durability of concrete by producing a denser pore structure when compared to the water cured samples by producing chemically stable calcium carbonate ($CaCO_3$) in place of calcium hydroxide ($Ca(OH)_2$) which is chemically unstable. Calcium hydroxide is soluble in water and gets leached out which makes the concrete porous. This carbonated samples produced a denser pore structure which resulted in lesser value of sorptivity.

4.5 ACID ATTACK

The percentage loss in compressive strength with the change in GGBS percentage during acid attack on concrete specimens at the ages of 28 and 56 days is shown in Table 4.7.

Table 4.7: Loss in compressive strength of different concrete mixes during acid attack

Curing age	28 days		56 days	
	Percentage loss in compressive strength		Percentage loss in compressive strength	
Replacement (%)	CC	WC	CC	WC
0	7.78	11.24	9.89	11.85
20	5.26	6.7	7.08	8.65
40	2.05	3.73	3.37	4.56
60	6.4	8.1	8.24	9.7

Fig 4.18 and 4.19 shows the change in percentage loss of compressive strength of different concrete mixes. From the figures it can be observed that all the concrete mixes containing GGBS showed greater resistance to acid attack when compared to the control mix and the concrete mix containing 40% GGBS showed the highest resistance to acid attack as the percentage loss in compressive strength was lowest. These results are analogous to the results obtained in compressive strength tests. It can also be observed that the carbonation cured samples showed greater resistance to acid attack when compared to the water cured samples.

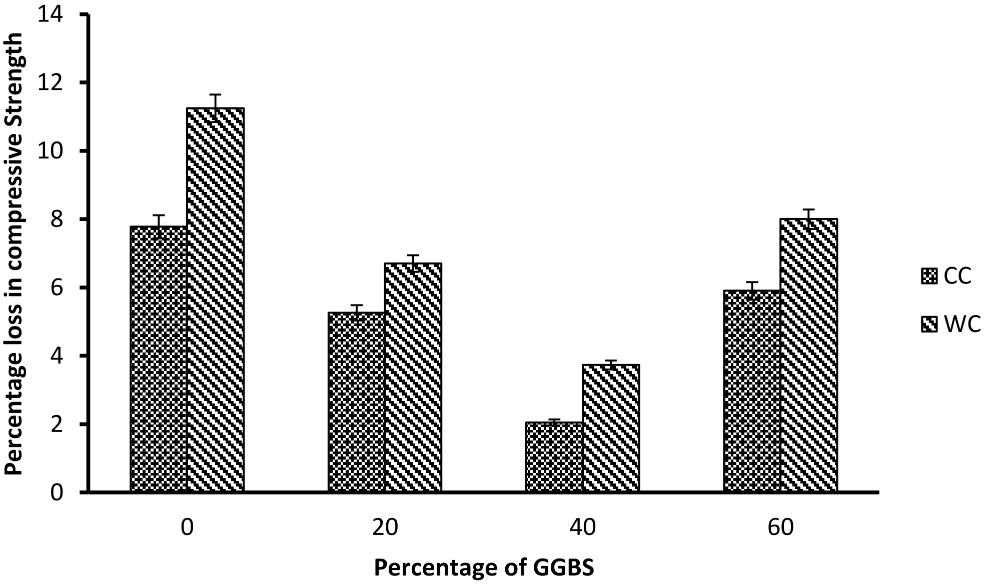


Fig 4.18: Percentage loss in compressive strength of different concrete mixes at the age of 28 days

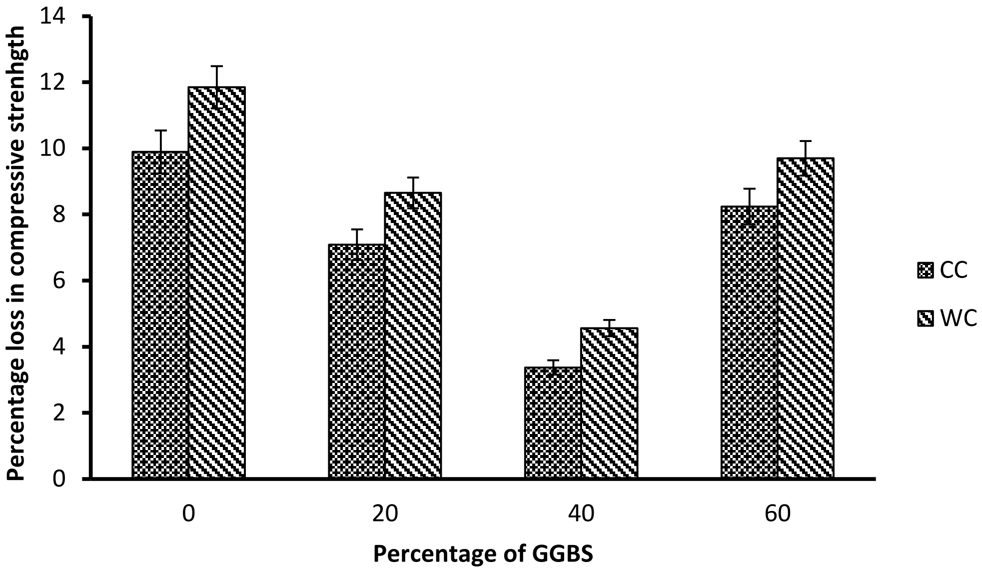


Fig 4.19: Percentage loss in compressive strength of different concrete mixes at the age of 56 days

4.6 MICROSTRUCTURE ANALYSIS

4.6.1 XRD analysis

XRD analysis was performed to identify the major phases produced by water curing and carbonation curing. Fig 4.20 and 4.21 present the results of XRD analysis of 0% GGBS concrete at the age of 3 and 28 days. The major phases identified were Quartz (SiO_2), calcium hydroxide ($Ca(OH)_2$), calcium carbonate ($CaCO_3$) and Dicalcium silicate (C_2S). From the graphs it can be observed that after the carbonation curing, calcium hydroxide phase was reduced significantly while there was a considerable increase in the calcium carbonate phase. It can also be observed that the production of calcium carbonate was not only due to the consumption of calcium hydroxide as the dicalcium silicate phase also exhibit significant decrease. This further confirms that calcium hydroxide produced by hydration of cement was converted in stable calcium carbonate by carbonation reaction. Further from graphs it can be observed that by continuing the water curing, the intensity of calcium hydroxide peaks increased indicating the progress of hydration reaction post carbonation curing without any hindrance.

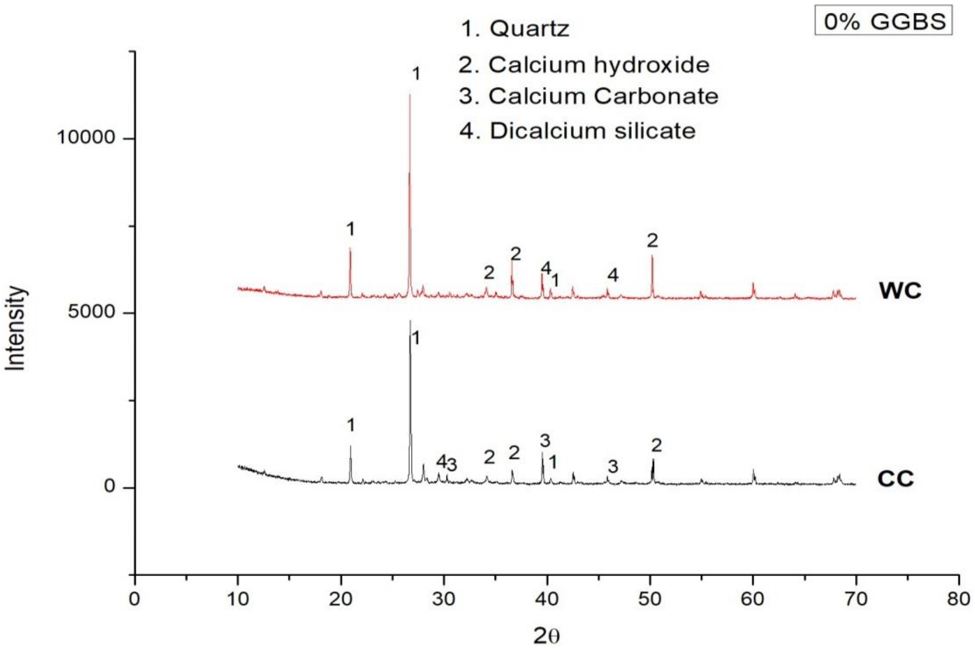


Fig 4.20: XRD analysis of 0% GGBS concrete at the age of 3 days

The results of XRD analysis of 40% GGBS concrete at the ages of 3 and 28 days are shown in Fig 4.22 and 4.23 respectively. From the graphs it can be observed that after the addition of GGBS the major phases observed were same as observed in the concrete containing 0% GGBS. This also shows the filler effect of addition of GGBS i.e. the impact was more of physical nature rather than chemical. It was also observed that change in microstructure due to change in curing process for GGBS incorporated mix was similar to what was observed for the control mix.

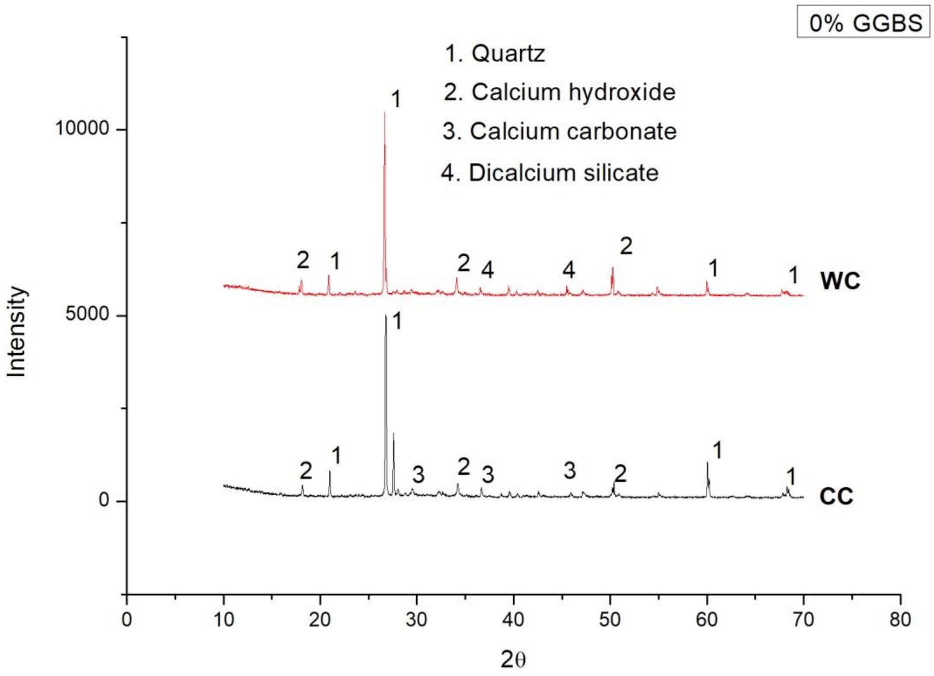


Fig 4.21: XRD analysis of 0% GGBS concrete at the age of 28 days

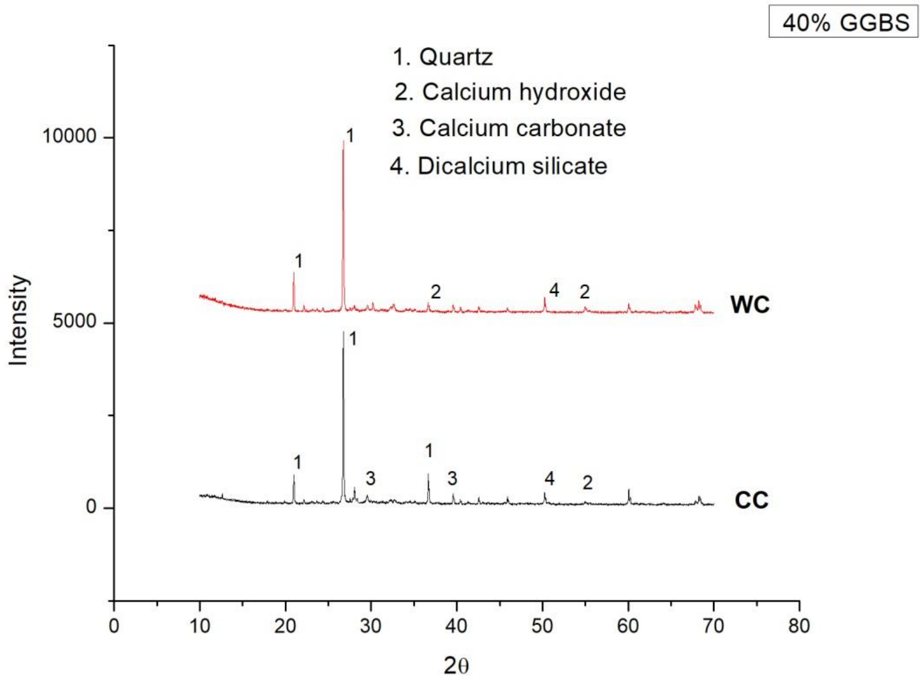


Fig 4.22: XRD analysis of 40% GGBS concrete at the age of 3 days

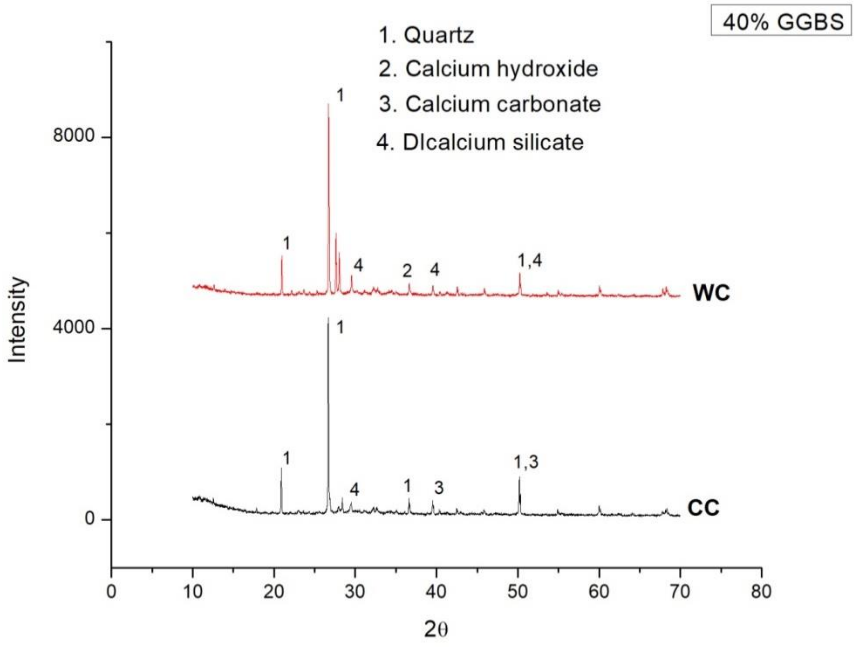
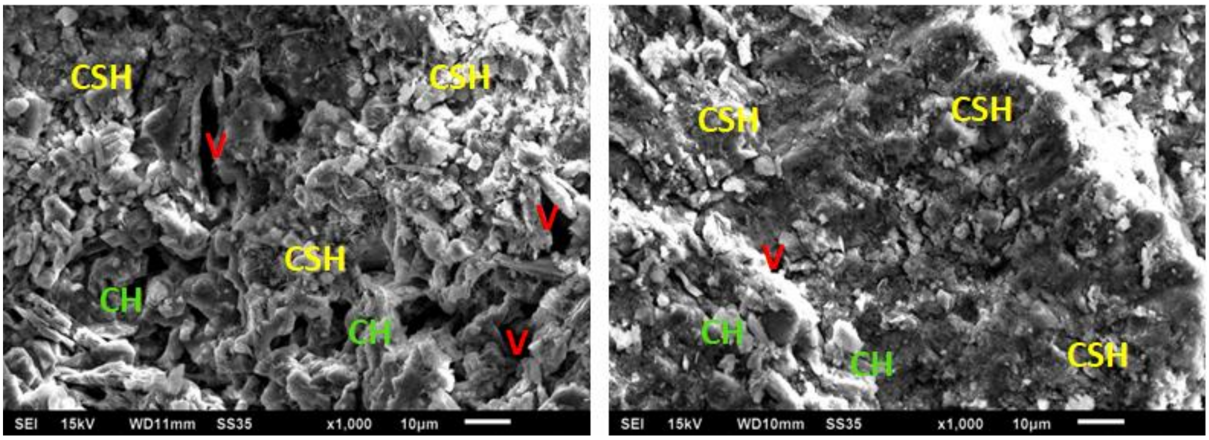


Fig 4.23: XRD analysis of 40% GGBS concrete at the age of 28 days

4.6.2 SEM analysis

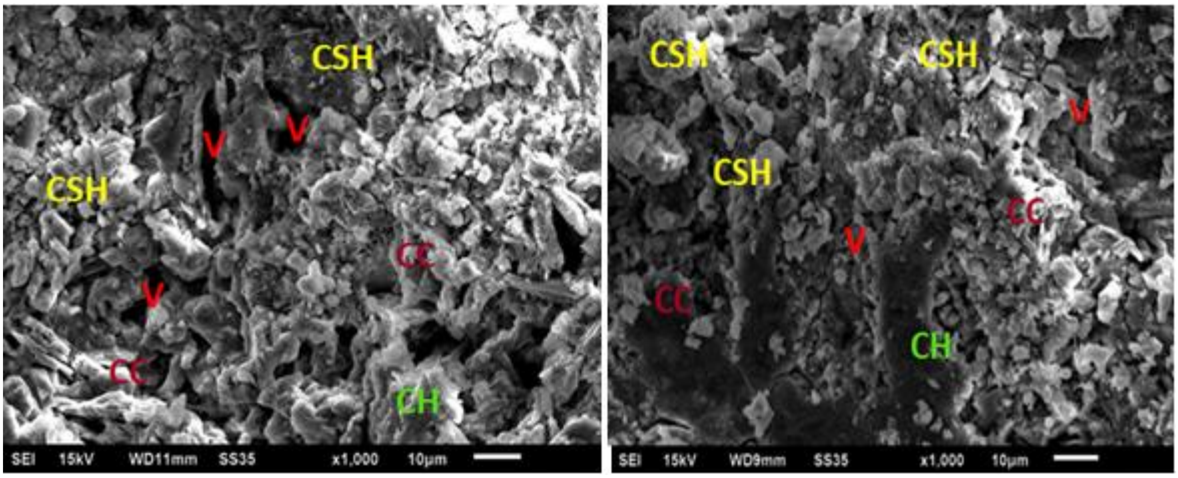
For the SEM analysis, the crushed samples were taken from the compressive strength testing and which were then made into chip form for the testing purpose. After the collection of samples the samples were put in the plastic bags to avoid any change in chemical composition after the testing age. The SEM tests were conducted in Sophisticated Analytical Lab in TIET, Patiala.

Fig 4.24(a) and 4.24(b) show the SEM micrographs of 0% and 40% GGBS concrete water cured samples at the age of 3 days. From the Fig 2.26 it can be observed that the sample containing 40 % GGBS had denser microstructure than the sample with 0% GGBS as more voids (V) are observed in the later. This is due to the reason that the averge particle size of GGBS was finer than cement due to which it filled the pores of concrete and produced a denser microstructure. This observation is analogous to the compressive strength results as more strength was observed in the concrete containing 40% GGBS.



(a) (b)

Fig 4.24: SEM micrographs of the water cured samples at the age of 3 days

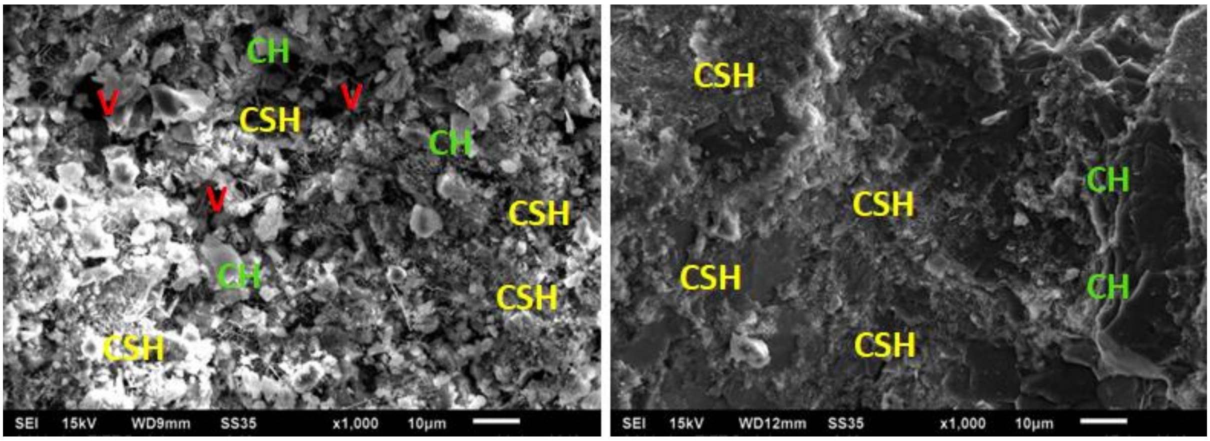


(a) (b)

Fig 4.25: SEM micrographs of carbonation cured samples at the age of 3 days

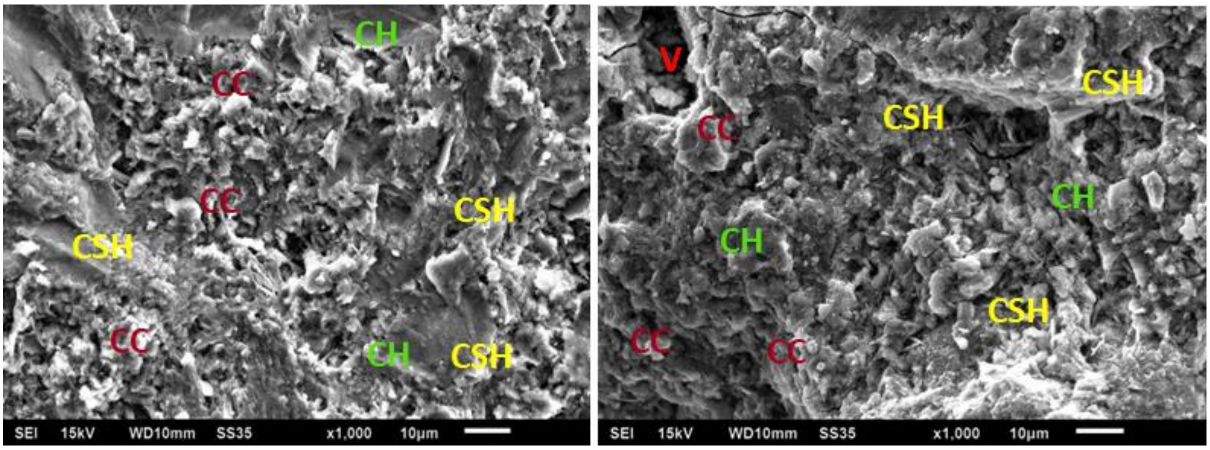
Fig 4.25(a) and 4.25(b) show the SEM micrographs of the 0% and 40% GGBS concrete carbonation cured samples at the age of 3 days. When compared to the water cured samples, carbonation cured samples contained calcium carbonate in place of calcium hydroxide which made the microstructure more dense and provided strength to the concrete. While comparing Fig 2.25(a) and 2.25(b) it can be seen that 40% GGBS has lesser voids when compared to the concrete containing 0% GGBS.

Fig 4.26(a) and 4.26(b) show the SEM micrographs of 0% and 40% GGBS concrete water cured samples at the age of 28 days. It can be observed that presence of CSH gel and CH (calcium hydroxide) was more at the age of 28 days. It can be also observed that 40% GGBS concrete had lesser number of voids as compared to concrete with 0% GGBS.



(a) (b)

Fig 4. 26: SEM micrographs of the water cured samples at the age of 28 days



(a) (b)

Fig 4.27: SEM micrographs of carbonation cured samples at the age of 28 days

Fig 2.27(a) and 2.27(b) shows the SEM micrographs of the 0% and 40% GGBS concrete carbonation cured samples at the age of 28 days. Also from Fig 2.28 and 2.29 it can be observed that in the carbonation cured samples CH content decreased while calcium carbonate content incresed when compared to the water cured samples and a denser microstructure was observed at 40% replacement level.

CHAPTER 5

CONCLUSIONS

This study investigated the effect of accelerated carbonation curing on the compressive strength, water absorption, chloride permeability, sorptivity and acid resistance of GGBS concrete. Microstructure analysis of the concrete specimens was done SEM and XRD techniques. On the basis of the results from the present study, following conclusions are drawn.

5.1 EFFECT OF GGBS ADDITION ON THE PROPERTIES OF CONCRETE

The compressive strength of the concrete mixes containing GGBS was higher than control mix at both early and the later stages due to the particle size of GGBS. The highest strength was found at 40% replacement, therefore it can be said that 40% was the optimum replacement level of GGBS in concrete. Water absorption, Chloride permeability and sorptivity decreased with the increase in percentage of GGBS. Acid resistance of the concrete mixes containing GGBS was greater than the control mix. The concrete mix containing 40% showed highest resistance to acid attack. From the microstructure analysis, it was found that sample containing GGBS as partial replacement of cement had denser microstructure than the control mix.

5.2 EFFECT OF ACCELERATED CARBONATION CURING ON THE PROPERTIES OF CONCRETE

- The compressive strength increased after the carbonation curing due to the formation of calcite in place of calcium hydroxide. But rate of strength gain was slower in the carbonation cured samples due to the lack of water. At the age of 56 days water cured samples showed higher strength than the carbonation cured samples.
- Water absorption and sorptivity of carbonation cured samples was lower than the water cured samples at all the ages due to the production of calcium carbonate which increased the durability of carbonation cured samples. The chloride permeability of carbonation cured samples was significantly lower than the water cured samples at the age of 3 days but this difference was reduced with the progress of hydration reaction.
- The carbonation cured samples showed greater resistance to acid attack as compared to the water cured samples. The loss in strength of carbonation cured specimens on acid exposure was much lesser as compared to water cured specimen.

- From the microstructure analysis it was found that in the carbonation cured samples, calcium hydroxide phase was reduced significantly while there was a considerable increase in the calcium carbonate phase which leads to a denser microstructure in carbonation cured samples causing an increase in strength and decrease in porosity of the concrete mix.

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