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# Effect of Carbonation on RC Structure using Different Materials

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**ABSTRACT:** The rate of carbonation in concrete is influenced by both its physical properties and exposure conditions. Therefore, service life prediction of reinforced concrete structures in an environment where is a probable cause of corrosion of steel in concrete can be made in terms of both the physical properties and the exposure conditions. Service life estimation due to carbonation is defined as the life when the carbonation front reaches the depth of reinforcing steel. This paper describes an experimental investigation carried out to study the effects of carbonation on RC Structure. Ordinary Portland cement (OPC) with a constant water/cement ratio of 0.5 was used in this study. Compressive strength and depth of carbonation using phenolphthalein solution were measured in order to observe the effect of carbonation. Concrete carbonation is a natural process The process of carbonation is almost impossible to avoid in untreated concrete that is exposed to the elements. As soon as the concrete is exposed to the air, the process of carbonation can begin: carbon dioxide slowly penetrates the surface of the concrete where it reacts with moisture in the pores and calcium hydroxide (which is one of the compounds in concrete) to form calcium carbonate. As carbon dioxide meets the pore water, a dilute carbonic acid is created which acts to reduce the concrete's natural alkalinity. The role of Supplementary Cementitious Materials (SCMs) like Ground granulated Blast Furnace Slag (GGBS) and Silica Fume (SF) has also been reviewed along with the influence of depth of carbonation.

**KEYWORDS:** Carbonation, Shrinkage, Compressive Strength, Phenolphthalein Solution, Ordinary Portland cement (OPC)

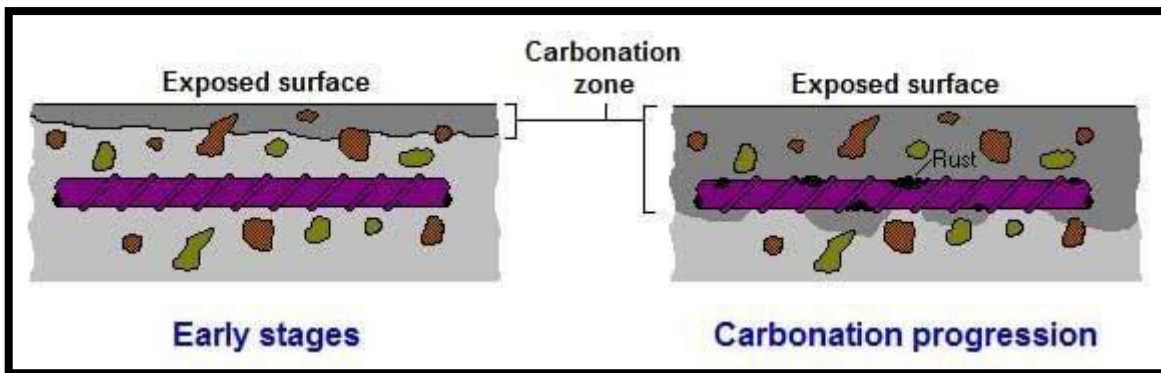
## I. INTRODUCTION

The need to design durable concrete structures in marine environment and chemically aggressive environments leads to increasing complete models and experiments to study deterioration phenomena concrete continuously involves ambient with its environment condition & physical ,chemical & . Some of these interactions usually induce or facilitate deterioration processes which may initiate the corrosion of the steel reinforcement embedded in concrete are given below:

- Chloride attack.
- Sulfate attack.
- Carbonation.
- Alkali-Aggregate reaction.
- Acid attack.
- Expose to sea water.

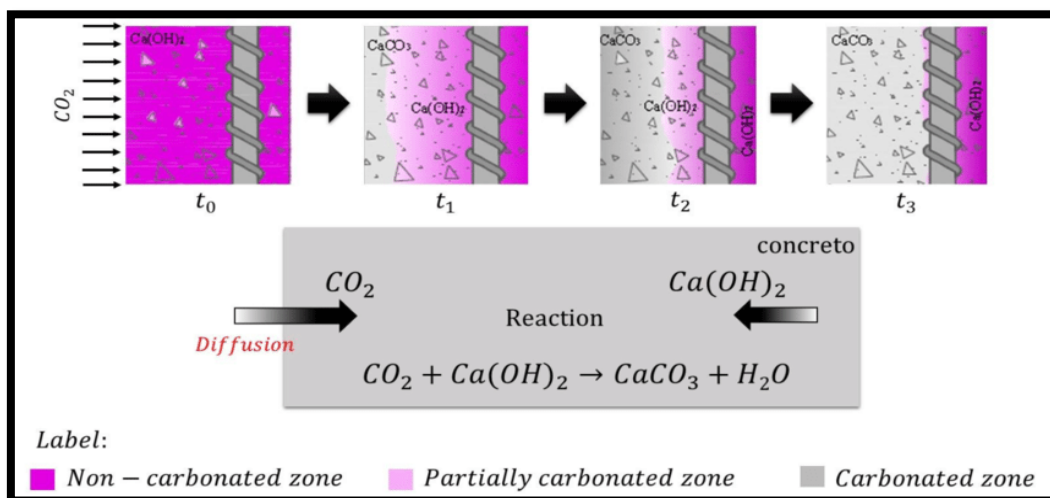
The present work focuses on carbonation effect on concrete structures, because Co<sub>2</sub> is omnipresent in atmosphere & specially in marine environment due to presence of chloride , its affect is more with the related ambient temperature & relative humidity. In the present scenario four case studies with various aged groups have been presented & carbonation effect on them also studied & recorded. As co<sub>2</sub> is the element of air the study of temperature & relative humidity is also an important factor .Because in low relative humidity i.e. < 30% & high relative humidity i.e. >80%, the effect of co<sub>2</sub> is very less on concrete structures. In low relative humidity co<sub>2</sub> remains in gaseous form & doesn't react with Ca(OH)<sub>2</sub> .Similarly in high relative humidity, the diffusion of CO<sub>2</sub> is not taking place on account of pores filled with water.

The carbonation of concrete is the prime deterioration factor in reinforced concrete (RC) structures. During carbonation, the atmospheric CO<sub>2</sub> penetrates the concrete and lowers its alkalinity. The problem in predicting carbonation is difficult to address, and a reliable probabilistic carbonation assessment is required to consider different variables such as the concrete quality, the chemistry of the reinforcing steel, and the quality of finishing materials. It is well known that carbonation affects the durability of concrete, involves CO<sub>2</sub> reaction with the hydration products of cement to reduce the pH of the concrete pore solution from about 12 to less than 9 and causes the formation of calcium carbonate. In the present study, we have used different finishing materials on concrete to minimize the effects of carbonation with a field survey and accelerated conditions. The present work focuses on carbonation effect on concrete structures, because CO<sub>2</sub> is omnipresent in atmosphere. Carbonation of concrete is a process by which carbon dioxide (CO<sub>2</sub>) from the air penetrates into concrete and reacts with calcium hydroxide in the presence of water to form calcium carbonates.



(Fig.1: Carbonation leads to the general corrosion along the full length of the bar)

The PH value of pore water in the hardened cement paste which was around 13 will be reduced to about 9.0. When all the Ca(OH)<sub>2</sub> has become carbonated, the PH value will reduce up to about 8.0. In such a low PH value, the protective layer gets destroyed and the steel is exposed to corrosion. The carbonation of concrete is one of the main reasons for corrosion of reinforcement, oxygen and moisture are the other components required for corrosion of embedding steel. The conversion of Ca(OH)<sub>2</sub> into CaCO<sub>3</sub> by the action of CO<sub>2</sub> results in a small shrinkage.



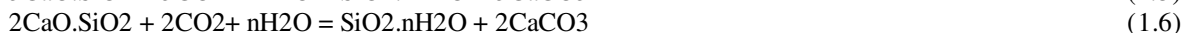
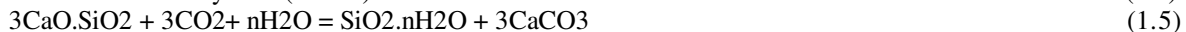
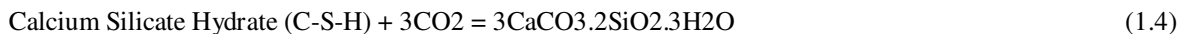
(Fig.2: Carbonation Stages)

**Chemistry of carbonation of concrete:**

The process of carbonation is a surface phenomenon and hence the amount of carbonation depends on the exposure duration and the porosity of the concrete. If the surface of the concrete is porous enough, the atmospheric carbon dioxide diffuses through the pores of surface concrete and dissolves in the pore solution of concrete to form carbonate ions due to the difference in concentration between the atmosphere and concrete pore structure. The gaseous carbon dioxide cannot react with the calcium phases of the cement. Based on the pH of the solution in which the carbon dioxide is dissolved, the carbonate ions are formed. When in contact with water at pH 7, bicarbonate ions are formed, but as the pH in the cement pore solution is high, the bicarbonates further disassociate to form carbonate ions.



This process involves consumption of  $\text{Ca}^{2+}$  ions, which leads to the dissolution of predominantly available calcium hydroxide ( $\text{Ca}(\text{OH})_2$ ) forming new  $\text{Ca}^{2+}$  ions. Because the solubility coefficient of dissolution of  $\text{Ca}(\text{OH})_2$  is  $9.95 \times 10^{-4}$  mol/L and solubility coefficient of formation of  $\text{CaCO}_3$  is  $0.99 \times 10^{-8}$  mol/L, this process continues till all the calcium ions are consumed to form  $\text{CaCO}_3$  (Lagerblad, 2005). It is now, no longer a speculation that apart from  $\text{Ca}(\text{OH})_2$ , other hydration products of cement and residual unhydrated cement compounds too react with  $\text{CO}_2$  to produce  $\text{CaCO}_3$  and silica gel (Claisse et al., 1999, Šauman, 1971, Slegers, 1976, Kobayashi, 1994).



$\text{CaCO}_3$  exists in three crystalline forms, calcite, aragonite and vaterite, where calcite is most stable. Calcium Silicates Hydrates (C-S-H) and Ettringite/ Monosulphate (Aft/ AFm) are in equilibrium when pH is high and calcium ions are present in pore solution. But due to the depletion of calcium ions and fall in the pH value, the C-S-H dissolves. Monosulphate and Ettringite decompose at pH of 11.6 and 10.6, respectively (Lagerblad, 2005). Excessive consumption of  $\text{Ca}^{2+}$  ions fosters negative charges, which are balanced by the subsequent formation of Si-OH group (Chen et al., 2006). When the  $\text{Ca}^{2+}$  ions from C-S-H start depleting, the Ca/Si ratio decreases. When the Ca/Si ratio is less than 1, and pH is around 10, it will transform to silica gel (Stronach&Glasser, 1997). CaO/SiO<sub>2</sub> of C-S-H in the fully carbonated zone is 0.85 and in that of the non-carbonated zone is 1.65 (Bary and Sellier, 2004). At a pH of 11.6, the Monosulphate decomposes to form Ettringite and aluminate compounds, whereas at a pH of 10.5 Ettringite decomposes to form sulfate ions and aluminum hydroxide compounds (gypsum). This is due to the drop in the value of pH, and is also observed in leached cement (Lagerblad, 2001).

Carbon dioxide simultaneously reacts with calcium hydroxide and calcium silicate hydrates, but the reaction with calcium hydroxide may be more rapid at the beginning. However, after the formation of calcium carbonate microcrystals on the surface of calcium hydroxide, the carbonation of calcium silicate hydrates becomes more rapid (Richardson, 2004, Thiery, 2007). The intake of carbon dioxide is a diffusion process, which is controlled by water saturation of the capillary system. The diffusion of carbon dioxide will slow down gradually as the thick layer of already formed calcium carbonate hinders the further diffusion of carbon dioxide. Thus, the speed of the transport is primarily governed by concentration gradients, transport medium and the thickness of already formed carbonated layer. Hence, to understand the extent and amount of carbonation, one has to differentiate the exposure conditions, size and geometry of porosity, the degree of saturation, type of binder, temperature, etc. (Lagerblad, 2005).

**Kinetics of carbonation:**

It is a well-established directive that the carbonation depth progresses with duration of exposure. The rate of carbonation depends on the speed at which the carbonate ions move in the concrete and react with cement paste. Nevertheless, the rate of carbonation decreases with time and is usually considered proportional to square root of exposure time (Sisomphon et al., 2007).

This can be theoretically proved from the laws of diffusion, with an assumption that the carbon dioxide concentration from the surface of concrete to the moving boundary layer of the carbonated zone is linear. Fick's first law of diffusion relates the diffusive flux (diffusion flow rate per unit area) to the concentration of vicinity, under the steady state assumption. It states that the flux goes from regions of high concentration to regions of low concentration, with a magnitude that is proportional to the concentration gradient. In one (spatial) dimension, the law is given by the following Equation.

$$J = -D (\partial\phi/\partial x) \quad (1.7)$$

where J is the diffusion flux (g/m<sup>2</sup>.s),

D' is Diffusion coefficient (m<sup>2</sup>/s), is concentration of carbon dioxide (g/m<sup>3</sup>),

'x' is the distance of carbonation boundary from the surface, (Depth of carbonation) The diffusion flux is the rate of mass growth, in this case CO<sub>2</sub>, and can be written as

$$J = dQ/dt \quad (1.8)$$

where 'Q' is the mass of chemically bound CO<sub>2</sub> in concrete (g) and can be written as

$$Q = m.x \quad (1.9)$$

where 'm' is the mass of CO<sub>2</sub> required to react with alkali phases (g/m<sup>3</sup>) contained in the unit volume of sample,

By combining Equations 1.7 to 1.9 and integrating over time (t),

$$x = \sqrt{2D.\phi.t/m} \quad (1.10)$$

Upon further simplification of Eq. (1.10) and relating the expression 'k' in terms of concentration, the coefficient of carbonation can be written as

$$k = \sqrt{2D \phi / m} \quad (1.11)$$

$$x = k\sqrt{t} \quad (1.12)$$

where 'k' is the rate of carbonation (m/s<sup>0.5</sup>). Assuming the values of 'D' and 'm' as sample property constants for each concrete, a relationship of carbonation coefficients can be generated in terms of carbon dioxide concentrations.

When the depth of carbonation reaches the depth of concrete cover, corrosion initiates. Hence it is safe to say that as long as the depth of carbonation does not reach the surface of reinforcement, corrosion is not initiated. The initiation time (t) for the corrosion can hence be written as

$$t = (C/k)^2 = C^2.m/2D.\phi \quad (1.13)$$

where 'C' is the concrete cover.

This time mainly depends on the physical properties of concrete and exposure conditions.

### *The importance of carbonation is*

- To indicate corrosion potential near future.
- To estimate service life where penetration of the carbonation front is critical.
- To monitor the effectiveness of procedures for re-alkalization of the cover layer.
- To make a rough estimate of concrete strength from the age of concrete & the relative humidity.
- To prepare service life model of structures
- To formulate a maintenance strategy for structures.
- To prepare a carbonation model

### *Factors affect rate of carbonation:*

The following factors have a significant effect on the rate of carbonation

1 External factors: Ambient relative humidity Concentration of carbon dioxide Surface protection

2 Internal factors: Grade of concrete Permeability of concrete Depth of cover to reinforcement Water-cement ratio

3 Other factors: Time of exposure Orientation of building

## II. PROPOSED METHODOLOGY

### 2.1.INTRODUCTION

Carbonation is one of the two main causes of corrosion of steel in concrete, the other is chloride attack. The result if the interaction of carbon dioxide gas with the alkaline hydroxides in the concrete, the carbonation process effectively drops the ph of the concrete to a level where the steel will corroded. The carbon dioxide dissolves in water to form carbonic acid, which can migrate to the reinforcing steel if the concrete is of poor quality (open pore structure, low cement content, high water cement ratio, or pure curing of the concrete). Carbonation is more common in old structures, particularly in buildings.



## 2.2.FEATURES

- Test can be carried out completely on the site.
- Gives depth of carbonation.
- Minimal operator training and no special equipment required.
- Utilizes only one environmentally safe dye.
- Results obtained in less than five minutes are easy to interpret.
- Economic, fast and easy to use.

## 2.3. PREPARATION OF PHENOLPHTHALEIN SOLUTION

- The 1% of phenolphthalein solution is made by dissolving 1gm of phenolphthalein in 90cc of ethanol.
- The solution is then made up to 100cc by adding distilled water.
- Then the solution is sprayed over the freshly broken concrete for carbonation test.

## 2.4. PROCEDURE

- A fresh concrete must be exposed.
- This can be done by core sampling.
- The suspect surface and splitting the core with a hammer and chisel.
- The surface is cleaned properly with wire brush.
- Otherwise the cross section of column or beam is to be exposed by chiseling and surface is cleaned properly or the concrete cover of suspected portion can be removed and cleaned.
- Then the phenolphthalein solution is sprayed over the broken surface or exposed prepared surface as cited above.
- If color is turned into pink, then surface is not affected by carbonation.
- If colorless, then the concrete surface is affected by carbonation.
- This pink color will show even up to a ph value of about 9.5.
- The carbonation front is measured.

## 2.5. COMPONENTS REQUIRED

- Sprayer.
- Phenolphthalein solution bottle.
- Wire Brush.
- Hammer.
- Chisel.
- Scale.
- Carrying case.

## 2.6. RANGE AND LIMITATIONS OF CARBONATION DEPTH MEASUREMENT TEST

The phenolphthalein test is a simple and cheap method of determining the depth Of carbonation in concrete and provides information on the risk of reinforcement corrosion taking place. The only limitation is the minor amount of damage done to the concrete surface by drilling or coring or surface dismantling.

## III. CONSTITUENTS INFLUENCE CARBONATION

### 3.1 Effect of water/cement ratio:

From various research studies it was identified that water/cement ratio has a profound effect on carbonation irrespective of the mix design. Water/cement ratio was found to be most authentic and reliable parameter that helps in predicting the resistance of normally vibrated concrete to carbonation. It has been concluded by the earlier research studies that the carbonation depth is directly related to water/cement ratio and it is identified that depth of carbonation increases with increase in water/cement ratio. It is also directly related to the age of the concrete. It has also been found that depth of carbonation has been reduced greatly by reducing water/cement ratio. It is observed at low values of water/cement ratio the depth of carbonation is low but there seems a continuous increase in depth of carbonation at higher values of



water/cement ratios. Some of the researchers have concluded that carbonation decreases with decrease in water/cement ratio in some tropical arid regions.

### 3.2 Effect of water/binder ratio:

It has been found that water/binder ratio has a significant effect on depth of carbonation. Water/binder ratio plays a vital role in defining the relationship between compressive strength and permeability of concrete. Water/binder ratio at lower levels does not influence carbonation depth but higher ratios influence other properties. Carbonation depth increases with increase in water/binder ratio. Hence it was found that carbonation depth is directly proportional to water/binder ratio. Slump values also had a tremendous impact on carbonation depth, increase in slump increases depth of carbonation. Fly Ash (FA) has also had a greater effect on carbonation depth and strength of concrete. High levels of water/binder ratio with fly ash have a substantial effect on all the properties.

### 3.3 Effect of Admixtures:

As it was observed from the previous studies strength of concrete reduces with increased depth of carbonation. Many of the industrial by-products like GGBS, SF, FA, Metakaolin etc are increasingly used in constructions as they contribute to the improvement of various other properties. They improve strength of concrete and results in reduction of carbonation depth, replacement of cement also facilitate some benefits like reduction of shrinkage, expansion etc. Some of the studies revealed that lower levels of replacement i.e. 0-30% replacements observed beneficial rather than higher replacements like beyond 60%. The compressive strength is improved by 30% replacement of FA. It was identified from previous studies the depth of carbonation of High Volume Fly Ash (HVFA) with 90 days curing period is nearly equal to plain concrete. It is true that FA increases carbonation depth, but with HVFA with curing period 90 days reduces the carbonates depth.

#### 3.3.1 Ground granulated blast furnace slag (GGBS):

The strength of the concrete and porosity chiefly depends on water/cement ratio and supplementary cementitious materials like GGBS, Silica fume, etc used. More particularly GGBS and Silica fume used as cement replacement materials in concrete. GGBS and Silica fume form less porous and offer good binding strength in concrete. The depth of carbonation depends on strength and porosity of the concrete.

#### 3.3.2 Silica fume (SF):

Silica fume is very effective in reducing permeability of cement in paste form and in concrete it also reduces porosity. It plays very significant role in the process of development of high strength and high performance concrete. The concrete made of SF will have very good bond strength and offers resistance to abrasion. The compressive strength will also be improved with the addition SF. The increase in compressive strength is also accompanied by increase in carbonation depth. When SF reacts with calcium hydroxide the pH value of pore solution is reduced and it indicates the initiation of carbonation process. The previous studies have revealed the fact that beyond 10% replacement of silica fume will show its affect on carbonation and is also responsible for corrosion.

### 3.4 Effect of porosity:

As per previous studies increase in porosity results in increasing depth of carbonation It means that when water content is increased porosity also increased which results in increase of depth of carbonation . When water content is reduced porosity is also reduced this results in reduction of depth of carbonation. Further it was observed that carbonation depth is increased in the environment where CO<sub>2</sub> presence is more.

### 3.5 Effect of cover:

The depth of carbonation is reduced primarily when the reinforcement is provided with substantial cover as per design specifications. Protected surfaces resist the diffusion of CO<sub>2</sub> thereby reduce the effect of carbonation. The effect of carbonation is more on the non protective areas rather than protected areas. It was proved by the earlier studies that plastering helps to the great extent in reducing carbonation affect. Previous studies have shown that both amount of



carbonation and depth of carbonation are drastically reduced when proper plastering is provided. Application of surface coating reduces carbonation levels to the maximum extent. It was suggested by previous studies that the cover thickness up to 40mm would be very effective in reducing the effect of carbonation. Double layer protective coatings were found very effective in preventing the diffusion of CO<sub>2</sub>. Application of surface coatings is a fundamental preventive and remedial measure to reduce the intensity of carbonation. Earlier researchers have found and suggested that a minimum of 25mm cover thickness is to be provided for effective prevention of carbonation. Replacement of FA is also found to be effective in reducing the intensity of carbonation.

### 3.6 Evaluation of Depth of Carbonation:

The phenolphthalein indicator method is a very popular method for measuring the depth of carbonation of concrete which involves spraying of solution on the concrete surface shows a change in color depending on the pH factor. The measurement was carried out immediately after the broken surface was exposed and after applying phenolphthalein indicator, which lose their colour, are to be judged as carbonated. Hand microscope is also a popular method which is being used to measure the depth of carbonation. It is necessary to record the average depth and maximum depth of penetration. The depth of carbonation is measured from the surface of the sample.

### 3.7 Effect of curing period:

Curing of concrete has an important contribution that influences many properties of concrete. It shows direct impact on strength and service life of the concrete. Heat of hydration is an exothermic reaction which takes place in concrete and liberates heat energy. Due to this process cracks are developed in structures subsequently and strength of the concrete is decreased. Proper curing is required to prevent this unwanted effect on concrete. It is observed from the previous studies that the strength of the concrete is increased with curing periods. Increase in curing period results in reduction of permeability. Increase in curing period increases strength of concrete and decreases depth of carbonation. The addition of mineral admixtures like GGBS and SF reduces the permeability and in turn the depth of carbonation is decreased. Hence it was concluded that curing period has direct impact on permeability, strength of concrete and depth of carbonation.

### 3.8 Effect of compressive strength:

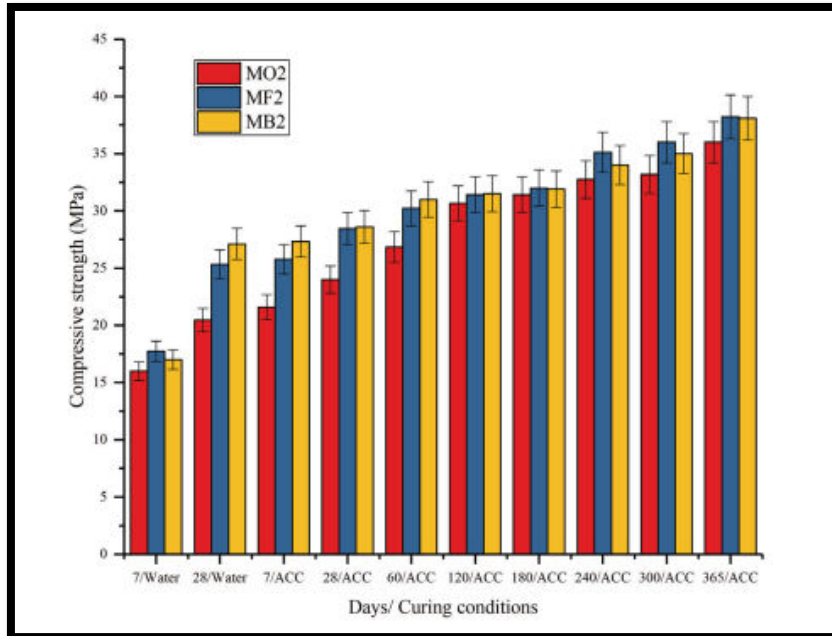
The strength of concrete depends on various factors such as mix proportion of the concrete, water/cement ratio, quantity of cement content, method and degree of compaction, type of curing and period of curing. From the earlier studies it was proved that the strength of concrete has direct influence on carbonation. Increase in compressive strength reduces depth of carbonation. It is observed that SCC offers very good resistance to porosity rather than normally vibrated concrete (NVC). Depth of carbonation is also decreased in case of self compacting concrete. SCC made of GGBS and SF offers good resistance to the carbonation effect. SCC is proved as the best concrete which reduces the depth of carbonation to the maximum levels. Mineral admixtures like GGBS and SF reduce porosity and increase strength of concrete and it leads to the reduction of carbonation effect.

### 3.9 Effect of grade of concrete:

Previous studies revealed the fact that the extent of carbonation is limited to surface layers of concrete. Increase in depth of concrete is also very slow and it may not exceed 20 mm in 50 years, whereas in porous concrete the depth of carbonation may be increased to 100 mm in 50 years since dense concrete prevent the diffusion of CO<sub>2</sub> effectively rather than porous concrete.

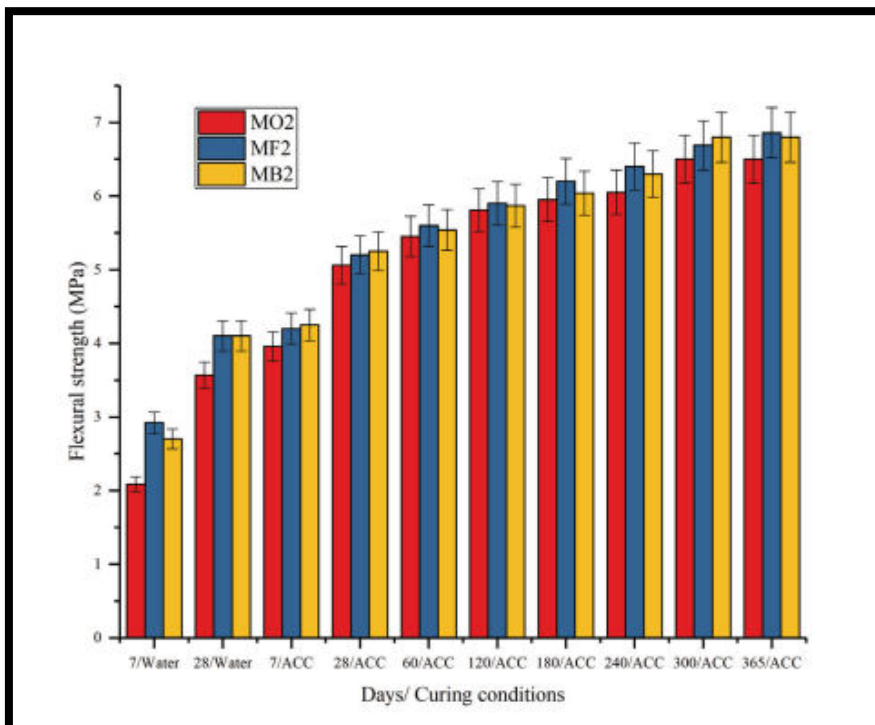


IV. RESULTS AND DISCUSSION

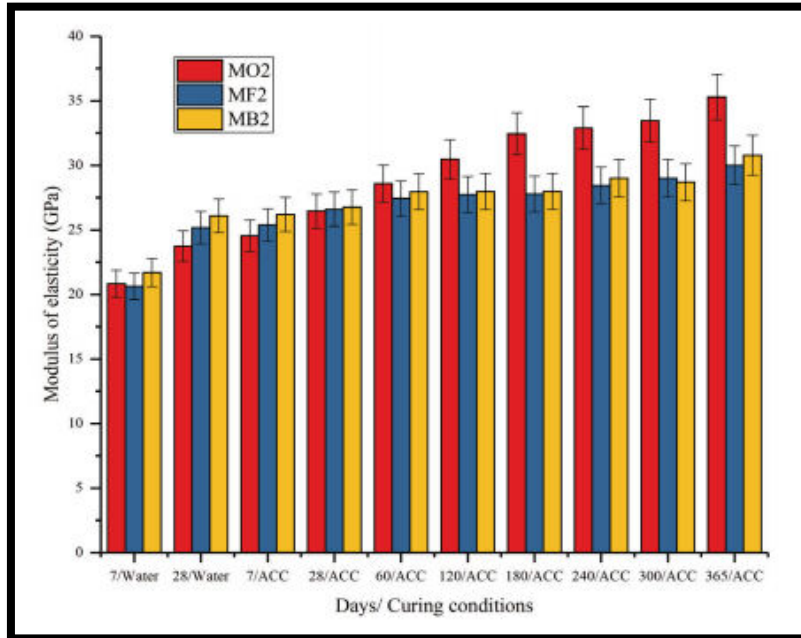


(Figure 4-4: Compressive strength of concrete mixes with water binder ratio 0.5)

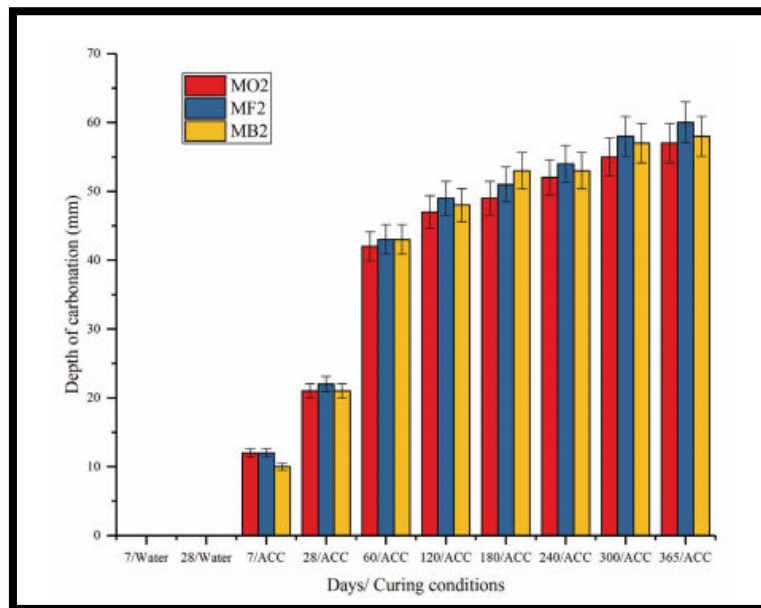
The gain of strength in concrete with cement replaced by blast furnace slag due to accelerated carbonation was initially higher and then the strength gain steadily dwindled when compared to the gain in strength in concrete with cement replaced by fly ash as can be seen from Figure 4.4.



(Figure 4-8: Flexural strength of concrete mixes with water binder ratio 0.5)



(Figure 4-12: Modulus of elasticity of concrete mixes with water binder ratio 0.5)



(Figure 4-20: Depth of carbonation of concrete mixes with water binder ratio 0.5)

### V. CONCLUSION

1. The influence of water/cement ratio is very much significant on the strength of the concrete since the strength of the concrete depends on water/cement ratio. The depth of carbonation depends on water/cement ratio higher water/cement ratio contributes to higher carbonation depth.
2. Increase in curing period reduces the carbonation depth. The resistant power of the concrete to carbonation is increased with sufficient and substantial curing periods.
3. To improve the resisting power of the plain concrete at least 7 days curing is mandatory.

4. Additions of admixtures modifies the pore structure of the concrete and reduce the porosity.
5. If porosity increases carbonation depth also increases hence a linear relationship exist between accelerated carbonation and porosity.
6. Addition of SCMs like GGBS and SF reduce the porosity of concrete and reduce the depth of carbonation.
7. The application of surface coatings and provision of proper cover considerably reduces the rate of carbonation. The service life of the concrete can be enhanced.
8. The compressive strength also depends on water/binder ratio and mineral admixtures both higher and lower water/binder ratio affects the properties of concrete.
9. The use of SCC has been proved to be the best to improve the durability characteristic of concrete in relation to the carbonation of concrete.

#### SCOPE OF FUTURE WORK

- The present paper deals only with two types of mineral admixture, i.e., fly ash and blast furnace slag as partial cement replacement materials. Other mineral admixtures such as silica fume or marble dust can be used to check its influence to resist carbonation as a partial cement replacement.
- The influence of curing duration on carbonation resistance of mineral admixture concrete.
- Influence of acrylic paint or epoxy paint coatings to resist the concrete carbonation may be studied.
- The influence of various other parameters such as humidity and the change in temperature in carbonation resistance could provide a more insightful knowledge in carbonation chemistry.

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