Experimental Study of Accelerated Carbonation Effects on Lightly Reinforced Geopolymer Concrete Slabs

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Abstract: **This paper describes an experimental study on the strength and durability aspects of lightly reinforced Geopolymer concrete slabs exposed to different durations of accelerated carbonation. The main objective of this paper is to study the effects of flexural strength in between the uncarbonated and carbonated slabs of different durations and to determine the depth of carbonation among carbonated slabs. This experiment consisted of 16 slabs which included 4 series (each series having 2 specimens with 10 and 20mm cover to reinforcement). Each slab is of size 1000x500x75mm and reinforced with 6mm MS bars at 230mm c/c at bottom in both directions First series consisted of control specimens and the other 3 series consisted of slabs subjected to 48,96 and 144hours of duration of carbonation. The M40 mix proportion of geopolymer concrete included fly ash, GGBS, alkaline solution (NaOH and Na_2SiO_3), Manufactured Sand, Coarse aggregate, superplasticizer and water. Each series of slabs were kept inside carbonation chamber for specific durations and tested for flexure by applying line loads over span/4 from the supports with two sides simply supported. Samples from carbonated specimens are sprayed with phenolphthalein solution to find the depth of carbonation. The results on flexure strength and depth of carbonation are discussed between control specimen and carbonated specimen. The analysis on the crack pattern, load-deflection behavior and the depth of carbonation are also discussed.**

Keywords—Geopolymer concrete, fly ash, GGBS, sodium hydroxide, sodium silicate, lightly reinforced, carbonation, flexure test, depth of carbonation test.

I INTRODUCTION

The use of concrete globally is second only to water and annual increase in production of cement is about 3%. For one ton production of cement nearly one ton of co_2 is liberated to the atmosphere this contributes about 65% of global warming hence to reduce the usage of OPC a best alternative was developed by davidovits i.e., Geopolymer materials. This includes the utilization of cementing particles such as fly ash, granulated blast furnace slag, metakaolin, rice husk ash, silica fume and the development of alternative binders for Portland cement.

Geopolymers are the class of binders manufactured by activation of solid alumina-silicate source material with a highly alkaline activating solution and aided by thermal curing. These have emerged as one of the best possible alternative to OPC binders, also due to their reported high early strength and resistance against acid and sulfate attacks apart from its environmental friendliness. Geopolymers are amorphous to semi-crystalline three-dimensional alumina-silicate polymers similar to zeolites.

Geopolymers consist of polymeric silicon-oxygen-aluminum framework with silicon and aluminium tetrahedral alternately linked together in three directions by sharing all the oxygen atoms. Geopolymerisation involves a chemical reaction between solid alumina-silicate oxides and alkali metal
silicate solutions under highly alkaline conditions yielding amorphous to semi-crystalline three-dimensional polymeric structures, which consist of Si-O-Al bonds. The geopolymerisation reaction is exothermic and takes place under atmospheric pressure at temperatures below 100°C.

Durability is a major concern for concrete structures exposed to aggressive environments. Many environmental phenomena are known to influence the durability of reinforced concrete structures. Carbonation is one of the major factors to cause structure deterioration

Fig 1: Carbonated structure

Carbonation process:

Carbonation is a neutralizing procedure in which carbon dioxide (CO_2) in the atmosphere react with calcium hydroxide ($Ca(OH)_2$) dissolved in the concrete pore water, produces calcium carbonate ($CaCO_3$) and water (H_2O). In addition hydrated calcium silicate (CSH), unhydrated tri-calcium silicate (C_3S) and bi-calcium silicate (C_3S) consume carbon dioxide. Carbonation changes the chemical composition and the microstructure of the concrete, thereby obviously affecting its chemical and mechanical properties. Carbonation is a very complex physical-chemical procedure where carbon di-oxide penetrates, diffuses and reacts from surface to inside the concrete. The primary reactions are;

$CO_2+H_2O \rightarrow H_2CO_3$

$Ca(OH_2)+H_2CO_3 \rightarrow CaCO_3+2H_2O$

$3CaO.2SiO.3H_2O.3H_2CO_3 \rightarrow CaCO_3.2SiO_2.3H_2O+3H_2O$

$3CaOSiO_2+3H_2CO_3 \rightarrow CaCO_3+SiO_2.3H_2O$

In the study of carbonation process, the relative humidity seems to be very important. The maximum carbonation velocity has been observed at the relative humidity level of 50%. At higher relative humidity levels, the samples seem to lose some compressive strength due to exposure to normal CO2 concentrations.

II MATERIALS

This section deals with the materials that are being used for this study. Materials obtained from the same sources were used throughout this work. Class F dry fly ash. used in this experimental work was obtained from the silos of Jindal thermal power station of bellary district, Karnataka state. Fly ash is the finely divided residue that results from the combustion of powdered coal and that is transported by the flue gases from the combustion zone to the practical removal system. The particle are spherical, finer than cement and mean size ranges from 1 to 150µm. The specific gravity, fineness and density of flyash are 2.45, 500m^2/kg and 1.4kg/m^3 respectively.

GGBS used in this experiment is JSW cement obtained from the bellary district, Karnataka.Ground granulated blast furnace slag is a by-product obtained from the blast-furnaces used to make iron. The specific gravity and fineness are 2.8 and 390m^2/kg. Coarse aggregate is of angular shaped crushed granite with maximum size of 12.5mm was used, fineness modulus, specific gravity and water obsorption are 5.2, 2.65 and 2% respectively. Fine aggregates used here is M-sand (Manufactered sand) having a fineness modulus, specific gravity and water absorption of 5.2,2.45 and 1.2% respectively conforming to grading zone-III as per I.S: 383 -1970. Potable water with pH value 7.15 was used for casting the geopolymer concrete.

III EXPERIMENTAL WORK

1. Mix design of geopolymer concrete:

In this M40 geopolymer concrete mix, total aggregates such as coarse and fine agg were taken as 77% of entire concrete mix by mass. This value is similar to OPC concrete which will be in the range of 75 to 80% of the entire concrete mix by mass. Fine aggregate was taken as 30% of the total aggregates. From the available literature, it is observed that the average density of geopolymer concrete is slightly lesser than that of OPC concrete (2400 kg/m^3). Knowing the density of concrete, the combined mass of alkaline liquid and solids can be arrived at. By assuming the ratios of alkaline liquid to solids as 0.5, mass of flyash and GGBS. The mass of alkaline liquid was found. To obtain mass of sodium hydroxide and sodium silicate solutions, the ratio of sodium silicate solution to sodium hydroxide solution was fixed to 2.5 as suggested by the literatures. In the present investigation, concentration of NaOH solution is taken as 14 M and the ratio of fly ash and GGBS is 50:50.

2. Preparation of geopolymer concrete:

In this experimental work NaOH solution of 14M concentration was chosen i.e., 14×40=560g of sodium hydroxide solids per liter of solution. Similarly, the mass of NaOH solids per Kg of solution for 14M concentration was measured as 404g. The sodium hydroxide solids were dissolved in water to make the solution. The mass of sodium hydroxide solids in a solution varied depending on the concentration of the solution expressed in terms of Molarity, and designated as M. The sodium silicate solution and sodium hydroxide solution were mixed together at least one day prior to use prepare the alkaline liquid. Initial one hour for every ten minutes stirring the solution properly to make the solution with uniform mix. After solution is prepared the composition is weighed and mixed in concrete mixture as conventional concrete and transferred into moulds as early as possible as the setting times are very low.

Table 1: Mix proportion of M40 grade Geopoymer concrete.

Design mix proportion for M40 grade concrete		
Particulars		*Quantity per m^3*
Fly ash		227 kg
GGBS		265 kg
10mm coarse aggregates		794 kg
Fine aggregates		728 kg
Alkaline solution	NaOH	76 kg
	Na_2SiO_3	114 kg
Water		99.2 kg
Super plasticiser		7.44 kg

3. Mixing:

It was found that the fresh Geopolymer concrete mix was grey in colour and was cohesive. The amount of water in the mix played an important role on the behaviour of fresh mix. All the ingredients as calculated in the above Table were weighed and mixed in the laboratory by hand mixing. Initially all the ingredients were mixed for three minutes (dry mix), after which, the alkaline solutions are added which is prepared one day prior and then all the above ingredients were mixed thoroughly for five minutes. At last finally calculated quantity of water and super plasticizer were added in order to pass workability. The workability of the fresh concrete was measured by means of the conventional slump test. The geopolymer concrete achieved a slump value of 100mm.

4. Casting:

Four slabs were cast at a time in a timber mould. A thin layer of oil was applied to the surface of the vertical timber formwork. In this Experimental Work, Moulds of the size 1000×500×75mm were prepared using timber. Sixteen slabs were casted. Among sixteen, nine slabs were casted with 20mm cover and rest with 10mm cover to reinforcement. Cover blocks were prepared using mortar. The cover blocks were placed along the bottom edges inside the mould upon which reinforcement is placed in the required manner. The mixed concrete were poured onto these moulds and vibrated using needle vibrator for about 1min to ensure that a pour is even and free of air bubbles so that the concrete will remain strong and have a smooth finish even after the formwork is removed. All the specimens were prepared in accordance with IS: 516. The specimens are kept in the mould for 24 hours after which they were removed from the mould.

5. Curing:

As before going to cure the specimens to an ambient temperature, the slab specimens were kept for rest period in order to get good bonding between the ingredients present in the moulds. After completion of the rest period, the specimens were demoulded and allowed to get cured for 28 days to attain the required strength.

6. Carbonation of Geopolymer concrete:

After the completion of curing process, the lightly reinforced geopolymer concrete slabs were exposed to carbon dioxide in the carbonation chamber. The slabs were divided into four series, one series of slabs were kept as control specimens and the other three series were subjected to different durations of carbonation such as 48hours, 96hours and 144hours respectively. Each series of slabs contained with two 20mm and two 10mm cover to reinforcement. Suitable housing arrangements were made in the carbonation chamber. All the slabs were arranged in the carbonation chamber as shown in the Figure 2. The carbon dioxide is supplied to the carbonation chamber by burning the rice husk, saw dust and other waste materials. Geopolymer concrete slabs are exposed to carbon dioxide for known duration in the carbonation chamber. Each series of slabs were taken out for known duration of carbonation and tested accordingly.


Fig 2:Slabs in carbonation chamber. Fig3: Carbonated slabs.

IV METHODOLOGY

1. Specifications of Slabs:

All the slabs used in this study were designed as lightly reinforced sections. In a lightly reinforced section the cracking capacity of the concrete is larger than the ultimate tensile capacity of the reinforcement. In these lightly reinforced members the ultimate moment carrying capacity may be less than the bending moment required to crack the member. In these circumstances only one crack may open at the highly stressed part of the member, and strains in the reinforcing will be concentrated at that location. If the steel yielding is concentrated at one location rather than distributed over a plastic hinge length, as in a normally reinforced member, the strains are much higher and, with low-cycle fatigue effects, could lead to fracture of the reinforcing steel.

Mild Steel reinforcement of 6mm diameter with yield strength 250 N/mm^2 were used as reinforcement in the slabs. The criterion for selecting MS bars was to make the slabs lightly reinforced. Spacing of bars was at 230mm c/c in both directions at tension zone. Five bars were provided along width wise and three bars were provided along length wise of the slabs.

For this experimental work, total number of 16 slabs of size 1000×500×75mm were casted to study the carbonation effects. These slabs are divided into four test series, as indicated in Table 3.15. Series I consisted of four slabs which were kept as Control Specimens. Series II, Series III and Series IV consisted of four slabs each subjected to accelerated carbonation durations of 48 hours, 96 hours and

144 hours respectively. For each series of slabs, two specimens were casted with 10mm and 20mm cover to reinforcement.

Table 2: Specification of slabs.

Slabs Specification			
Series No	*Cover to Reinforcement*	*Duration of Carbonation*	*Abbrevation used*
Series I	10mm	Control Specimen	GSCA1
			GSCA2
	20mm		GSCB1
			GSCB2
Series II	10mm	48 Hours	GS48A1
			GS48A2
	20mm		GS48B1
			GS48B2
Series III	10mm	96 Hours	GS96A1
			GS96A2
	20mm		GS96B1
			GS96B2
Series IV	10mm	144 Hours	GS144A1
			GS144A2
	20mm		GS144B1
			GS144B2

2. Flexure Test:

Figure 4 shows the set-up used for testing lightly reinforced geopolymer concrete slabs. When slabs were ready for testing, (after having reached the required strength) they were lifted manually and positioned as shown in figure on the loading frame. The middle of the slab is aligned with the centreline of the jack. All slabs were simply supported. A distance of 50mm was left between the centreline of the supports and the end of the slab. A system of spreader beams was placed on the slabs so arranged to allow two equal concentrated loads at a distance of span/4 from each support. Fibreboard packing pieces were used between the supports and the lower surface of slabs, and between the spreader beams and the upper surface of slabs.

Fig 4: Arrangements for test.

The test configuration and loading procedure were according to recommendation of the IS code. All slabs were simply supported and tested with two symmetrically placed line loads. A single hydraulic jack was used to apply load. The load was distributed to the slab through a spreader beam system, which resulted in two line loads being applied to the specimen. It took approximately three days from the start of testing to failure of the last slab. Two Dial gauges were used to measure deflection which were placed at mid span and at the support. Deflection at the mid-span was registered for one point and at the span/4 region. The deflections were recorded at each loading increment. The gauges were positioned under the slab to measure the mid-span deflection and to control load v/s deflection.

The load was applied on to the specimen with the use of hydraulic jack (capacity of 150kN) attached to a pumping mechanism. Load is applied by the jack acting against a reaction beam, which is restrained by an anchorage system.

The static loading was applied by the hydraulic jack to the spreader beams, and transmitted to the slab as a two line loads across the slab width at a distance of span/4 i.e., 0.25m from each support. The load was increased gradually in small increments (2.5kN). The loads and displacement readings were taken at each increment. The load was incremented till the failure load.

3. Depth of Carbonation:

The solution is sprayed onto freshly broken surface which has been cleaned by the dust and loose particles. The measurement should be carried out immediately after the broken surface has been exposed and that second reading should be taken after 24 hours have elapsed.

The carbonation depth on the surface of the slab is measured by spraying 1% phenolphthalein acting as indicator solution. After spraying, the noncarbonated area which pH is above a value in the range of 8.4 to 9.8 would become purple. If no longer coloration occurs, carbonation has taken place and thus the depth of the carbonated surface layer is measured. The distance between the color change boundary and the concrete surface is measured as the carbonation depth. When these slabs have a carbonated area the color of phenolphthalein will change. Phenolphthalein is the indicator favorite by RILEM. Transition areas which lose their color after 24 hours are to be judged as carbonated. The depth of carbonated area will be measured. It is necessary to record the average depth and maximum depth of penetration.

Fig 5: Depth of carbonation.

V RESULTS AND DISCUSSIONS

1. Observation on Flexure Test:

This section deals with the discussions on failure patterns, crack patterns and the load deflection relationship. The following observations were made during flexure test:

i. In control specimen slabs, the first crack was developed at 25kN load on the bottom right side layer under the line load. As the loading increased, minor cracks were formed at the left side layer of the line load while the existing crack was enlarged. Further load was applied gradually, the cracks which were formed propagated through the depth of the slab under the right side layer of the line load. The ultimate load taken by the slab was 27kN and the major cracks were observed under one of the line load.

ii. In Series II slabs, the first crack was formed at 27.5kN load at the bottom right side layer under the line load. As loading increased, cracks were formed at the flexure region while the existing cracks below the line load propagated towards shear region and enlarged. Further load was increased gradually, the cracks propagated through the depth under both the line loads and ultimate load on the slab was 28kN.

iii. In Series III slabs, the first crack was formed at 27.5kN load on the bottom left side layer under the line load. As loading increased, new cracks were developed on the other side of the line load while the existing cracks were enlarged. Gradually load was incremented, a small length of crack was formed at flexure region and the cracks propagated through the depth under the line loads and the ultimate load on the slab was 30kN.

iv. In Series IV slabs, the first crack was formed at 30kN load at bottom layer of the slab under both the line loads. As loading was increased, the existing cracks below or near the line loads were enlarged and crack on the right side bottom layer extended to the shear zone. Further load was increased gradually, the cracks propagated through the depth under both the line loads and ultimate load taken by the slab was 33.5kN

Fig 6: Failure Pattern in Geopolymer Concrete Slabs.

2. Result of Flexure Test:

From the results, it can be concluded that the deflection reduces with increase in carbonation period and the ultimate load increases with increase in carbonation period.

Table 3: Results of flexure test.

Flexure Test Results			
Slab Type	*Max. Deflection (mm)*	*First Crack Load (kN)*	*Ultimate Load (kN)*
GSCA1	14.15	25.0	27.0
GSCA2	14.05	26	26.5
GSCB1	14.95	25.0	26.5
GSCB2	14.26	25.0	26.5
GS48A1	11.95	22.5	25.0
GS48A2	13.69	27.5	28.0
GS48B1	12.25	20.0	22.5
GS48B2	13.98	25.0	27.5
GS96A1	11.95	27.5	30.0
GS96A2	12.96	25	27.5
GS96B1	13.35	22.5	25
GS96B2	13.05	27.5	29.0
GS144A1	11.86	27.5	30.0
GS144A2	12.08	30	33.5
GS144B1	12.05	25.0	27.5
GS144B2	12.25	27.5	31.0

Figure 7, shows the load-deflection relationship of slabs under flexure.

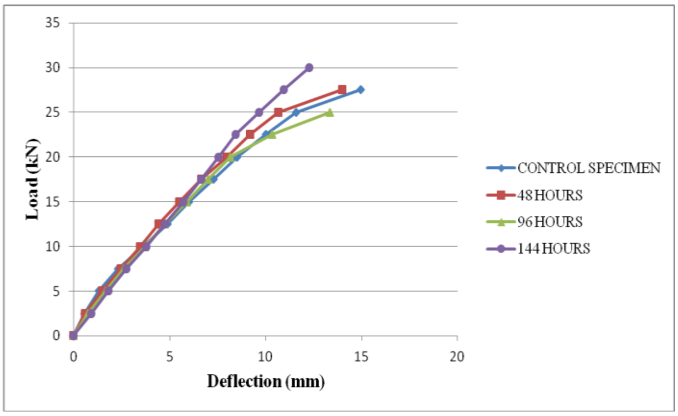

Fig 7: Comparison of load deflection curve

3. Observations and Results of Carbonation Test:

For Series II slabs with 10mm cover, the carbonation depth was found to be in the range of 0.75mm to 0.95mm and with 20mm cover, it was observed that variation is from 0.8mm to 0.9mm.

For Series III slabs with 10mm cover, the carbonation depth was found to be in the range of 0.8mm to 1.05mm and with 20mm cover, it was observed that variation is from 0.95mm to 1mm.

For Series IV slabs with 10mm cover, the carbonation depth was found to be in the range of 1.15mm to 1.4mm and with 20mm cover, it was observed that variation is from 1.1mm to 1.25mm.

Table 4 shows the average depth of carbonation encountered on each series of carbonated slabs.

Table 4: Summary of Average Depth of Carbonation

Average Depth of Carbonation			
Slab Series	*Cover to reinforcement*	*Sample Area*	*Average Depth of Carbonation*
Series II	10mm	Center and corner	0.85
	20mm		0.85
Series III	10mm	Center and corner	0.95
	20mm		0.90
Series IV	10mm	Center and corner	1.20
	20mm		1.10

From the Graph, we can suggest that the depth of carbonation increases as duration of carbonation increases. The slabs with 10mm cover have higher depth of carbonation when compared with the slabs having 20mm cover.

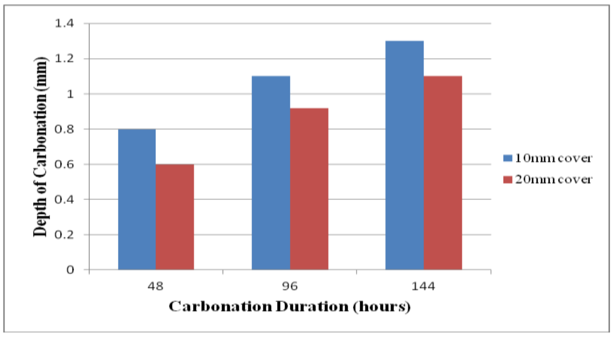

Fig 8: Comparison b/w duration and depth of carbonation.

Relationship between the carbonation duration and ultimate load is shown in the figure. From the fig, It is observed that the ultimate load of the slabs gradually increases from Series I to Series IV. This suggests that the load increases as the carbonation duration increases.

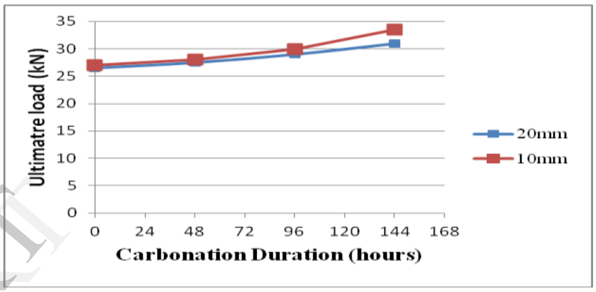

Fig 9: Ultimate Load- Carbonation duration plot.

VI CONCLUSIONS

1. All the cracks were developed between two line loads (i.e., in the zone of pure bending). Hence, the slab failed due to flexure.
2. The load – deflection curve obtained on lightly reinforced geopolymer concrete slabs can be used to predict the ultimate load capacity of balanced design slab sections.
3. In comparison with the control specimen, the ultimate load carrying capacity of the slab increased by 3.80% for 48 hours of duration of carbonation and ultimate load carrying capacity of slabs was increased by 6.80% from 48 hours to 96 hours of carbonation duration. Finally an increment of 10.50% is observed from 96 hours to 144 hours of carbonation duration.
4. The strength of the slab increases with increase in duration of carbonation and the deflection decreases. Hence it can be concluded that carbonation reduces the ductile nature of the slabs.
5. The 10mm cover slab shows 15% increase in penetration of

   carbon than the 20mm for 48 hours of carbonation, whereas it increased by 5% for 96 hours carbonation and 10% for 144 hours.
6. It can be concluded that the depth of carbonation increases

with decrease in depth of cover to the reinforcement.

7. The variation of ultimate load carrying capacity of 10mm and 20mm Cover to reinforcement are similar.
8. The density of the Geopolymer concrete increases with carbonation.

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