

An Experimental Study on Replacement of Recycled Coarse Aggregates Instead of Coarse Aggregates in High Strength Concrete

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Abstract: Globally, the utilization of concrete particularly high-strength concrete has been increasing day-by-day due to rapid industrialization and infrastructural developments. An enormous quantity of natural coarse aggregate is required for making concrete to meet the huge demand. The natural resources of coarse aggregate are depleting rapidly all over the world and urgently need to be conserved. On the other hand, millions of tonnes of construction and demolition (C&D) wastes are being generated from different sources. The disposal of these huge quantities of C&D waste is posing a big problem to the local administration and environment. Further, there are areas where the natural coarse aggregates are scarcely available and are hauled from long distances. These issues have to be addressed urgently. A review of the literature suggests that obtaining the coarse aggregates from C&D waste is a possible solution to these issues. Therefore, in the present work, an experimental attempt has been made to utilize the recycled coarse aggregate (RCA) from C&D waste to the maximum possible extent for producing the high-strength concrete.

The experimental work has been carried out in two phases: (i) Influence of processing technique on RAC and (ii) Influence of mixing approaches on RAC. The mix proportion of M75 grade was kept constant throughout the study. First, the influence of processing technique on the properties of high-strength RAC has been studied to select the most suitable processed recycled aggregate for making high-strength concrete. In the second phase, the influence of various two-stage mixing approaches on the properties of high-strength RAC has been studied to select the most appropriate two-stage mixing approach after that the resultant concrete mixes are: i) Mechanical properties (Compressive Strength, Flexural strength, Split Tensile Strength, ii) Durability properties (Acid Resistance, Sea Water Resistance) have been studied and compared with nominal cement concrete.

Index Terms: Geo polymer concrete, BRHA, Compressive Strength Split Tensile, Durability Properties

I. INTRODUCTION

Concrete, the predominantly used construction material in the world has gained its popularity because of its multiple benefits like relatively low cost of production, ease of handling, capacity to be moulded into desired shape, achievement of desired strength ranging from low to very high, serviceability and durability. The principal ingredient of concrete is cement, generally Ordinary Portland Cement (OPC) which acts as the binder and holds the aggregates intact. But unfortunately, OPC is found to be associated with some adverse effects on environment. The production of OPC is highly energy intensive and emits high amount of CO₂ into the atmosphere which contributes significantly to the 'Green House' effect. Bhanumathidas & Mehta (2001) stated that the production of one tonne of cement consumes nearly about 1.5 tonnes of earth minerals and also one tonne of CO₂ is released into the atmosphere. The raw materials required for cement production are non-renewable and are depleting at a rapid rate. But at the same time, a number of industrial and agro wastes with inherent cementitious properties are produced abundantly. But they are mostly disposed into landfills. Employing such by-products as alternates for cement has various benefits including conservation of environment, sustainability of resources and solving the disposal problem of by-products.

II. LITERATURE REVIEW

A. Concrete and Environment

The production of cement is increasing about 3% every year (McCaffrey 2002). The production process of one tonne of cement emits about one tonne of CO₂ into the atmosphere, resulting from the de-carbonation of limestone in the kiln during the manufacture of cement and the combustion of fossil fuels (Roy 1999). The yearly global cement production of 1.6 billion tonnes is responsible for about 7% of the total CO₂ emission into the atmosphere. Portland cement production is not only one of the most energy-intensive processes but also is responsible for enormous amount of greenhouse gas emission. The production of one tonne Portland cement utilizes nearly 4GJ energy (Mehta 2001).

India is the second major cement producing country next to China and has 137 large and 365 mini cement plants. It is expected that the industry will continue to increase the annual cement output in coming years and India's cement production will grow at a Compound Annual Growth Rate (CAGR) of around 12% during 2011-12 - 2013-14 to reach 303 Million Metric Tonnes. Cement Manufacturing Association (CMA) is targeting to achieve 550 MT capacities by 2020 (Vora 2011). Malhotra (2004) stated that the industrial developments in China and India are affecting the environment adversely in two ways. First, the installation of new cement plants is increasing substantially the CO₂ emissions, and second, very large capacity thermal power stations result in availability of huge amounts of fly ash and bottom ash that are not being recycled properly.

B. Ground Granulated Blast Furnace Slag

Ground Granulated Blast furnace Slag (GGBS) is a by-product obtained from the blast furnace slag during the making of iron. The cementitious properties of blast furnace slag were discovered in the late 19th century and it has been widely used in cement and concrete manufacturing for over 100 years. To produce GGBS, the granulated blast furnace slag is dried and then ground to a fineness similar to that of Ordinary Portland cement. In concrete making, GGBS is generally used in combination with Portland cement. The ratio of GGBS and cement can be varied depending on the technical requirements for a particular application (Civil & Marine 2007). In India, about 7.8 million tonnes of blast furnace slag is produced annually. The disposal of the slag as a waste fill is a problem and associated with a number of environmental hazards. With the projected growth and development in the steel industry, the amount of GGBS production is likely to increase many folds and environmental problem will thus pose a larger threat (Tamilarasan & Perumal 2010).

The steps involved in the conceptual model of geo polymerization are shown in Figure 2.1.

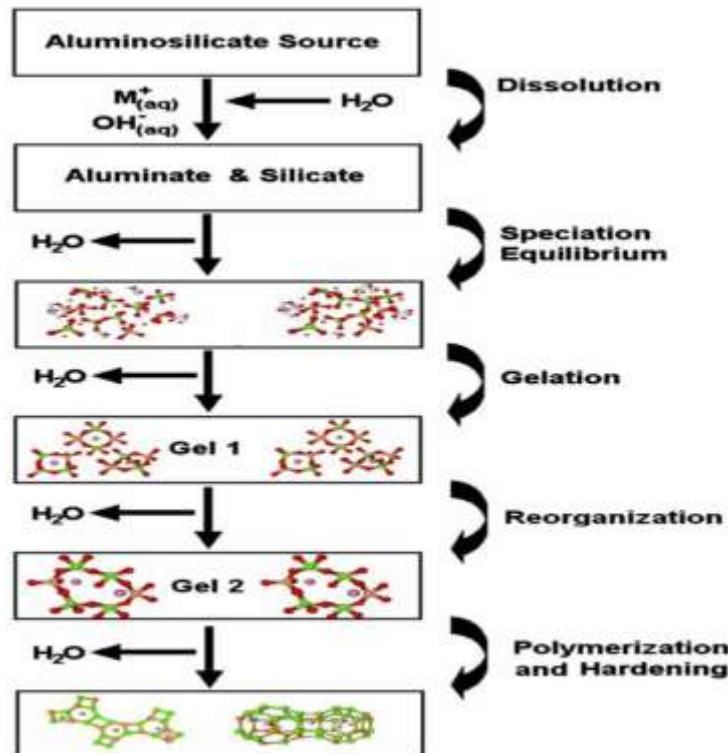


Figure 2.1 Conceptual model of geo polymerization (Duxon et al, 2007)

C. Black Rice Husk Ash (BRHA)

Black Rice Husk Ash (BRHA) is a residue gained from the uncontrolled burning of rice husk. It is basically unprocessed rice husk ash which is black in color due to high carbon content. Krishna rao et al (2000) studied the formation of black particles in rice husk silica ash. They reported that, the combustion of rice husk always results in the formation of silica rich ash which varies in color from grey to black and contains inorganic impurities along with un burnt carbon. The presence of carbon particles gives black color to the rice husk ash. Also, the un burnt carbon in the black particles cannot be removed by oxidation as it is immobile with silica. The presence of such high un burnt carbon content limits the usage of BRHA as a construction material even though it is quite rich in silica. But it has applications in some other areas like improving dispersive soil, blending with lime to solidify heavy metal before disposing in landfill and also to improve properties of polymer (Piyaphanuwat & Asavapisit 2009).

D. BRHA in Concrete

Although BRHA has not had much scope so far, understandably as a building material, there are indeed a few studies that confirm the potential worth of this material to be used in concrete. Noorvand et al (2013) used untreated BRHA as a cement replacement in proportions of 10%, 20% and 30%. Nano TiO_2 was also added in dosages of 0.5%, 1.0% and 1.5% and blended into cement for assessing the mechanical properties and micro structural changes in mortars. BRHA lowered the compressive strength of samples at 7 days up to 5%, 17%, and 27% when cement was replaced with 10%, 20% and 30% of BRHA. However, higher strength development was observed from 7 to 28 days when BRHA content increased from 10% to 30%. The incorporation of nano TiO_2 compensated the strength loss caused by BRHA replacement and the strength development from 7 to 28 days was more in 20% and 30% BRHA comparing that of 10% BRHA samples when nano TiO_2 was added exposed to hydrochloric (HCl) and sulphuric (H_2SO_4) acid attacks were studied. Two different BRHA replacement percentages 20% and 40% were used. With increase in the percentage replacement of BRHA, the drying shrinkage and depth of carbonation of concrete increased. However, BRHA had a positive effect on the autogenous shrinkage and weight loss of concretes exposed to hydrochloric and sulphuric acid attacks. From the results, they concluded that ground BRHA can be effectively utilized as a pozzolanic material and also to improve the durability of concrete.

E. Properties of Geopolymer Concrete

A lot of extensive studies have been conducted on geo polymer concrete and its performance in relation to various fresh and hardened properties is well documented. Indicators of strength and durability are the focal points of most of the studies on geo polymer concrete. Geo polymer concrete is proved to have high early strength, lesser shrinkage, resistance against reinforcement corrosion, acid and sulphate resistance, freeze-thaw resistance, fire resistance and resistance to alkali-aggregate reaction.

S. No.	Mixture No.	Mean compressive strength	Age of concrete(days)	Modulus of Elasticity (GPa)	Poisson's Ratio
1)	23	89	90	30.8	0.16
2)	24	68	90	27.3	0.12
3)	25	55	90	26.1	0.14
4)	26	44	90	23.0	0.13

Table 2.1 Young's modulus and Poisson's ratio of GPC (Hardjito & Rangan 2005)

The initial strength development of GPC was faster than PCC.

- In confined GPC, the spiral confinement improved the strength, strain at peak stress, strain ductility ratio and energy absorption capacity of GPC. Hence it is suitable for earthquake resistant design since.
- When the volumetric ratio of confinement was increased from 1.36% to 4.10%, the strength of GPC was increased by 20% to 110%.
- The strain ductility ratio and energy absorption capacity of GPC increased by 11.4 and 5.4 times respectively in comparison with unconfined GPC.

The stress-strain curves of GPC and PCC specimens are shown below in Figure 2.2.

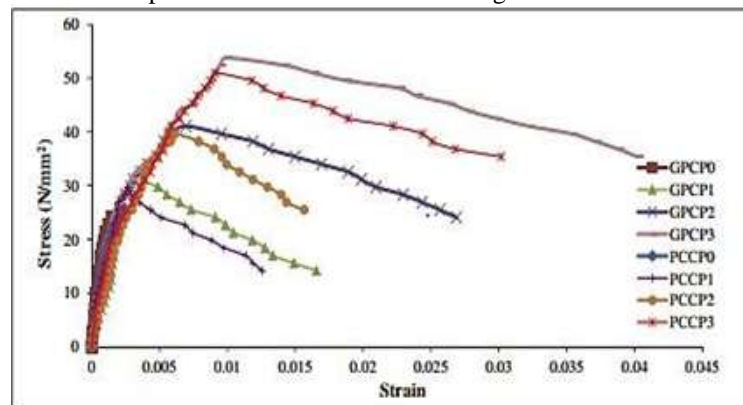


Figure 2.2 Stress-Strain curves of GPC and PCC (Ganesan et al., 2014)

F. Concluding Remarks

From the review of literature, it is clear that the research on geo polymer concrete is taking a quantum leap and there are enough comprehensive evidences available now to consider geo polymer as the best alternative for OPC concrete. At the same time, most of the published literature deal mainly on the investigation of fly ash as the primary source material for geo polymer concrete. Besides, there are certain research studies that mention the disadvantages of fly ash and also emphasize the focus on other materials like GGBS and RHA. GGBS as a primary source material for geo polymer concrete has a lot of advantages and has been proved to perform better over fly ash, whereas RHA as a silica source brings additional benefits to the table, when used as a partial replacement material. Even then, there is only little inquiry available concerning the durability aspect of geo polymer concrete incorporating the aforesaid materials. The viability of using BRHA in concrete is also discussed in the literature review. As per the author's knowledge, there are no studies available on the usage of BRHA in geo polymer concrete. Hence, this investigation on the durability of geo polymer concrete incorporating GGBS and BRHA is unique .

III. METHODOLOGY AND EXPERIMENTAL SETUP

A. Methodology

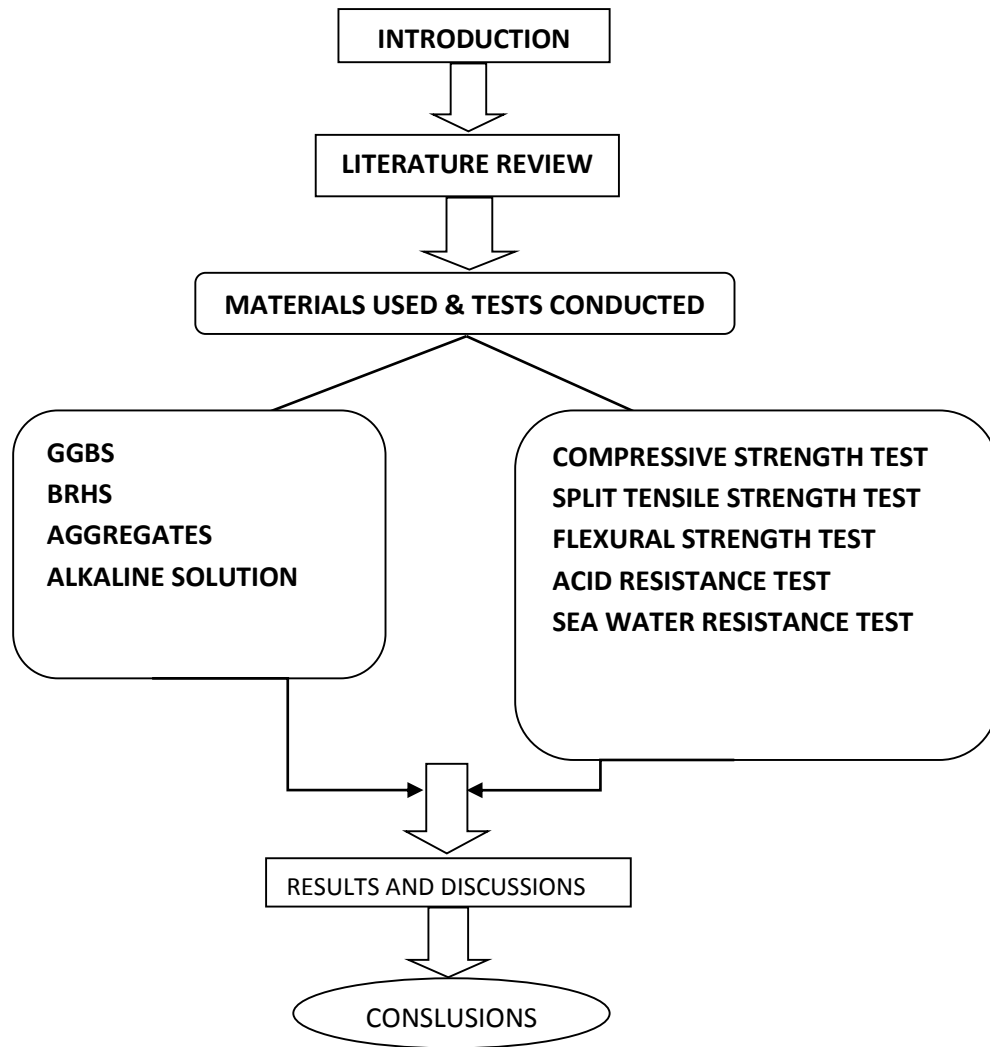


Figure 3.1 Methodology

B. Material Properties

GGBS conforming to the specifications of IS 12089-1987 was used as the primary binder to produce GPC in which BRHA was replaced from 0% to 30%. GGBS was obtained from Vizag Cement Works ACC cements limited, Visakhapatnam, India. The chemical composition and physical properties of GGBS were tested (as per ASTM D3682-01) in Material Testing House Laboratories, Viskhapatnam and are given in Table 3.1.

S. No	Property	Value
1.	Silicon-di-Oxide (SiO ₂)	31.25 %
2.	Aluminium tri oxide (Al ₂ O ₃)	14.06 %
3.	Ferric Oxide (Fe ₂ O ₃)	2.80 %
4.	Calcium Oxide (CaO)	33.75 %
5.	Magnesium Oxide (MgO)	7.03 %
6.	Loss on Ignition	1.52%
7.	Specific gravity	2.61
8.	Blaine fineness	4550 cm ² /g

Table 3.1 Properties of GGBS

BRHA was obtained from a rice mill near Sontyam Visakhapaynam. It was finely ground in a ball-mill for 30 minutes and passed through 75µ sieve (Rashid et al, 2010) before using in GPC production. The chemical composition and physical properties of BRHA were tested (as per ASTM D3682-01) in Material Testing House Laboratories, Viskhapatnam and are given in Table 3.2.

S. No	Property	Value
1.	Silicon-di-Oxide (SiO ₂)	93.96 %
2.	Aluminium tri oxide (Al ₂ O ₃)	0.56 %
3.	Ferric Oxide (Fe ₂ O ₃)	0.43 %
4.	Calcium Oxide (CaO)	0.55 %
5.	Magnesium Oxide (MgO)	0.40 %
6.	Loss on Ignition	9.79%
7.	Specific gravity	2.14
8.	Blaine fineness	5673 cm ² /g

Table 3.2 Properties of BRHA

C. Mix Proportions

Since there are no standard codal provisions available for the mix design of geo polymer concrete, the density of geo polymer concrete was assumed as 2400 kg/m³ and other calculations were made based on the density of concrete as per the mix design given by Lloyd & Rangan (2010). The combined total volume occupied by the coarse and fine aggregates was assumed to be 77%. The alkaline liquid to binder ratio was taken as 0.40. As there are no standard mix design procedures available to estimate the target Strength of GPC and besides this being a relatively new type of concrete that is still in developmental stage, minimum target strength was taken as 30 MPa, considering it as a regular strength concrete. GGBS was kept as the base material for making the control GPC specimens (GP). Then BRHA was used to replace GGBS in the mix in three different proportions, 10% (GPR1), 20% (GPR2) and 30% (GPR3), for the rest of the mixes used in the investigation. The mix proportions of GPC are given Table 3.3.

S. No	Quantities	Proportions (kg/m ³)			
		GP	GPR1	GPR2	GPR3
1.	GGBS	394	355	315	276
2.	BRHA	0	39	79	118
3.	Coarse aggregate	1201	1201	1201	1201
4.	Fine aggregate	647	647	647	647
5.	Sodium hydroxide	45	45	45	45
6.	Sodium silicate	113	113	113	113
7.	Super-plasticizer	8	8	8	8
8.	Water	59	59	59	59

Table 3.3 Mix proportions of GPC

D. Preparation of Test Specimens

The materials for the mixes were weighed and first mixed in dry condition for 3-4 minutes. Then the alkaline liquid which is a combination of sodium hydroxide and sodium silicate solutions along with super-plasticizer were added to the dry mix. Then some extra water about 15% by weight of the binder was added to improve the workability. The mixing was continued for about 6-8 minutes. After the mixing, the concrete was placed in steel moulds

by giving proper compaction. Precautions were taken to ensure uniform mixing of the ingredients. Two types of curing were used for the specimens to be tested for the study on the influence of curing temperature on the compressive strength. One set of cubes was oven cured and the other set was cured under ambient condition. For oven curing, initially the cubes were placed along with their moulds the oven immediately after casting at two different temperatures, 60°C and 90°C respectively for 24 hours. Then the cubes were de-moulded and kept as such in the oven at the same respective temperatures for another 24 hours. Then they were taken out and allowed to cure in the room temperature till the required day of testing. For the ambient curing, the cubes were kept under room temperature after casting and de- moulded after 1 day and further cured in the room temperature till the day of testing. For all other tests, the specimens were prepared by adopting the oven curing procedure at 60°C.

E. Tests Conducted

i. Compressive Strength Test

The compressive strength of GPC was tested as per IS 516:1959. The permissible error was not to be greater than $\pm 2\%$ of the maximum load. Several studies discuss the influence of salient parameters on the compressive strength of GPC. Hardjito and Rangan (2005) listed out 12 parameters that influence the strength of GPC. Among them, the curing temperature and concentration of NaOH particularly have a lot of impact on the compressive strength of GPC. Palomo et al (1999) concluded that the curing temperature is a reaction accelerator in geo polymers. Nazari et al (2011) deduced that the concentration of alkaline solution has a main effect on the strength of GPC. Accordingly, two parameters viz., the influence of curing temperature and the influence concentration of sodium hydroxide on the compressive strength of GPC were studied separately. The influence of sodium hydroxide concentration was studied for three different molarity of NaOH viz., 5 M, 8 M and 11 M. For this study, all the specimens were heat cured at 60°C. Also, the influence of curing temperature on the compressive strength of GPC was studied for three different curing conditions viz., ambient, 60°C and 90°C. For this study, the concentration of NaOH was fixed as 8 M for all the specimens. Cube specimens of size 150 mm were cast for each proportion and tested for their compressive strength at the ages of 3, 7, 28 and 90 days. All the specimens were tested using Compression Testing Machine (CTM) under a uniform rate of loading of 140

kg/cm²/min until failure and the ultimate load at failure was taken to calculate the compressive strength. Tests were carried out on triplet specimens and the average compressive strength values were recorded. The test setup is shown in Figure3.2.



Figure 3.2 Test setup of compressive strength

ii. Split Tensile Strength Test

The split tensile strength test was carried out as per IS 5816:1999. The apparatus test precision was the same as IS 516:1959. Cylindrical concrete specimens of size 150 mm diameter and 300 mm height were cast and tested for their splitting tensile strength using a CTM at the ages of 3, 7 and 28 days. Figure 3.5 shows the test setup.



Figure 3.3 Test setup of split tensile strength

iii. Flexural Strength Test

The flexural strength of GPC was carried out as per IS 516:1959. The permissible error was not to be greater than $\pm 0.5\%$ of the applied load. Beams of size 700 mm \times 150 mm \times 150mm were cast and then tested using Universal Testing Machine (UTM) at the ages of 3, 7 and 28 days. The flexural strength test setup is shown in Figure3.3.



Figure 3.4 Test setup of flexural strength

iv. Acid Resistance Test

The resistance of GPC to acids was determined on cubes of size 100 mm after 28 days from the day of casting. The initial weights of the specimens were noted and the respective cubes were immersed in 3% hydrochloric acid (HCl) and 3% sulphuric acid (H₂SO₄) separately for a further periods of 30, 60 and 90 days. The concentration of the solution was maintained throughout this period. After 30, 60 and 90 days, the specimens were taken out of the acid water. The surfaces of the cubes were cleaned, weights of the specimens were registered and then they were tested using the compression testing machine of 2000 kN capacity under a uniform rate of loading of 140 kg/cm²/min. The losses in weight and the compressive strength of the GPC cubes were then calculated. The GPC specimens immersed in the acids are shown in Figure3.4.



Figure 3.5 GPC specimens immersed in acids

v. Sea water Resistance Test

For conducting the seawater resistance test, the procedure followed was similar to the one that was followed for the acid resistance test. GPC cubes of size 100 mm were cast for the test. After 28 days from the date of casting, the initial weights of the specimens were noted and then they were immersed in the seawater mediate obtained from the shore of Rushikonda , Viskhatnam for periods of 30, 60 and 90 days. After the respective durations, the specimens were taken out of the seawater. The surfaces of the cubes were cleaned, weights of the specimens were registered and then they were tested using the compression testing machine of 2000 kN capacity under a uniform rate of loading of 140 kg/cm²/min. Weight loss and compressive strength loss measurements were calculated for the specimens at 30, 60 and 90 days from the time of immersion in sea water. GPC specimens immersed in seawater are shown in Figure 3.5.



Figure 3.6 GPC specimens immersed in seawater

IV. RESULTS AND DISCUSSIONS

A. General

Over five hundred specimens were cast and tested to examine the strength and durability of GPC made with GGBS and BRHA. Tests were conducted on GPC with three different levels of BRHA replacement 10%, 20% and 30%. The results show the variation in compressive strength of GPC with respect to the influence of curing temperature and NaOH concentration at 3, 7, 28 and 90 days of testing. Further the flexural strength, splitting tensile strength and elastic modulus of the GPC specimens were also tested. In terms of durability, parameters including sorptivity, chloride penetration, corrosion resistance, acid resistance and sea water resistance of GPC were assessed. Charts have been drawn to depict the variations in the aforesaid strength and durability parameters of GPC specimens at different proportions of BRHA replacement. The test results are discussed below.

B. Strength Tests

i. Compressive Strength Test

Influence of sodium hydroxide concentration

The influence of molarity of sodium hydroxide (NaOH) solution on the compressive strength of GPC was studied for three different molar concentrations of NaOH viz., 5 M, 8 M and 11 M. All the specimens were heat cured at 60°C. The compressive strength results are given in Table 4.1 and the variations of compressive strength of GPC specimens corresponding to the three different molar concentrations of NaOH are shown in Figures 4.1, 4.2 and 4.3 respectively.

S. No	NaOH concentration	Mix	Average compressive strength (MPa)			
			3 days	7 days	28 days	90 days
1.	5 M	GP	56.2	60.5	62.7	65.5
		GPR1	58.9	61.4	62.9	66.1
		GPR2	39.9	41.4	43.3	45.4
		GPR3	17.8	18.6	19.1	21.0
2.	8 M	GP	60.9	66.5	69.3	72.5
		GPR1	62.3	67.6	70.7	73.2
		GPR2	44.7	46.3	51.5	54.1
		GPR3	19.2	20.5	22.5	24.1
3.	11 M	GP	67.1	72.1	74.3	77.4
		GPR1	69.1	75.1	76.8	80.0
		GPR2	49.5	54.5	56.6	59.5
		GPR3	21.4	22.8	23.4	25.7

Table 4.1 Compressive strength of GPC at different NaOH concentrations

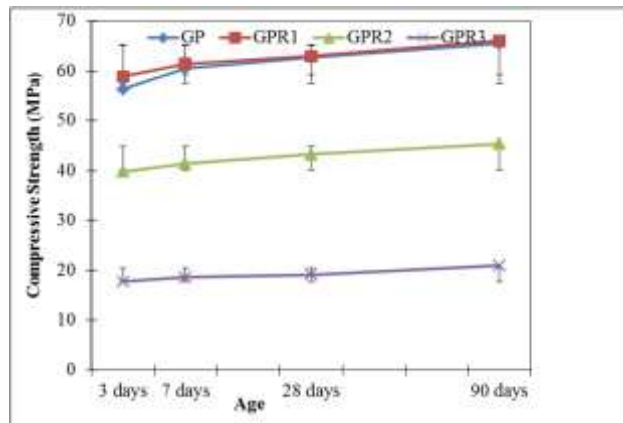


Figure 4.1 Compressive strength of GPC at 5 M NaOH concentration

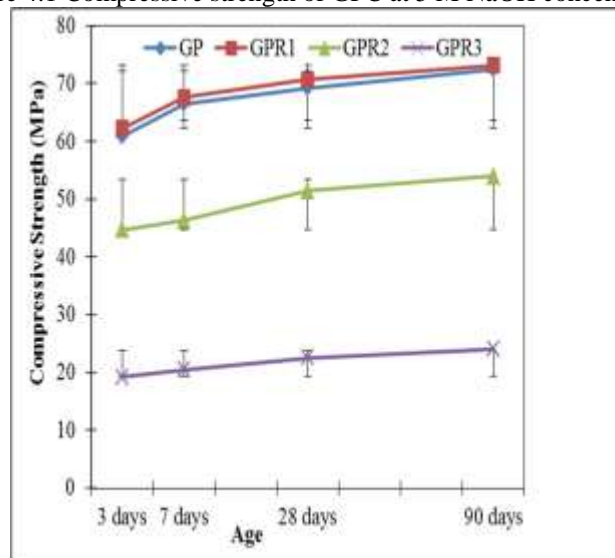


Figure 4.2 Compressive strength of GPC at 8 M NaOH concentration

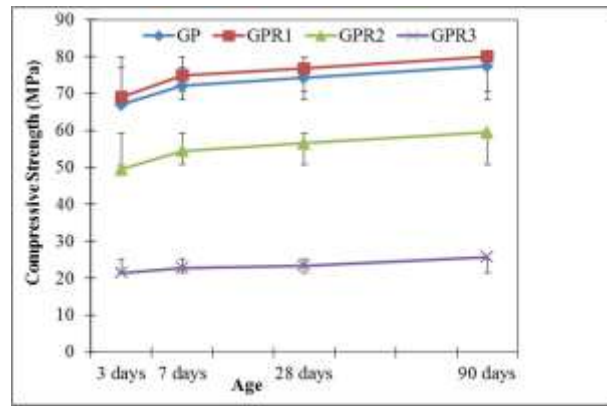


Figure 4.3 Compressive strength of GPC at 11 M NaOH concentration

From the results, it can be seen that the compressive strength of GPC increased with increase in NaOH concentration. At 28 days, the strength increase of control specimen (GP) ranged from 10 to 18% for the corresponding rise in molarity starting from 5 M to 8 M and then to 11 M. The increase in NaOH concentration could have increased the rate of dissolution of silica and alumina ions in the alkaline solution resulting in the compressive strength gain. The GPC mix developed by Rajamane et al (2012) completely using GGBS showed an average 28th day compressive strength of 63 MPa as compared to the corresponding compressive strength of 49 MPa of the control Portland pozzolana cement concrete (PPCC) used in their study. In the current study, at all three levels of NaOH molarity, the control GPC specimen (made fully with GGBS) exceeded the 28th day strength of both the GGBS based GPC and the conventional concrete of the literature referred above. This again shows that the performance of GPC is better than conventional concrete and this fact has been proved by various other researchers also.

Further, with the addition of BRHA, there is a slight increase in the compressive strength at 10% replacement level (GPR1). Comparing the control specimen GP, the 28th day strength increase for GPR1 is 0.38% at 5 M, 2.1% at 8 M and 3.4% at 11 M concentration of NaOH. The increase in molarity improves the dissolution of fine BRHA particles and accounts for the strength improvement despite the fact that it is only marginal. For the other mixes (GPR2 and GPR3), the compressive strength decreased with increase in BRHA proportion. The excessive addition of silica rich BRHA could have possibly increased the unreactive silica content in the mix which resulted in the strength reduction. But at the same time all the mixes except GPR3, surpassed the target strength of 30 MPa and strengths as high as 76.83 MPa for GPR1 and 56.61 for GPR2 at 11 M NaOH concentration could be witnessed. GPR3 did not attain any substantial strength at all three concentrations of NaOH.

While observing the rate of strength gain with respect to age, the GPC achieved majority of its strength well within its first week from the time of casting. Both the control and BRHA added GPC specimens showed a similar trend of strength gain against age. For instance, at 8 M concentration, the strength increase for GP was 9.2% from 3rd to the 7th day and it was only 4.2% from 7th day to the 28th day. There was only a further 4.7% increase in strength when tested at 90 days. For GPR1 the strength increase was 8.5%, 4.6% and 4.3% at the respective time intervals. Similar trend was seen with the other mixes also. As observed by Hardjito and Rangan (2005), the chemical reaction of the heat-cured geopolymer concrete is a substantially fast polymerization process that takes place within hours and that is the main reason for the compressive strength not being influenced by age. This behaviour is apparently in contrast to the behaviour of OPC concrete, where the hydration process would continue to occur overtime.

C. Splitting Tensile and Flexural Strength Tests

The results of splitting tensile and flexural strengths of the geopolymer concrete at 3, 7 and 28 days are given in Table 4.3 and the variation of the split tensile strength and flexural strength for the various mixes are shown in Figures 4.7 and 4.8 respectively.

S. No	Mix	Split tensile strength (MPa)			Flexural strength (MPa)		
		3 days	7 days	28 days	3 days	7 days	28 days
1.	GP	6.2	6.4	6.7	5.1	5.7	6.1
2.	GPR1	6.5	6.7	6.9	5.7	6.3	7.1
3.	GPR2	3.7	3.9	4.3	3.2	3.6	4.1
4.	GPR3	0.8	0.9	1.1	0.9	1.0	1.3

Table 4.3 Splitting Tensile and Flexural Strength Tests of GPC

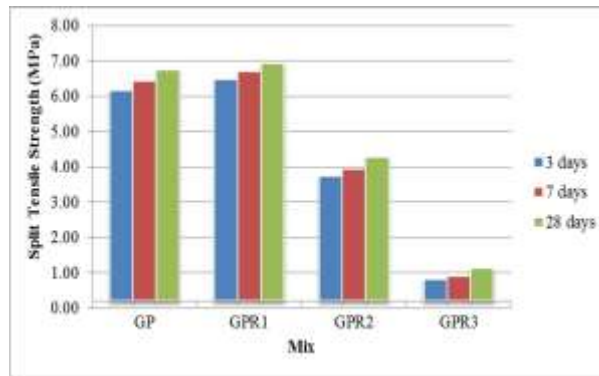


Figure 4.4 Splitting tensile strength of GPC

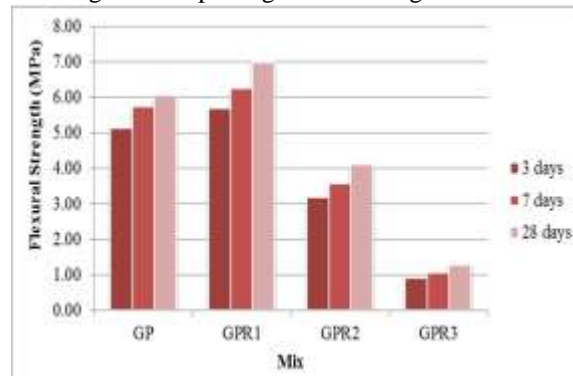


Figure 4.5 Flexural strength of GPC

When comparing the 10% BRHA replaced mix GPR1 with control mix GP, there was a slight improvement in both split tensile and flexural strengths. The heat curing of the specimens along with a suitably increased SiO₂/Al₂O₃ ratio and higher fineness of BRHA particles might have assisted the dissolution of ions and poly condensation mechanism of the geo polymer framework. Also, the co-existence of the secondary calcium silicate hydrate phase along with the primary geo polymer phase is another reason for the improvement in the mechanical strength as observed by Yip et al (2005). But with further increase in BRHA content, the split tensile and flexural strength seemed to get decreased. Similar results were reported by Jing Liu et al (2014) while using palm oil fuel ash as a binder for the geopolymer concrete. The reason for the reduction in the mechanical strengths beyond 10% BRHA replacement could be due to the fact that the BRHA particles possess a different silicate structure and when the SiO₂/Al₂O₃ ratio exceeds very high, the kinetics of the polymerization mechanism is inhibited due to the difference in solubility of GGBS and BRHA and thus the production rate of geopolymer gel is reduced as deduced by Kusbiantoro et al(2012). The experimental E values were then compared with the equivalent theoretical E values. The theoretical and experimental E values are given in Table 4.4.

S. No	Mix	Compressive strength (MPa)	Theoretical E (MPa)	Experimental E (MPa)
1.	GP	69.80	41773	36155
2.	GPR1	71.34	42231	38183
3.	GPR2	50.18	35418	27252
4.	GPR3	22.92	23937	17007

Table 4.4 Theoretical and experimental E values of GPC

The 10% BRHA replaced mix GPR1 has a higher elastic modulus than the control mix GP. The increase in E value was about 5.7% for GPR1. Both the mixes GP and GPR1 showed E values as high as 36155 MPa and 38183 MPa respectively. The possible reason for such high values of elastic modulus could be the co-existence of the secondary C-S-H phase along with the primary geo polymer phase. The other two mixes GPR1 and GPR2 show reduced elastic modulus in comparison with the control mix. The possible reason for the decrease in elastic modulus could be attributed to the reduction in strength due to inappropriate silica-alumina ratio from excessive addition of BRHA.

Comparing the theoretical and measured E values obtained from the stress-strain curves of GPC, the actual experimental values were less than that of the predicted values. The additional strains caused from the experimental setup and loading mechanism might have been the reason for such variation between the theoretical and experimental values. Similar results are reported by Khadiraniakar & Sanni (2014) for fly ash and GGBS blended geopolymer concrete.

D. Durability Test

The weight and compressive strength losses of GPC on exposure to 3% solution of H₂SO₄ at 30, 60 and 90 days from the time of immersion are shown in Table 4.5 and the variations of the strength and weight losses are shown in Figures 4.9 and 4.10 respectively.

S. No	Mix	Weight loss (%)			Strength loss (%)		
		30 days	60 days	90 days	30 days	60 days	90 days
1.	GP	0.25	3.45	6.1	3.3	10.25	15.2
2.	GPR1	0.1	2.85	4.9	2.9	9.6	13.4
3.	GPR2	0.1	3.1	5.2	3.2	10	13.9
4.	GPR3	0.4	5.6	10.8	9.8	24	39.5

Table 4.5 Weight and strength losses of GPC on exposure to H₂SO₄

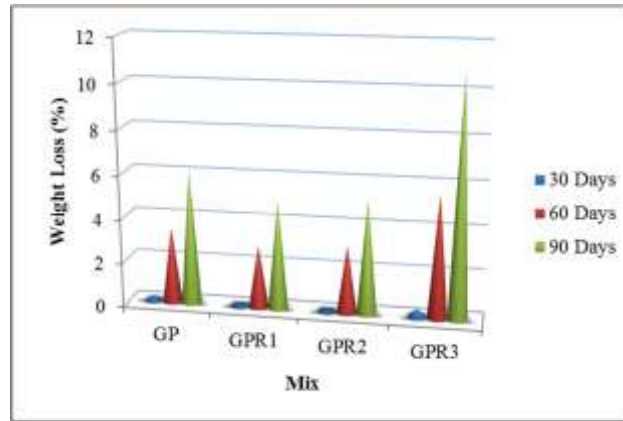


Figure 4.6 Weight loss of GPC on exposure to H₂SO₄

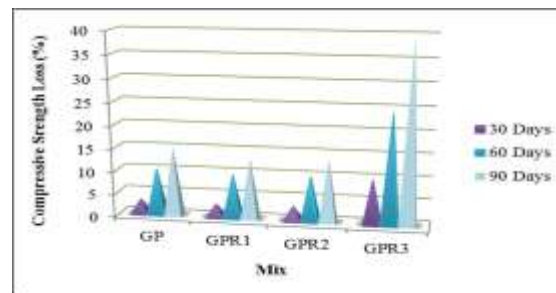


Figure 4.7 Compressive strength loss of GPC on exposure to H₂SO₄

The weight and compressive strength losses of GPC on exposure to 3% solution of HCl at 30, 60 and 90 days from the time of immersion are shown in Table 4.6 and the variations of the strength and weight losses are shown in Figures 4.11 and 4.12 respectively.

S. No	Mix	Weight loss (%)			Strength loss (%)		
		30 days	60 days	90 days	30 days	60 days	90 days
1.	GP	0	1.8	4	2.1	8.8	12.4
2.	GPR1	0	1.15	3.1	1.8	8.5	11.5
3.	GPR2	0	1.4	3.5	1.9	9.1	12.1
4.	GPR3	0.2	3.8	8.6	7.1	16.3	24.6

Table 4.6 Weight and strength losses of GPC on exposure to HCl

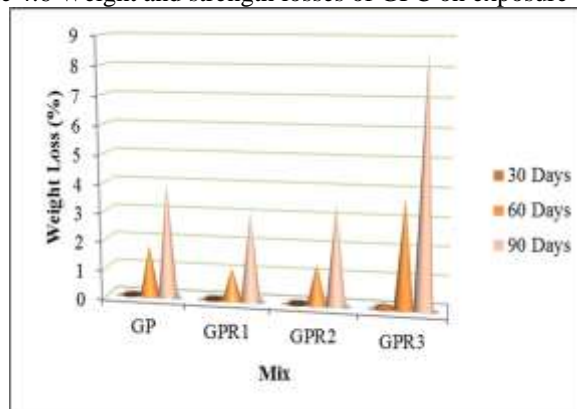


Figure 4.8 Weight loss of GPC on exposure to HCl

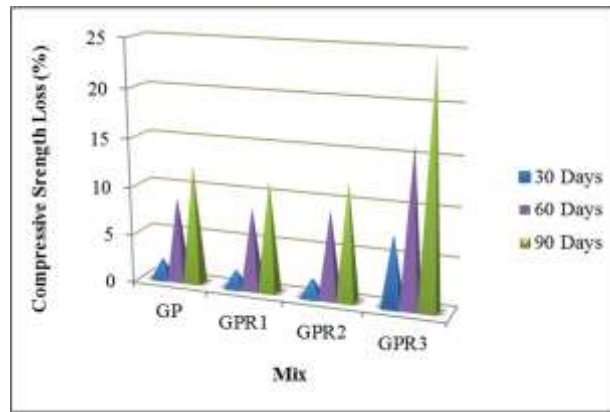


Figure 4.9 Compressive strength loss of GPC on exposure to HCl

The strength and weight loss percentages of GPC after exposure to 3% solutions of H_2SO_4 and HCl at 30, 60 and 90 days indicate that the addition of BRHA had a beneficial effect on the acid resistance of GPC. GPR1 and GPR2 specimens showed lower losses than the control specimens.

E. Cost Comparison

A basic comparison of the production cost of GPC (up to 10% BRHA replacement) was worked out considering the mix proportions of current study with conventional OPC concrete (OPCC) of M30 and M40 grades whose mix proportions were calculated as per IS 10262-2009. In view of the in-situ application of concrete, GPC with ambient curing has been assumed for comparison with OPCC. The material proportions were considered for 1 m^3 quantity of concrete and the current market rates (approximate) of materials were used for the comparison.

The material proportions of concrete are given in Table 4.8. The unit rates of the materials and cost corresponding to their proportion per cubic meter of GPC and OPCC were worked out and listed in Table 4.9.

S. No	Materials	Proportions (kg/ m^3)			
		GP	GPR1	OPCC(M30)	OPCC (M40)
1.	Cement	0	0	320	350
2.	GGBS	394	355	0	0
3.	BRHA	0	39	0	0
4.	Coarse aggregate	1201	1201	1301	1285
5.	Fine aggregate	647	647	786	776
6.	Sodium hydroxide	45	45	0	0
7.	Sodium silicate	113	113	0	0
8.	Super-plasticizer	8	8	6	7
9.	Water	59	59	137	137

Table 4.8 Material proportions of GPC & OPCC

S. No	Materials	Cost per kg (₹)	Cost per m^3 (₹)			
			GP	GPR1	OPCC(M30)	OPCC(M40)
1.	Cement	9	0	0	2880	3150
2.	GGBS	2	788	710	0	0
3.	BRHA	0.5	0	20	0	0
4.	Coarse aggregate	3	3603	3603	3903	3855
5.	Fine aggregate	2.5	1618	1618	1965	1940
6.	Sodium hydroxide	33	1485	1485	0	0
7.	Sodium silicate	8	904	904	0	0
8.	Super-plasticizer	125	1000	1000	750	875
9.	Water	0	0	0	0	0
TOTAL			9398	9340	9498	9820

Table 4.9 Cost of GPC & OPCC

Comparing GPC made fully with GGBS (GP) and conventional M30 grade OPC concrete, there is a cost saving of ₹100 i.e. 1.1%. While comparing with M40 grade OPCC, the cost saving is ₹422 i.e. nearly 4.5% for GP. With addition of BRHA, there is some further saving of cost. Comparing GPR1 and M30 grade OPCC, the cost saving is ₹158 i.e. about 1.7% whereas it is ₹480 i.e. 5.1% in comparison with M40 grade OPCC. The comparative cost saving of GPC with M30 and M40 grades OPCC in ₹ is shown in Figure 4.10 and the corresponding percentage cost saving is shown in Figure 4.11.

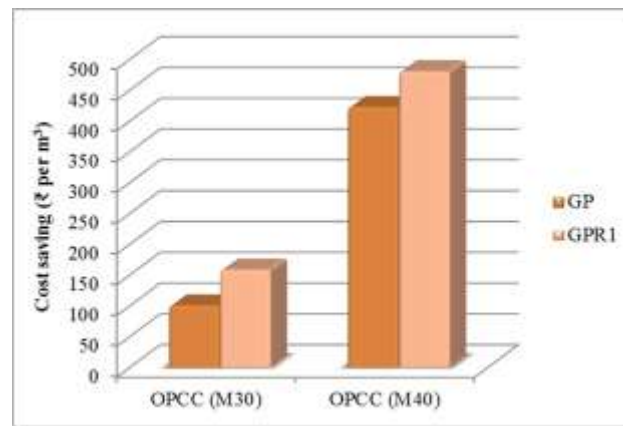


Figure 4.10 Comparative cost savings of GPC to OPCC in %`

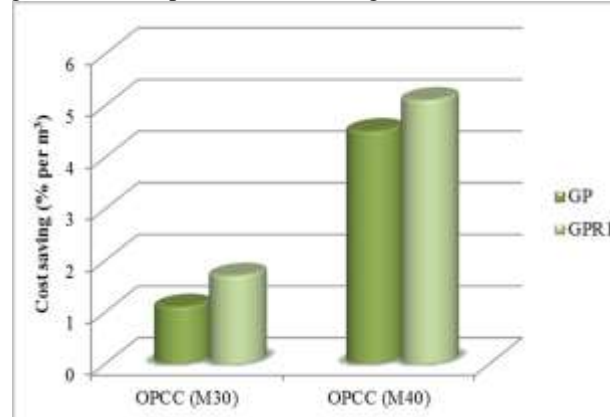


Figure 4.11 Comparative cost savings of GPC to OPCC in %

From this fundamental comparison, it is understood that there is some saving of cost in using GPC against OPCC. Although the percentage-wise savings may outwardly look less for one cubic meter of concrete, when it comes to the enormous volumes of concrete that are being used in construction, these savings can be definitely substantial.

CONCLUSION

The following conclusions can be drawn from this limited experimental investigation.

- The experimental results show that it is possible to produce geo polymer concrete possessing substantial strength and durability using GGBS and BRHA.
- The strength increase ranged between 10 to 18% for the corresponding rise in molarity starting from 5 M to 8 M and then to 11M.
- Oven curing resulted in higher compressive strength than ambient curing. However, ambient curing gave strength up to 53 MPa for 100% GGBS and up to 40 MPa for 10% BRHA replacement.
- While comparing oven curing at a temperature of 60°C and ambient curing, the strength increase at 28 days was 45% for GPR1 and nearly three times for GPR2specimens.
- Increase in curing temperature to 90°C had only a moderate increase in the compressive strength. Hence oven curing at 60°C could be preferred for the GPC when BRHA is added.
- Addition of BRHA beyond 10% had a retarding effect on the compressive strength. Although up to 20% replacement, the target compressive strength was surpassed and strength as high as 51 MPa was reached at 28days.
- The strength gain was substantial till 7 days and became moderate till 28thday. As evident from the 90th day compressive strength results, the strength gain beyond 28 days was only marginal for GPC.
- The incorporation of BRHA in geo polymer concrete increased its corrosion resistance. The corrosion initiation period was 34 days for GPR1 and 36 days for GPR2, whereas it was only 23 days for the GP specimen.
- BRHA added GPC specimens showed good resistance against acid attack and seawater attack as the weight and strength losses were lower for 10% and 20% replacement levels than the control specimens.
- Addition of BRHA beyond 20% is not beneficial in geo polymer concrete. The 30% BRHA replaced specimens neither achieved significant strength nor proved to be durable.
- From the cost perspective, there is a definite saving of cost in the production of GPC over conventional concrete. While comparing, as the grade of the conventional concrete increases the cost saving also increases for the corresponding GPC mix.
- The reflection of cost savings can be more significant if the volume of production of concrete is massive.

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