Sulphuric acid resistant ecofriendly concrete from geopolymerisation of blast furnace slag

N P Rajamane a, M C Nataraja b, N Lakshmanan c, J K Dattatreya d & D Sabitha e

SRM University, Kattankulathur 603 203, India,
Department of Civil Engineering, S J College of Engineering, Mysore 570 006, India
CSIR-Structural Engineering Research Center, Chennai 600 113, India
Siddaganga Institute of Technology, Tumkur 572 103, India
CSIR-National Geophysical Research Institute, Hyderabad 500 007, India

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In this study, geopolymer is prepared from ‘ground granulated blast furnace slag’ (GGBS)—a powder from grinding the by-product of slag waste from blast furnace of steel plants. For comparison, conventional cement, Portland pozzolana cement (PPC) containing fly ash was considered. To achieve simultaneous acidic and sulphate attack, sulphuric acid is used for durability studies. The test data indicate that on exposure to 2% and 10% sulphuric acids, the losses in weight, thickness and strength of geopolymer concrete (GPC) are significantly much less than those for Portland pozzolana cement concrete (PPCC). The GPCs have inorganic polymers of alumino-silicates as binder, generally without any free lime. Therefore, GPCs resist acid attack better than free lime containing conventional concretes containing Portland cement. The binding action in GPC is through geopolymerisation of GGBS using alkaline activator solution (AAS) made of sodium hydroxide and sodium silicate solutions. The geopolymer eliminates use of Portland cement in structural concretes by utilizing the industrial by-product GGBS, thereby reducing considerably the carbon footprint measured by ‘embodied energy’ and ‘embodied carbon’, i.e., ‘CO₂e emission’ of concrete.

Keywords: Geopolymer, Sulphuric acid, Portland pozzolana cement, Fly ash, Blast furnace slag powder, Sodium hydroxide, Sodium silicate

Portland cement, a conventional binder in concretes, has performed satisfactorily in most of the civil engineering applications. However, this cement is highly internal-energy-intensive (with high ‘embodied energy’ contents) and also, its production involves emission of green house gas of CO₂ and concrete made with this cement were observed to be less durable in some of the very severe environmental conditions. These facts have urged engineers to look for development of alternate concretes. In this regard, geopolymer concretes (GPCs) have emerged as potential candidate materials.

These new concretes utilise industrial wastes in the form of fly ash (FA) and ground granulated blast furnace slag (GGBS) which are activated by alkaline medium to produce ambient temperature cured inorganic polymeric binder (called as geopolymers) in the form of alumino-silicates. However, in order to make these new concretes acceptable in practical applications, they should be shown to possess both adequate strength and durability characteristics. These aspects were studied in the extensive investigations carried out at CSIR-SERC, Chennai. The test results discussed in this paper are with regards to sulphuric acid resistance of GPC made from GGBS only. Since the above mentioned industrial wastes become ‘geopolymeric resource material’, they can be now considered as by-products, instead of so called waste. Though the term, ‘geopolymer’ has become more common to represent the synthetic alkali aluminosilicate material (produced by reaction of a solid aluminosilicate with a highly concentrated aqueous alkali hydroxide or silicate solution), it is worthwhile to note that the following nomenclatures are also reported to describe similar materials: (i) inorganic polymer, (ii) low-temperature aluminosilicate glass, (iii) alkali-activated cement, (iv) alkali-activated binders, (v) geocement, (vi) alkali-bonded ceramic, (vii) inorganic polymer concrete, (viii) hydroceramic, (ix) mineral polymers, (x) inorganic polymer glasses, (xi) alkali ash material, (xii) soil cements, (xiii) alkali activated aluminosilicate.

It is seen that ‘geopolymer’ is a versatile binder being studied by scientists of various backgrounds and expertise, but, having good potential to become...
Aims of Present Study

Since Portland pozzolana cement (PPC) is the most easily available cement in the market at present, it was chosen to produce a typical conventional cement concrete. GGBS based GPC mix was selected based on the earlier works carried out at CSIR-SERC. The cylindrical specimens (75 mm dia × 75 mm height) were employed for studying the resistance of concretes to 2% and 10% sulphuric acid solutions and 100 mm cubes for evaluating compressive strengths. Besides visual observations, changes in weight and strength after predetermined exposure periods to acid were recorded. The sulphuric acid resistance test is a very severe durability test on concretes since this acid combines the effects of both acidic and a sulphate environment simultaneously and therefore, the actual test duration is much shorter than many other durability tests.

GPC being a new material of construction, requires to be assessed for both strength and durability characteristics. The GPC utilises industrial by-product of blast furnace slag from steel plants. The test data in this paper is expected to enable the engineers to examine the durability aspects of the GPC from GGBS which is obtained after grinding the slag and consider them for construction of actual structures. The test data of this study provides a basis for complete elimination of highly energy intensive Portland cement from concrete which is the most widely used construction material. The new concrete produced from the industrial by-product slag would not only have low carbon footprint with low ‘embodied energy’ and ‘low carbon dioxide emission’, but also it is more durable material with higher and faster strength development capability.

Though this paper deals with sulphuric acid resistance of concretes, it is necessary to look at many other parameters such as sulphate attack, chloride diffusion, water absorption, stability of geopolymeric gel formed, bond strength of GPC with steel bars, corrosion protection to embedded steel, alkalinity level of matrix formed and flexural and other structural behaviour of reinforced concrete sections are also important. These aspects are covered in many earlier studies. However, we must note that ‘geopolymer’ is a very generic word and this can form from a variety of geopolymeric source materials, such as fly ash, GGBS, metakaolin, rice husk ash, synthetic alumina and silica apart from possibility a large number of activator solution formulations. Therefore, unlike, Portland cement, careful understanding of different geopolymeric composites is necessary.

Experimental Procedure

Materials

Properties of materials are described in Tables 1a-1f. It may be noted here that any concrete requires fine aggregates (particles smaller than 4.75 mm) and coarse aggregates (particles larger than 4.75 mm) so that a packing of these two inert filler materials creates minimum space for binder paste in the concrete mix and this is required from economic point of view also since binder portion is generally the most expensive in any concrete mix. The river sand as fine aggregate and crushed granite stone as coarse aggregate are very commonly adopted for conventional concrete mixes and the same were chosen for GPC mixes. The test data also showed that the chosen aggregates act satisfactorily as almost inert filler system in both types of concretes.

The fly ash described in Table 1c is Class F and was obtained from North Chennai Thermal Power Plant where fly ash is being collected dry through electrical precipitators.

Preparations of test specimens

The mix proportions (Table 2) were arrived by trial mixes, so that the satisfactory workability with a slump cone value of at least 100 mm is achieved and the mix was easily compactable by a laboratory table.
vibrator. Ingredients were weighed in digital balances; mixing was done in a pan mixer for a minimum period of 5 min to achieve the uniformity in the mix. The freshly prepared mix was weighed for density and placed into the steel mould in three layers and compacted using a laboratory table vibrator. The specimens were demoulded after 24 h of casting. GPC specimens were self cured by storing them openly under ambient laboratory conditions (temperature 25-35ºC, relative humidity of 65-85%). The conventional Portland pozzolana cement concrete (PPCC) specimens were kept submerged in water for effective curing.

The alkali activator solution (AAS) mentioned in Table 2 is made from the mixture of sodium hydroxide solution and sodium silicate solution. The quantity of this liquid AS taken was 55% by weight of binder which, in the present case of GPC is GGBS. This binder/AAS ratio of 0.55 provided sufficient workability to the fresh GPC mix. The AAS can be considered to consisting of Na$_2$O and SiO$_2$ besides water. As Na$_2$O is more important from geopolymerisation point of view, its content with reference to geopolymeric binder was computed and this was found to be about 5% as mentioned in Table 2.

### Acid attack test on concrete specimens

The concentrated sulphuric acid (98% concentration and density of 1.84 g/cc) was used to prepare the sulphuric acid of 2% and 10% concentrations. For this, following formula was used:

$$\text{Concentration of acid} = \frac{\text{Amount of acid}}{\text{Volume of water}}$$
\[ R = D_1 \times [(C_1 / C_2) - 1] \] … (1)

where, \( C_1 \) is %concentration of commercially available conc. sulphuric acid, \( D_1 \) is density of conc. sulphuric acid of concentration \( C_1 \) (g/mL), \( C_2 \) is %concentration of desired diluted sulphuric acid for testing, \( R \) is volume of water added per mL of sulphuric acid of concentration, \( C_1 \) to get diluted sulphuric acid of concentration, \( C_2 \).

Thus, it was noted that about 11 mL of 98% concentrated sulphuric acid (conc. \( \text{H}_2\text{SO}_4 \)) was required to be mixed with 989 mL of distilled water to get 1 L of 2% acid solution for test. On the other hand, 1 L of 10% acid solution is obtained by mixing 58 mL of 98% concentrated sulphuric acid (conc. \( \text{H}_2\text{SO}_4 \)) with 942 mL of distilled water. The cylindrical specimens were submerged in acid solution kept in a plastic tubs such that there was a minimum of 30 mm depth of acid over the top surface of specimens. The pH of the solution was monitored periodically using pH meter and also by titration with standard alkaline solution. The specimens are taken out from acid tank at the end of each test period for visual observation for deteriorations and washed in the tap water before weighing in digital balance of 0.1 mg accuracy and then testing for compressive strength in an UTM.

### Results and Discussion

#### Fresh concrete properties

The workability of all the concrete mixes (measured by Abram’s Slump Cone following the procedure given in IS:1199) was more than 100 mm which was sufficient for satisfactory compaction by use of table vibrator. The mixes were also cohesive with almost zero or very little bleeding. The fresh concrete density of GPC and PPCC were almost similar (Table 2).

Though setting times of GPC were not measured explicitly, however, they were found to be satisfactory for GPC mix by observing that the minimum working time available for fresh GPC mix was about 45 min and the demoulding operations could be easily carried out after 24 h of casting.

Efflorescence in GGBS based geopolymer was not observed in the present study, though it has been reported by some workers. But, during study on several GPC mixes, depending upon the formulation of alkali activator solution, authors noticed that sometimes, greenish layer gets formed on surface of test specimens made of some GPCs. This did not affect the structural properties of GPCs. OPC based concretes, however, did not show noticeable efflorescence.

The shrinkage characteristics of the mixes were not measured directly in the present study. However, by careful inspection of the different mixes prepared, it

### Table 2—Details of concretes

<table>
<thead>
<tr>
<th>Mix Id</th>
<th>GPC</th>
<th>PPCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>% Fly ash</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>% GGBS</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>% Portland Cement</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>Binder composition (% by mass)</td>
<td>0.55</td>
</tr>
<tr>
<td>5</td>
<td>Activator solution (AS)</td>
<td>AAS</td>
</tr>
<tr>
<td>6</td>
<td>Na\textsubscript{2}O in AS as % binder</td>
<td>5.6</td>
</tr>
<tr>
<td>7</td>
<td>Superplasticiser % Binder</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>Slump, mm</td>
<td>120</td>
</tr>
<tr>
<td>9</td>
<td>Density, kg/m\textsuperscript{3}</td>
<td>2375</td>
</tr>
<tr>
<td>10</td>
<td>Ingredient contents of concretes, kg/m\textsuperscript{3}</td>
<td>Fly ash</td>
</tr>
<tr>
<td></td>
<td>Ground granulated blast furnace slag (GGBS)</td>
<td>428</td>
</tr>
<tr>
<td></td>
<td>Portland cement</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Binder</td>
<td>428</td>
</tr>
<tr>
<td></td>
<td>Sand</td>
<td>642</td>
</tr>
<tr>
<td></td>
<td>Coarse aggregate</td>
<td>1070</td>
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<tr>
<td></td>
<td>Activator solution, kg/m\textsuperscript{3}</td>
<td>235</td>
</tr>
<tr>
<td></td>
<td>Alkali activator solution specific gravity</td>
<td>1.16</td>
</tr>
<tr>
<td></td>
<td>Activator solution, L/m\textsuperscript{3}</td>
<td>203</td>
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</tbody>
</table>

GPC = Geopolymer Concrete, PPCC=Portland Pozzolana Cement Concrete, AAS=Alkali Activator solution
could be observed that the GPC mixes were almost similar to Portland cement based concrete mixes. Though some authors had reported noticeable shrinkage of GPCs, the present formulation of the GPC mix did not result in exhibition of shrinkage related effects of the mixes. Compression strength

The average 28 days compression strength of GPC was 63 MPa which increased only marginally to 65 MPa at 90 days; corresponding values for PPCCs were 48 and 74 MPa (Table 3a, Fig. 1a). Thus, GPC had gained almost its full strength at the end of 28 days.

Table 3a—Test data on concretes

<table>
<thead>
<tr>
<th>Mix Id</th>
<th>Binder Composition (% by mass)</th>
<th>% Fly ash</th>
<th>% GGBS</th>
<th>% Portland Cement</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td></td>
<td>0</td>
<td>100</td>
<td>0</td>
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</table>

<table>
<thead>
<tr>
<th>Mix Id</th>
<th>Binder Composition (wt%)</th>
<th>% FA</th>
<th>% GGBS</th>
<th>% OPC</th>
<th>%Na2O in AS* as % binder</th>
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</thead>
<tbody>
<tr>
<td>2</td>
<td></td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>5.6</td>
</tr>
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<table>
<thead>
<tr>
<th>Mix Id</th>
<th>Compressive Strength, MPa</th>
<th>fc1d</th>
<th>fc7d</th>
<th>fc28d</th>
<th>fc90d</th>
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<tbody>
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<td>6</td>
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<td>44</td>
<td>63</td>
<td>65</td>
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<table>
<thead>
<tr>
<th>Mix Id</th>
<th>Rate of strength development</th>
<th>fc1d/fc28d (%)</th>
<th>fc7d/fc28d (%)</th>
<th>fc28d/fc28d (%)</th>
<th>fc90d/fc28d (%)</th>
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<td>7</td>
<td></td>
<td>48</td>
<td>70</td>
<td>100</td>
<td>103</td>
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</tbody>
</table>

Table 3b—Test data on concretes

<table>
<thead>
<tr>
<th>Mix Id</th>
<th>Binder composition</th>
<th>% FA</th>
<th>% GGBS</th>
<th>% OPC</th>
<th>%Na2O in AS* as % binder</th>
<th>Exposure to 2%H2SO4</th>
<th>% Reduction in GPC*</th>
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<tr>
<td>2</td>
<td></td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>5.6</td>
<td>30 days</td>
<td>96</td>
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</table>

<table>
<thead>
<tr>
<th>Mix Id</th>
<th>Weight loss (%)</th>
<th>% Reduction in GPC*</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>30 days</td>
<td>95</td>
</tr>
<tr>
<td>10</td>
<td>60 days</td>
<td>57</td>
</tr>
<tr>
<td>11</td>
<td>90 days</td>
<td>48</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mix Id</th>
<th>Thickness loss (mm)</th>
<th>% Reduction in GPC*</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>30 days</td>
<td>95</td>
</tr>
<tr>
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<td>60 days</td>
<td>57</td>
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<tr>
<th>Mix Id</th>
<th>Strength loss (%)</th>
<th>% Reduction in GPC*</th>
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<tr>
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<td>57</td>
</tr>
<tr>
<td>11</td>
<td>90 days</td>
<td>48</td>
</tr>
</tbody>
</table>

Note: Binder/AS ratio in PPCCs is water-binder ratio or water-cement ratio
AS= Activator solution for GPC is made from mixture of sodium silicate (molar ratio 2.2) and sodium hydroxide solutions
GPC = Geopolymer cement concrete, PPCC=Portland pozzolana cement concrete

% Reduction in GPC = 100*(OPCC-GPC)/OPCC

Compression strength

The average 28 days compression strength of GPC was 63 MPa which increased only marginally to 65 MPa at 90 days; corresponding values for PPCCs were 48 and 74 MPa (Table 3a, Fig. 1a). Thus, GPC had gained almost its full strength at the end of 28 days.
days where as PPCCs continued to gain considerable strength after 28 days also (Fig. 1b). It may be noted that these strength levels are quite adequate when compared with the minimum structural grade recommended in IS 456-2000 for ‘extreme’ exposure condition. In present study, the 1 day strength of GPC was about 30 MPa which is quite high and hence, the present GPC may be considered as high early strength concrete, which is useful in faster construction of structures since the GPC studied does not require any external curing and only ambient conditions are enough for the geopolymerisation reactions and subsequent strength gain. In contrast, OPC based concretes need always careful curing through exposure to moisture or water.

The data in Table 3a and Fig. 1b show that the GPC has higher ratios of $f_{1d}/f_{28d}$ and $f_{7d}/f_{28d}$ than those of PPCC indicating faster rate of development than PPCC. The strength increase beyond 28 day up to 90 day in case of PPCC is 54% which is substantial as compared to this value being only about 3% for GPC, thereby confirming that the GPC develops fast its ultimate strength compared to PPCC. This is a useful and desirable property in structural concretes.

**Sulphuric acid attack**

Figures 2a-2c show a contrast between acid resistances of GPC and PPCC specimens at for 30, 60 and 90 days of exposure to 2% sulphuric acids and the difference increases with exposure time. The percentages weight and strength losses for the mixes and also estimated thickness loss due to attack by 2% sulphuric acid increases with increased exposure period (Table 3b). At the end of 90 days, the PPCC specimens were found to be in highly deteriorated state with almost complete loss of integrity, but, the GPC specimens had almost maintained their integrity with minor visible distress seen on the surface when examined visually, even though there were substantial losses of strength (Figs 2a and 2b, 3a-3c). The % strength losses in GPC after exposure of 30, 60 and 90 days to 2% $H_2SO_4$ were 3.7%, 10% and 11.1% (corresponding weight losses being 0.1%, 2.7% and 4.5%) respectively and these numbers for PPCC were quite high at 17.4%, 31.4% and 36.2% (corresponding weight losses being 2.3%, 6.3% and 8.7%) (Table 3b).
Similar observations can be made in respect of depth of deterioration (thickness loss) also. The above observations were valid also when the loss of weight was converted into estimated average depth of deterioration due to penetration of sulphuric acid computed using the following formula:

\[ p = 1 - \left[ \frac{1 - 2 \times (T / H_1)}{(1 - (T / R_1)^2)} \right] \quad \ldots \quad (2) \]

where,

\[ T = \text{estimated average depth of deterioration} = \text{Change in radius} \]

\[ H_1 = \text{initial height of specimen} \]

\[ R_1 = \text{initial radius of specimen before acid exposure} \]

\[ (R_1 - T) = \text{radius of specimen after exposure} \]

\[ (H_1 - 2 \times T) = \text{height of specimen after exposure} \]

\[ P = \text{fractional weight loss} = \frac{W_1 - W_2}{W_1} = \frac{\text{weight loss/initial weight}}{W_1} \]

\[ W_1 = \text{initial weight of specimen before acid exposure} \]

\[ W_2 = \text{weight of specimen after acid exposure} \]

\[ W_1, W_2, H_1 \text{ and } R_1 \] are known, and \( T \) can be computed from above equation. These values are given in Table 3b and Fig. 3a.

After 90 days, the PPCC specimens had typically external exposure of the coarse aggregate; the surfaces were rough and yellowish in colour (Figs 3b and 3c). The expansive nature of chemical reaction has happened in the PPCC specimens since a perceptible increase in porosity of specimens was noticed. The free lime available in the hydrated cement matrix get reacted by acid resulting in formation of gypsum and also the calcium aluminate phases of both hydrated and the unhydrated portions of cement in the matrix also get attacked by sulphate ions leading to formation of ettringite which is an expansion creating compound. These PPCC specimens could be considered to have reached their ultimate level of very existence itself. In contrast, the GPC specimens were almost intact even though significant strength losses had occurred. This is evident from the estimated depths of deterioration which were 0.02, 0.5 and 0.8 mm only, for 30, 60 and 90 days of 2% \( H_2SO_4 \) acid exposure for GPC whereas these numbers for PPCC were as much as about 0.4, 1.1 and 1.5 mm (Fig. 2b).

The above observations made on 2% sulphuric acid are almost similarly valid for attack by 10% sulphuric acid also (Fig. 2b). Thus, it is clear that GPC had comparatively very high resistance to sulphuric acid attack. The reductions in deterioration in respect of
weight loss, deterioration depth, and strength loss can be as much as 48% to 96% if PPCC is replaced by GPC for 2% acid attack and this range becomes 13% to 76% in case of 10% acid attack (column 3 in Table 3b, Fig. 3a). This can be attributed to the fact that the GPCs do not have free lime content in its matrix and geopolymers themselves are not easily attacked by acids.\(^5\)

Even though free lime was not measured in the present case, published literature indicate that because of nature of chemical reactions occurring in geopolymer concretes, possibility of free lime is very less and instead of calcium silicate hydrate (C-S-H) gel (which is a binder portion in Portland cement based matrix) aluminosilicate polymeric system is formed and this involves no evolution of free lime.

Superior acid resistances (particularly to sulphuric acid) of geopolymer concretes in general have been reported by many researchers.\(^44-45\) The PPCC do contain free lime content in its matrix due to hydration reactions of Portland cement portion of the PPC and this free lime and also the hydrated Portland cement matrix C-S-H gel of the matrix are easily attacked by acids in general, especially more by the sulphuric acid.\(^2,43\)

### Ecological Analysis of Concretes

Embodied energy (EE) and embodied carbon dioxide emission (ECO\(_2\)e) of concretes were computed to examine the ecological effects of the concretes.\(^47,48\) The EE is the energy consumed for the raw material extraction, transportation, manufacture, assembly, installation, disassembly and deconstruction for any product system over the duration of a product’s life. The embodied carbon (ECO\(_2\)e) is the CO\(_2\)e released for the raw material extraction, transportation, manufacture, assembly, installation, disassembly and deconstruction for any product system over the duration of a product’s life. The data on EE and EC for the ingredients and the concretes were taken from the literature.\(^47-53\) The computations are shown in Table 4a and the benefit of GPC over PPCC are given in Table 4b (Fig. 4).
The EEs of GPC and PPCC were 1116 and 1809 MJ/m$^3$ (Table 4) and thus the GPC was 38% lower in energy requirement (Fig. 4). The ECs of GPC and PPCC were 88 and 316 kgCO$_2$/m$^3$ and thus the GPC was 72% lower in CO$_2$ emission. Therefore, the GPC can be considered as more ecofriendly. It may be noted here that the PPCC considered here itself had 28% fly ash and if the conventional concrete is made of OPC only (which is often the case still in many projects), the GPC would still look more advantageous. Because of high cost of AAS, the GPC is found to be about 22% costlier, but, it had much higher early strengths at 1 day and 7 day there by offering many construction advantages which are not accounted here in costing. Moreover, if the present PPCC is modified and re-designed to possess same strength as that of GPC at 28 day, the cost of PPCC would be higher than the present estimate thereby reducing the difference between the costs of the two concretes.

However, if 28 day strength is taken as criterion, the energy required to produce one MPa of concrete strength is about 18 MJ/m$^3$ only which is 53% less than required for PPCC. Similarly, the CO$_2$ emitted to produce one MPa of strength is about 1 kg/m$^3$ only which is 79% less than that of PPCC (Table 4b, Fig. 4). Thus, the GPC is ecologically superior to PPCC from consideration of energy required for strength also. It may be concluded here that the GPC is always advantageous ecologically as compared to PPCC.

Ecological analysis of concretes presented in this paper can be taken as only indicative in nature and actual computations needs to consider many parameters such as transportation costs, etc. It is worthwhile to note here that geopolymer being a relatively new binder, it becomes a necessity for engineers to study the literature published by eminent scientists before adopting the same in any practical application.

Conclusions
The following conclusions can be drawn from the study presented in this paper:

(i) It was seen that the geopolymer concrete (GPC) mix could be produced easily using equipment similar to those available for conventional cement concretes. GGBS, when used as geopolymer source material, produced geopolymer binder due to addition of sodium hydroxide-silicate based activator solution. The geopolymers formed in the reactions produced high grade structural concretes by self-curing mechanisms only. The strength level achieved are much more than the minimum grade specified for “extreme” exposure condition of IS 456-2000.

(ii) The GPC is found to be more acid resistant, since the specimens even after 90 days of immersion in both 2% and 10% sulphuric acid solutions, remained almost intact. In contrast, the Portland pozzolana cement (PPC) based PPCC specimens had deteriorated with very obvious external damaged surfaces accompanied by noticeable bulging. It may be recognised here that PPCC mix has both pozzolanic fly ash and Portland cement as binder and this concrete is reported to the better than OPC based concretes. Therefore, GPC could be considered as superior to both OPC and PPC concretes from the durability as well as strength considerations.

(iii) The industrial by-product of GGBS based GPC of the present study, was found to possess much higher acid resistance when measured in terms of loss of weight and reduction in compressive strength on acid attack, as compared to PPCC. The test data presented in this paper confirms that the GPC is a good candidate material of constructions from both strength and durability considerations. It is to be noted here that the 1 day strength of 30 MPa recorded in GPC here is actually indicative of GPC being a high early strength concrete since this strength level is generally very difficult to achieve in Portland cement based conventional concretes. The rate of strength development of GPC is also higher since the ratio of 1 day strength to 28 day strength and also the ratio of 7day strength to 28 day strength are both much higher.
higher than those observed for PPCCs. Thus, it is seen that the GPC offers many advantages in actual constructions also.

(iv) Since the GPC does not have any Portland cement, it can be considered as less energy intensive (i.e., low ‘embodied energy’), in contrast, Portland cement based concrete is very highly energy intensive material since Portland cement is one of the very high ‘embodied energy’ which is reported to be next only to aluminium and steel. Apart from less energy intensiveness (actually very low ‘embodied energy’), the GPC utilises the industrial by-product for producing the binding system in concrete, therefore, GPC should be considered as highly eco-friendly material of construction.

Acknowledgements

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