Performance of self-compacting geopolymer concrete containing different mineral admixtures

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Received 14 August 2014; accepted 2 January 2015

Self-compacting geopolymer concrete is an innovative concrete that does not require vibration for placing and compaction. It is able to flow under its own weight, completely filling formwork and achieving full compaction, even in the presence of congested reinforcement. In this paper fly ash was replaced by different mineral admixtures, which reduces the cost of self compacting geopolymer concrete especially if the mineral admixtures are waste or industrial by-product. This paper presents an experimental investigation on strength aspects like compressive, flexural and split tensile strength of self-compacting geopolymer concrete containing different mineral admixtures and workability tests for different mineral admixtures (slump, L-box, U-box and T50) are carried out. The methodology adopted is that mineral admixtures GGBFS and silica fume are replaced by 10%, 20%, 30% and 5%, 10% and 15% respectively for fly ash and performance is measured and compared. The influence of mineral admixtures on the workability, compressive strength, splitting tensile strength and flexural strength of self-compacting concrete is investigated. It is observed that when mineral admixtures used in self-compacting geopolymer concrete, only 6% of super-plasticizer necessary to achieve a given fluidity. From this view point, a cost effective self-compacting concrete design can be obtained.

Keywords: Self-compacting geopolymer concrete, Fly ash, Silica fume, Ground granulated blast furnace slag

Self-compacting concrete is a complex system that is usually proportioned with one or more additions and one or more chemical admixtures. A key factor for a successful formulation is a clear understanding of the role of the various constituents in the mix and their effects on the fresh and hardened properties. Successful self-compacting concrete must have high fluidity (for flow under self-weight), high segregation resistance (to maintain uniformity during flow) and sufficient passing ability so that it can flow through and around reinforcement without blocking or segregating. The longer curing time improves the geopolymerisation process resulting in higher compressive strength. Increase in compressive strength was observed with increase in curing time. The compressive strength was highest when the specimens were cured for a period of 96 h however; the increase in strength after 48 h was not significant. Compressive strength of concrete increased with the increase in curing temperature from 60°C to 70°C however an increase in the curing temperature beyond 70°C decreased the compressive strength of self-compacting geopolymer concrete. One alternative to reduce the cost of self-compacting concrete is the use of additions. Due to the better engineering and performance properties, additions such as silica fume, fly ash, and ground granulated blast-furnace slag are normally included in the production of high-strength and high-performance concrete. The most often used fillers increasing viscosity of self-compacting concrete mixtures are fly ash, glass filler, limestone powder, silica fume and quartzite filler. More recently, environmental arguments began to prevail, in particular the need to decrease the overall CO2 production related to the use of cement in concrete.

Fly ash, ground granulated blast furnace slag and silica fume were the most frequently applied in self-compacting concrete. The incorporation of mineral admixtures also eliminates the need for viscosity-enhancing chemical admixtures. The lower water content of the concrete leads to higher durability, in addition to better mechanical integrity of the structure. It is also known that some mineral admixtures may improve rheological properties and reduce thermally-induced cracking of concrete due to the reduction in the overall heat of hydration and
increase the workability and long-term properties of concrete. One of the most important differences between self-compacting concrete and conventional concrete is the incorporation of mineral admixture. Since cement is one of the most expensive components of concrete, reducing the cement content is one of the economical solutions. Besides these economical benefits, the use of by products or waste materials reduces environmental pollution.

The influence of different superplasticizer dosage on compressive strength and micro-structure characteristics of interfacial transition zone (ITZ) prepared with fly ash based self-compacting geopolymer concrete (SCGC). The correlations between compressive strength development and microstructure of interfacial transition zone were also investigated. Concrete specimens were prepared with different superplasticizer (SP) dosage namely 3%, 4%, 5%, 6% and 7% and cured at 70°C for duration of 48 h. Field emission scanning electron microscope (FESEM) observations revealed that improved performance of concrete was found when the compressive strength increased through formation of dense ITZ between the aggregate and binder matrix at higher SP dosage. There are good correlations between compressive strength and micro-structure characteristics of interfacial transition zone. The FESEM analysis revealed that relatively a loose and porous interfacial zone was found between the binder and aggregate for low SP dosage and theses loose and porous ITZ decreased the performance of concrete by lowering the compressive strength; however, a dense ITZ was found between the aggregate and binder matrix for higher SP dosage that enhanced the concrete performance by increasing the compressive strength. Geopolymer is a novel engineering binder with lower environmental impacts (CO₂ emission, embodied energy and global warming potential) than ordinary Portland cement (OPC). Geopolymers can be synthesized from mixing high alkaline activators by industrial by-products such as fly ash and slag as the aluminosilicate source materials. Superplasticizers (SPs) are one of the common used admixtures added to conventional OPC concrete to improve its workability, rheology and mechanical properties. SPs are intended for use with OPC paste, mortar and concrete. The suppliers of SP do not intend them to be used in geopolymer mixes since SPs are attacked by alkaline solutions and degrade rapidly. However, some SPs can be used with geopolymer with limited effectiveness. This study presents a state of the art review of the effect of different SPs on slag and fly ash based geopolymers.

The use of optimum level of palm oil fuel ash (POFA), ground granulated blast furnace slag (GGBS) and low calcium fly ash (FA) with manufactured sand (M-sand) to produce geopolymer mortar. Eleven mixtures were prepared with varying binder contents with the POFA content varying between 25% and 100%; the other constituent materials such as fine aggregate and water were kept constant. All the specimens were cured in oven for 24 h at 65°C and thereafter kept in room temperature (about 26-29°C) before testing for the compressive strength. The highest compressive strength of about 66 MPa was achieved for the mortar containing 30% of POFA and 70% of GGBS with a total binder content of 460 kg/m³. The increase in the POFA content beyond 30% reduces the compressive strength. The density reduction after 3 days was found negligible. The influence of high-calcium fly ash (HCFA) on selected properties of fresh and hardened self-compacting concrete and high performance self-compacting concrete. HCFA was used as an additive for concrete (up to 30%) or as a main constituent in cement. Studies have confirmed the possibility of HCFA use in self-compacting concrete, while maintaining the assumed workability of fresh concrete and compressive strength of hardened concrete. HCFA should be processed by grinding, and its amount in the mixture should not be higher than 30% of the cement's mass. Cements that contain HCFA as the main component can be used in both normal and high performance self-compacting concrete. Studies have also confirmed the possibility of the use of high-ash, multi-component cements containing HCFA (CEM X – “CEM V/A (S-W)”) for the new generation of concrete.

In this study, it is aimed to investigate the effect of fly ash, silica fume, and ground granulated blast furnace slag as mineral admixtures on the fresh and hardened properties of self-compacting geopolymer concrete. Fresh concrete tests such as slump-flow, L-box, T₅₀₀, U-box and hardened concrete tests such as compressive strength, split tensile strength, flexural strength were conducted.

**Experimental Procedure**

**Materials**

Locally available river sand conforming to grading zone II of IS: 383-1970 was used and crushed stones...
of nominal size 12.5 mm conforming to IS 383-1970 was used. The specific gravity of coarse aggregate was 2.77. The maximum size of the coarse aggregate was restricted to avoid the blocking effect in self-compacting concrete. The amount of coarse aggregates in self-compacting concrete mixtures is much lower than in traditional vibrated concrete. On the other hand, they contain a high amount of fine fillers and/or additives to increase the viscosity. In this way, the stability of the mix is maintained, bleeding is reduced, and separation of coarser aggregates is avoided. The specific gravity of sand was 2.65. Besides this the byproducts, flyash was obtained from Salem Thermal Power Plant, India, silica fume from Meridian Science and Technologies, ground granulated blast furnace slag from Agni Steel Plant, Erode, Tamilnadu, India. In general, the approach of minimizing free water content to enhance stability can result in self-compacting concrete mixtures with a low yield stress and moderate-to-high viscosity levels. The low water content requires a relatively high dosage of high range water reducers to obtain the required deformability especially with the lower binder contents. A new generation based polycarboxylic ether was used. In terms of effectiveness polycarboxylic ether is higher compared to other bases and it also works at low dosages than other types of superplasticizers. The pH of superplasticizer was greater than 6. The characteristic properties and mineralogical composition of these three mineral admixtures are given in Table 1.

Mix proportions
The mix design in the case of self-compacting geopolymer concrete is inverse to that of conventional concrete. The design is made by the help of EFNARC guidelines. For this study, proportions of water and solids for various molarities like 8M, 10M, 12M and 14M are taken. The water to geopolymer solids (W/G’s) ratio by mass for all the mixes was maintained at 0.33 and the total powder content was fixed at 450 kg/m³. To obtain the required workability characteristics of SCGC, a water content of 12% and superplasticizer dosage of 6% by mass for the binder were used. Based on the above discussions mix proportions have been arrived for Fresh SCGC as shown in Table 2.

Seven mixes with different replacements of mineral admixtures were prepared and examined to quantify the properties of self-compacting geopolymer concrete. Table 3 presents the composition of self-compacting geopolymer concrete mixtures. The mineral admixtures GGBFS and silica fume are replaced by 10%, 20%, 30% and 5%, 10%, 15%, respectively for fly ash by mass. The water/geopolymer solids mass ratio (w/G) was selected as 0.33. Many different test methods have been developed in attempts to characterize the properties of self-compacting concrete. So far no single method or combination of methods has achieved universal approval and most of them have their adherents. Similarly no single method has been found which characterizes all the relevant workability aspects so each mix design should be tested by more than one test method in order to obtain different workability parameters. The total powder content was varied as 400 kg/m³, 450 kg/m³, 500 kg/m³ as iterative values and finally is fixed as 450 kg/m³. A polycarboxylate-based high range water reducing admixture was used along with these mixes, apart from the control mix. Some design guidelines have been prepared from the acceptable test methods. The workability related fresh properties for molarity of 8M, 10M, 12M, and 14M of SCGC were assessed through slump flow, T₅₀cm, Slump flow, V-funnel, L-box and U-Box test methods. Based on the results taken from workability tests the optimized molarity is chosen for SCGC.

Example molarity calculation
The solids must be dissolved in water to make a solution with the required concentration. The concentration of sodium hydroxide solution can vary in different molar. The mass of NaOH solids in a solution varies depending on the concentration of the solution. For instance, NaOH solution with a concentration of 12 molar consist of 12×40 = 480 g of NaOH solids per litre of water, were 40 is the molecular weight of NaOH. It may be noted that the mass of water is the major component in both the alkaline solutions. The mass of NaOH solids was
used for the determination of split tensile strength. Cylindrical moulds of size 150 mm × 300 mm were cube moulds of 150 mm × 150 mm × 150 mm, while Casting, curing and testing box tests were performed for this purpose.

Casting, curing and testing

For characterizing SCC. Slump flow, V-funnel, and L-box tests were done to study the workability of self-compacting concrete in terms of mean spread diameter. The minimum value of self compacting geopolymer concrete to be 650 mm and a maximum of 800 mm for a fresh self-compacting concrete. During the slump flow test, the time required to reach 50 cm diameter of slump flow is measured (T_{50}). The slump-flow test (Fig. 1) test is used to determine the filling ability of the concrete. The time taken for the concrete to flow down is noted in seconds. The slump-flow test judges the capability of concrete to deform under its own weight against the friction of the surface with no external restraint present. Because of the viscous nature of some self-compacting concrete mixtures, the slump-flow measurements were carried out. At the same time, the slump-flow time (T_{50}) was measured when the concrete was slumping until it reached 50 cm of flow. The V-funnel and L-box tests were performed according to the procedure given by European Federation Committee.

The maximum time that can be taken by a self-compacting geopolymer concrete mix in V-funnel is measured as 361 g/kg of NaOH solution with a concentration of 12 molar.

Alkaline liquid

Generally alkaline liquids are prepared by mixing of sodium hydroxide solution and sodium silicate at the room temperature. When the solutions mixed together the both solution start to react with each other there polymerization process take place. It liberate large amount of heat so it is recommended to leave it for about 20 min thus the alkaline liquid is ready as binding agent.

Preparation of fresh SCGC

For the production of fresh SCGC, fine powdered materials (i.e., fly ash, and fine aggregate) were firstly placed in a pan mixer and blended manually. Afterwards, the coarse aggregate in saturated surface dry condition was added to the mixer and mixed mechanically for about 2.5 min. At the end of this dry mixing, a well-shacked premixed liquid mixture, containing alkaline solution, superplasticizer, and extra water, was added in the mixer. This duration was not less than 3 min. The freshly prepared concrete mix was then assessed for the essential workability tests required for characterizing SCC. Slump flow, V-funnel, and L-box tests were performed for this purpose.

Casting, curing and testing

Compressive strength studies were carried out on cube moulds of 150 mm × 150 mm × 150 mm, while cylindrical moulds of size 150 mm × 300 mm were used for the determination of split tensile strength.

### Table 2 – Mix proportions for fresh SCGC

<table>
<thead>
<tr>
<th>Mix</th>
<th>Fly ash (kg/m³)</th>
<th>FA (kg/m³)</th>
<th>CA (kg/m³)</th>
<th>NaOH(kg/m³)</th>
<th>Na₂SO₃(kg/m³)</th>
<th>W/G</th>
<th>SP</th>
<th>Extra water</th>
</tr>
</thead>
<tbody>
<tr>
<td>8M</td>
<td>450</td>
<td>850</td>
<td>1000</td>
<td>57</td>
<td>143</td>
<td>0.33</td>
<td>6%</td>
<td>12%</td>
</tr>
<tr>
<td>10M</td>
<td>450</td>
<td>850</td>
<td>1000</td>
<td>57</td>
<td>143</td>
<td>0.33</td>
<td>6%</td>
<td>12%</td>
</tr>
<tr>
<td>12M</td>
<td>450</td>
<td>850</td>
<td>1000</td>
<td>57</td>
<td>143</td>
<td>0.33</td>
<td>6%</td>
<td>12%</td>
</tr>
<tr>
<td>14M</td>
<td>450</td>
<td>850</td>
<td>1000</td>
<td>57</td>
<td>143</td>
<td>0.33</td>
<td>6%</td>
<td>12%</td>
</tr>
</tbody>
</table>

### Table 3 – Mixture proportions for self-compacting geopolymer concrete (kg/m³)

<table>
<thead>
<tr>
<th>Mix proportion</th>
<th>Fly ash (kg/m³)</th>
<th>Silica Fume (kg/m³)</th>
<th>GGBFS (kg/m³)</th>
<th>FA (kg/m³)</th>
<th>CA (kg/m³)</th>
<th>NaOH (kg/m³)</th>
<th>Na₂SO₃ (kg/m³)</th>
<th>W/G</th>
<th>SP</th>
<th>Extra water</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1 (0% GGBFS &amp;SF)</td>
<td>450</td>
<td>-</td>
<td>0</td>
<td>850</td>
<td>1000</td>
<td>57</td>
<td>143</td>
<td>0.33</td>
<td>6%</td>
<td>12%</td>
</tr>
<tr>
<td>M2 (10% GGBFS)</td>
<td>405</td>
<td>-</td>
<td>45</td>
<td>850</td>
<td>1000</td>
<td>57</td>
<td>143</td>
<td>0.33</td>
<td>6%</td>
<td>12%</td>
</tr>
<tr>
<td>M3 (20% GGBFS)</td>
<td>360</td>
<td>-</td>
<td>90</td>
<td>850</td>
<td>1000</td>
<td>57</td>
<td>143</td>
<td>0.33</td>
<td>6%</td>
<td>12%</td>
</tr>
<tr>
<td>M4 (30% GGBFS)</td>
<td>270</td>
<td>-</td>
<td>135</td>
<td>850</td>
<td>1000</td>
<td>57</td>
<td>143</td>
<td>0.33</td>
<td>6%</td>
<td>12%</td>
</tr>
<tr>
<td>M5 (5% SF)</td>
<td>427.5</td>
<td>22.5</td>
<td>-</td>
<td>850</td>
<td>1000</td>
<td>57</td>
<td>143</td>
<td>0.33</td>
<td>6%</td>
<td>12%</td>
</tr>
<tr>
<td>M6 (10% SF)</td>
<td>405</td>
<td>45</td>
<td>-</td>
<td>850</td>
<td>1000</td>
<td>57</td>
<td>143</td>
<td>0.33</td>
<td>6%</td>
<td>12%</td>
</tr>
<tr>
<td>M7 (15% SF)</td>
<td>382.5</td>
<td>67.5</td>
<td>-</td>
<td>850</td>
<td>1000</td>
<td>57</td>
<td>143</td>
<td>0.33</td>
<td>6%</td>
<td>12%</td>
</tr>
</tbody>
</table>
In the L-box test, the test was started by removing the control gate at once to allow the flow of self-compacting concrete through the horizontal obstruction in the box and then the ratio of $h_2/h_1$ were determined, if the concrete flows freely as water, at rest it will be horizontal and therefore the ration will be equal to unity. The minimum acceptable value is to be 0.8. The U-box test method is used to measure the filling ability of self-compacting concrete. The height of the concrete in both the compartments is measured and this test gives a direct measurement of filling ability. The difference in height $h_1-h_2$ is the filling height. If the concrete flows freely as water, at rest it will be horizontal. The acceptable value of filling height is 30 mm maximum as suggested by European standards. The strength studies were carried out at both 7th and 28th day for these mix proportions. Figures 2-6 show the values of fresh properties of different molarities and Fig. 7 shows the compressive strength for various molarity. Based on these results molarity is fixed to 12 and self-compacting geopolymer concrete mix proportions are shown in Table 3. Tables 4-6 show the mechanical strength obtained for different mixes. Curing methodology used is ambient curing which was done for periods of 14 and 28 days. After casting, the specimens were kept in heat for 48 h then the specimens were kept in the ambient temperature till the test was conducted.

**Results and Discussion**

In this study, fresh and hardened properties of self-compacting geopolymer concrete were investigated by using waste materials (silica fume, and blast furnace slag) at different replacement rates for fly ash. The ability of such studies is done according to appropriate criteria given by European standards. In the present study, such properties of self-compacting concrete produced with fly ash, silica fume and blast furnace slag were investigated based
on fresh concrete tests, specifically workability tests, and strength studies.

**Fresh properties**

The slump flow values for self-compacting geopolymer concrete with fly ash, silica fume and blast furnace slag immediately after the mixing process are presented in Table 5. In terms of slump flow, all self-compacting concrete mixtures exhibited satisfactory slump flows in the range of 660–690 mm, which is an indication of good deformability. Higher replacement levels have shown better slump values which can be inferred from Table 5. Also it can be seen that blast furnace slag series have shown better slump. When fly ash is replaced by mineral admixtures, a lower dosage of superplasticizer 6% is required to maintain the flow. Fly ash series had more superplasticizer dosage to provide same slump flow than other mixtures and have shown good slump-flow values.

$T_{50}$ times as indicators of viscosity of highly flowable concrete mixes. Lower time indicates greater flowability. The $T_{50}$ was influenced by the dosage of water and super plasticizer. The volume of coarse aggregate, a good flow ability with increasing fly ash, silica fume and blast furnace slag content till 30% is observed, afterward flow time increases but with some bleeding and segregation. Good relationship exists between slump flow and $T_{50}$ for various mixtures of self-compacting geopolymer concrete which can be inferred from Figs 8 and 9. The root mean square value to be highly satisfied for all these relations.

V-funnel test was performed to assess the flowability and stability of the self-compacting concrete. For self-compacting concrete a flow time of 10 s is considered appropriate. The inverted cone shape restricts flow, and prolonged flow time may

<table>
<thead>
<tr>
<th>Test methods</th>
<th>Units</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slump flow</td>
<td>mm</td>
<td>650</td>
<td>800</td>
</tr>
<tr>
<td>$T_{50}$</td>
<td>s</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>L-box</td>
<td>$h_2/h_1$</td>
<td>0.8</td>
<td>1</td>
</tr>
<tr>
<td>V-funnel</td>
<td>s</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>U-box</td>
<td>$h_2-h_1$</td>
<td>0</td>
<td>30</td>
</tr>
</tbody>
</table>

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Fig. 3 – $T_{50cm}$ slump flow tests for various molarity

Fig. 4 – V-funnel tests for various molarity

Fig. 5 – L-box tests for various molarity

Fig. 6 – U-box tests for various molarity

Fig. 7 – Compressive strength for various molarity
giving some indication of the susceptibility of the mix to blocking. Hence, the value obtained from the experimental investigation is within the limit of European standards. The increase in coarse aggregate causes the increase in V-funnel time. L-box ratio indicates the filling and passing ability of each mixture. L-box test is more sensitive to blocking. There is a risk of blocking of the mixture when the L-box blocking ratio is below 0.8. The obtained L-box values are tabulated in Table 5. From Fig. 10, it is also found that the filling capacity was more than 80%.

If the concrete flows as freely as water, at rest it will be horizontal, so $H_2/H_1 = 1$. Therefore the nearer this test value, the ‘blocking ratio’, is to unity, the better the flow of the concrete. The effect of increase in the volume of coarse aggregate on the L-box test indicated a significant decrease of the blocking ratio. The U-type test was used to assess the self-compactability of concrete. If the concrete flows as free as water, at test it will be horizontal, so $H_1-H_2 = 0$. Therefore the nearer this test value, the filling height is to zero, better the flow and passing ability of the concrete. From the test result of self-compacting concrete mix the value obtained for the U-box test is within the limit of European standards.

**Mechanical properties**

The compressive, split and flexure studies at different ages are shown in the Tables 6-8.
compared to that of the control mixture with 100% fly ash increasing amounts of mineral admixtures generally increases the strength. Thus, it is clear that the roles of slag and silica fume act as mineral admixtures increasing the compressive strength of slag and silica fume series. But, the blast furnace slag series has shown the best performance both at 14 days and 28 days at 30% replacements. This is due to the physical nature of better packing and fineness of it\(^1\). Higher replacements of slag also have resulted in increase in strength. At the early stage, pozzolanic reactions of fly ash and silica fume were not sufficient to increase compressive strength. But at 28 days the slower pozzolanic reactions played a part in the silica fume mix. In the case of fly ash and blast furnace slag, filling of the voids between the larger particles, and increasing production of secondary hydrates by pozzolanic reactions with the lime resulting from the primary hydration enhances compressive strength\(^\)\(^2\).

**Conclusions**

The tests were performed to determine the fresh and mechanical properties of self-compacting geopolymer concrete mixtures and the following conclusions can be drawn from this study:

(i) All the self-compacting geopolymer concrete mixes had a satisfactory performance in the fresh state. Among the mineral admixtures considered, the blast furnace slag series had a good workability properties compared to silica fume series.

(ii) In general the use of mineral admixtures improved the performance of self-compacting concrete in fresh state and also avoided the use of viscosity modifying admixtures.

(iii) The results of the mechanical properties (compressive, split and flexure) had shown significant performance differences and the higher compressive strength has been obtained for slag series. Also the increase in replacement levels has resulted in decrease in strength in silica fume series. So 30% replacement of slag levels could be of optimum consideration for both flowability as well mechanical properties.

(iv) The evaluation of the mixes indicates the more critical changes in self-compacting concrete occur when there is an excess mineral admixture, less fly ash, excess superplasticizer, and excess sand, excess coarse aggregate.

(v) The most critical test for evaluating the self-compacting concrete loss seems to be slump flow; i.e, robustness is assured if the parameters of these tests are satisfied.

(vi) Optimum water/powder ratio was chosen as 0.33 by weight, the ratio greatly beyond or less than this may cause segregation and blocking tendency in self-compacting geopolymer concrete mixtures.

**References**


**Fig 9** – Relationship between slump flow (mm) and T\(_{50}\) (s) for GGBFS

**Fig. 10** – L-box ratio (\(h_2/h_1\)) versus slump flow (mm)