Rheological and mechanical characterization of self-compacting concrete with utilization of supplementary sustainable cementitious materials

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Abstract. Self-Compacting Concrete (SCC) being a sustainable high-performance concrete capable of flowing through congested reinforcement and can fill the shuttering without any external energy. The investigation focuses on the effect of waste materials generated from industries on the fresh and mechanical properties of SCC. Experiments were carried out to develop SCC by using Fly Ash (FA) and Ground Granulated Blast Furnace Slag (GGBFS) as Supplementary Cementitious Material (SCM). Light weight Perlite Aggregates (PA) were used as a partial replacement material in M-Sand. Workability tests were conducted to check the rheological properties of developed SCC mix in accordance with the European Federation of National Associations Representing for Concrete (EFNARC) guidelines. An optimal mix was developed satisfying the criteria as per EFNARC. The developed mix design exhibited a significant reduction in cement content. Ordinary Portland Cement (OPC) was replaced with 31% of FA and GGBFS is kept constant at 31%. The specimens were cured in water under ambient temperature. Performance of the developed mix in terms of compressive strength at different ages of 7, 28, 56 and 90 days were also examined. The results showed that SCC developed with industrial wastes provide adequate workability and strength with a substantial reduction in the cement content. Hence, the developed SCC with FA and GGBFS along with PA can be used as a sustainable concrete due to its high strength for the infrastructure development.

Keywords: Self-compacting concrete, Perlite aggregate, Sustainable, Chemical admixture, Workability, EFNARC

1. Introduction
The application of disaster resilient solutions into the construction industry has been a new step by introducing more sustainable materials in the current scenario, where waste materials are utilized to reduced cement quantity. SCC being one of the major advancement in construction technology which imparts a pace in construction, reduction in manpower, ease in placing, compaction and finishing, improved durability and strength capacity. The composition of SCC is very much comparable to normal concrete but in order to achieve the self-compaction, admixtures are being used. Here waste materials or industrial by-products have been used for the production of SCC thereby making the concrete a green product and the selection of admixtures as a disaster resilient material to play a vital
role during adverse situations. Many of the researches has been conducted on development and testing of concrete to improve the behaviour, starting from typical development to advanced level enhancements. Vijaya et al [1] conducted an experimental research on the on fresh properties of waste plastic fibre reinforced SCC. The concrete mixes with varying percentage of waste plastic fibre were developed based on the NANSU (Nan-Su method of mix design) method. The results of fresh property tests are compared with the acceptance criteria of EFNARC guidelines. Alyousef et al [2] evaluated the workability behaviour of the Marble Sludge Grout (MSG) as a function of the added water content. The gassing of SCC with MSG with variable water/sludge ratios was done. The results have shown that the marble particles of grout is totally dissolved when the water/sludge ratio was equal to 1:2.5. And it also shows that the gassing with MSG allows to obtain SCC having both the properties of self-compaction and self-levelling. Ramezanianpour et al [3] carried out an experimental study on fresh and hardened properties of SCCs by replacing the cement and aggregates with volcanic pumice (VP) as natural pozzolans. SCC mixes containing silica fume (SF) and vibrated concrete (VC) mixture the results proved that, natural pozzolans have enhanced the mechanical properties and durability of SCC and reduced the chloride penetration, significantly. Uysal [4] presented the benefits of using limestone, basalt and marble powder as partial replacement of cement in order to develop self-flowing concrete. The w/p ratio was fixed as 0.33 for all mixes. The fresh concrete properties are determined according to EFNARC guidelines. The results showed that the inclusion of waste mineral admixtures improved the consistency of SCC as well as produced economical mix. Sukumar et al [5] developed SCC by replacing the powder with high volume FA based on conventional design. For gaining the strength at early ages compared to concrete of same grades suitable relations were established to determine the compressive strength and the tensile strength for different mixes of SCC. The results shown that the rate of gain in strength for different mixes of SCC was slightly higher than the strength of vibrated concrete of the same grades. The possible outcome is to alter the construction sector to move towards the sustainability concept and substituting additives such as mineral admixtures and light weight mineral aggregates in concrete. The study of "eco-efficient", "green" or "sustainable" concrete has greater importance. The current study aims at emphasis the possibility to produce sustainable SCC with green materials and to evaluate its fresh and hardened properties.

2. Research Significance

SCC has many benefits but its extensive use remains limited due to the lack of development of appropriate guidelines. This problem can be solved by conducting more tests on the SCC. This experimental work aims to promote the development of sustainable SCC, by incorporating waste materials. Also to chase its fresh concrete mix properties to confirm the flow ability and to attain the required strength.

The use of FA and GGBFS with PA in production of concrete addresses the problem of disaster resilient solution and sustainability. Firstly, the use of PA which is having enhanced properties under worst thermal condition would improve the thermal properties of the concrete mix. Secondly, the reuse of waste material reduces pollution in the environment. Although concrete mixes containing several waste materials have been significantly studied throughout the previous literatures, development of SCC mix with FA and GGBFS utilizing PA have not been explored. It is a disaster resilient and sustainable practice which is essential for the current construction practices. Therefore an extensive investigation have been carried out for the proper understanding of properties of concrete mixes with FA and GGBFS utilizing PA which will be the alternate to conventional concrete. This study helps to provide adequate understandings so as to assist the inclusion of PA for the development of SCC into the construction industry.
3. Experimental study
The experimental investigation is divided into two phases viz. Phase I: Mix design for SCC with Manufactured Sand (M-Sand), FA and GGBFS (replacement materials for cement), and PA (replacement material for M-Sand). Phase II: Fresh and Mechanical concrete properties were tested for conforming the adequacy of replacement materials in the proposed SCC mix. The present study is based on the IS 10262 (2009) guidelines, which is used to design the mix of SCC, also the test properties has been compared as per the EFNARC guidelines and IS 516 (1959).

4. Materials

4.1 Cement, Fly Ash, Ground Granulated Blast Furnace Slag
In this investigation, OPC was used in accordance with IS 12269 (2013). The various properties of OPC such as normal consistency (as per IS 4031-IV (1988)), initial and final setting time (as per IS 4031-V (1988)), compressive strength (as per IS 4031 (1988)) were determined as per relevant standards. The cement used for the experimental investigation was of 53 grade and purchased from single source. The physical and chemical properties are given in Table 1 and Table 2 respectively. One of the main cause for the environmental pollution is waste materials generated from coal and steel industry such as FA and GGBFS. Figure 1(a) and 1(b) shows the FA and GGBFS used in this study. The mechanical properties of the concrete can be enhanced with the use of FA and GGBFS as a partial replacement of cement. Class-F FA complying with specific standards is used for the present study. GGBFS an important by-product from the furnaces that used to make iron or steel. It can be used as SCM which delays setting time and the gain in strength will be at a slower pace however the overall strength development will be higher. The chemical and physical properties of FA and GGBFS are mentioned in Table 2.

![Figure 1](image_url)

Figure 1. Materials used (a) Fly ash and Figure 1(b) GGBFS
### Table 1. Physical properties of 53 grade OPC

| Property                        | Minimum Requirements as per IS 12269-2013 Code |
|---------------------------------|-----------------------------------------------|
| Fineness (m²/kg)                | Not less than 225                             |
| Density (kg/m³)                 | -                                             |
| Consistency (%)                 | -                                             |
| Initial Setting Time (min)      | Not less than 30                              |
| Final Setting Time (min)        | Not more than 600                             |
| Specific Gravity                | 3.15                                          |
| Compressive strength (MPa)      |                                               |
| 3 days                          | Not less than 27                              |
| 7 days                          | Not less than 37                              |
| 28 days                         | Not less than 53                              |
| Colour                          | Pale Grey                                     |

### Table 2. Chemical components of OPC, FA and GGBFS

| Mineral Admixture (%) | OPC   | FA   | GGBFS |
|-----------------------|-------|------|-------|
| SiO₂                  | 18.78 | 58.50| 37.73 |
| Fe₂O₃                 | 3.40  | 3.45 | 1.11  |
| Al₂O₃                 | 8.75  | 28.25| 14.42 |
| CaO                   | 61.33 | 2.25 | 37.34 |
| MgO                   | 2.25  | 0.30 | 8.71  |
| Na₂O                  | 0.85  | 0.56 | -     |
| K₂O                   | 2.20  | 1.26 | -     |
| TiO₂                  | 0.25  | 995  | -     |

### 4.2 Aggregates

Crushed angular stone is used as coarse aggregate. The maximum grain size of aggregate used in the mix is 12.5 mm. The aggregates were used in saturated surface dry condition (SSD). The basic tests are conducted based on IS 383 (2016). The properties of coarse aggregate are mentioned in Table 3. The fine aggregate used for the investigation is M-Sand in accordance with IS 383 (2016). The specific gravity of M-Sand is calculated as 2.68 as per IS 2386 (1963). The aggregate is conforming to grading Zone II complying with the sieve analysis. The fine aggregate has more importance in the design of SCC mix, which affects the flow of concrete. The physical properties are mentioned in Table 3. Figure 2 demonstrates the distribution of particle size of fine and coarse aggregate.

### Table 3. Physical properties of coarse and fine aggregates

| Coarse Aggregate | Fine Aggregate |
|------------------|----------------|
| Type             | Crushed        | Type             | M-Sand         |
| Specific gravity | 2.66           | Specific gravity | 2.68           |
| Bulk Density     | 1560           | Bulk density(kg/m³) | 1788           |
| Size of aggregate (mm) | 10               | Fineness modulus | 2.91            |
4.3 Water
Potable water is the key content which is used for casting and curing of specimens which satisfies the requirements of IS 456 (2000).

4.4 Perlite Aggregate
PA used as a partial replacement of fine aggregate. As per ASTM C 332 (1999), the sieve analysis of perlite is confirmed. The composition and properties of perlite is given in Table 4. PA utilized for the investigation is shown in Figure 3.

![Figure 3. Light Weight Perlite Aggregate](image)

**Table 4. Physical properties of perlite aggregate**

| Physical properties | Chemical composition |
|---------------------|----------------------|
| Form & Colour       | Coarse &v White      | Silica (SiO₂) % | 72-76% |
| Bulk density(kg/m³) | 70                   | Alumina (Al₂O₃) % | 11-16% |
| Particle Size       | 90% between 3.00mm to 0.6mm | Potassium (K₂O) % | 2-5% |
| Hardness            | 5.5                  | Sodium (Na₂O) %  | 1.5% |
| pH                  | Neutral              | Calcium (CaO) %  | 0.6-2.4% |
| Free moisture       | 0.5% Max             | Ferric (Fe₂O₃)%  | 0.6-1.4% |
4.5 Chemical Admixture
Superplasticizer used for the development of SCC mix is based on Poly-Carboxylate Ether (PCE) in lieu with IS 9103 (1979). The properties are mentioned in Table 5.

| Description                        | Properties         |
|------------------------------------|--------------------|
| Form & Colour                      | Liquid & Yellow    |
| Volumetric mass @ 200°C            | 1.05 kg/litre      |
| pH                                 | Minimum 6.0        |
| Alkali content (gms)               | 1.5                |

5. Test methods

5.1 SCC Mix Design
Mix design procedure followed as per the guidelines presented in IS 10262 (2009) for the present investigation. Using the EFNARC (2005) guidelines self-compatibility is achieved by adjusting the mix proportion of the normal concrete. Cement is replaced using FA and GGBFS to make the concrete mix greener. The flow and mass transport properties of concrete such as capability of filling, passing and resistance segregation were tested with the slump flow, J-ring and V-funnel tests and found to be within the recommended limits. The methodology followed for the investigation is shown in Figure 4.
5.2 Properties of fresh SCC
The guidelines and acceptance criteria’s recommended in EFNARC (EFNARC 2002 & 2005) are used for the assessment of rheological characteristics of the designed mix. By using this guidelines, it is possible to determine the filling capability, passing capability and segregation resistance. The slump flow test, T500, J-ring test, V-funnel were conducted. The diameter of the slump flow and time taken to reach 500mm (T500) is noted. The diameter and the ring height difference is measured from J-ring test. The V-funnel test is used to determine the flow capacity of the concrete. The flow time at T3 minutes is found to check the segregation of concrete. The test set up details are shown in Figure 5(a) to 5(d).

5.2.1 Properties of Fresh SCC. The permissible limits as per EFNARC (2005) guidelines for workability tests on fresh SCC are detailed in Table 6. Comparing Table 6 and Table 7 it can be concluded that the developed SCC mix is satisfying the workability criteria as per the guidelines.

| Test                  | Flow Property          | Permissible Range |
|-----------------------|------------------------|-------------------|
|                       |                        | Min   | Max   |
| Slump flow (mm)       | Filling                | 650   | 800   |
| T500 mm Slump flow (sec) | Filling                | 2     | 5     |
| J-Ring (mm)           | Passing                | 0     | 10    |
| V-Funnel sec)         | Filling                | 8     | 12    |
| V-Funnel at T3 min (sec) | Resistance against segregation | 0     | +3    |

Figure 5(a)-5(d). Workability test set up

5.3 Mechanical Properties
Compressive strength test was carried out on 150 x 150 x 150 mm cube specimen at 7, 28, 56 and 90 days respectively on a compression testing machine of capacity 2000 kN. Triplicate samples were tested for each age and the strength values are considered as per IS 516 (1959).

6. Experimental Results

6.1 Fresh Properties of SCC
The trial mixes were developed to check workability characters as per EFNARC (2005) guidelines. The self-consolidating property was achieved by adjusting the cement-powder ratio and water-powder ratio along with superplasticizer. The result obtained are given in Table 7. Figure 6 illustrates the different workability tests conducted to investigate the fresh concrete properties of SCC incorporating varying content of FA and GGBFS along with light weight PA. The result indicates that the light weight content has a positive effect on the rheological properties of developed mix. The shape and size of the PA having uniform spherical edges is the fluidity enhancing factor which affects the consistency
of concrete. The PA require less effort to overrule their frictional resistance to enhance the fluidity. The diameter of concrete spread varied between 660 to 680 mm, which satisfied the acceptance criteria for workability tests for SCC mixes as per EFNARC guidelines. The slump flow showed its highest value for the mix with 31% of GGBFS replaced for cement and 2.5% PA replaced for M-Sand and least for the mix with zero replacement of PA. The corresponding $T_{500}$ time of the corresponding mix to reach the 500 mm diameter spread was noted. There is a decrease in flow time from 2.90 sec (control mix) to 2.73 sec (2.5% PA) in the SCC mix developed with FA and for SCC utilized with GGBFS 2.45 sec (control mix) to 2.20 sec (2.5% PA). It is also noted that the time taken to empty the V-Funnel is also similar to that of $T_{500}$ test. In order to investigate the passing ability of developed mix J-ring test was conducted. All the mixes showed satisfactory results in the test.

![Figure 6. Workability test for fresh SCC as per EFNARC guidelines](image)

**Table 7. Results of workability tests**

| Mix No. | Description of Mix                        | Slump Flow (mm) | $T_{500}$ Flow Time (sec) | J-Ring (mm) | V-Funnel (sec) | V-Funnel $T_5$ (sec) |
|---------|-------------------------------------------|-----------------|---------------------------|-------------|----------------|---------------------|
| 1       | 69%OPC+31%FA+100%MS+0%PA                 | 660             | 2.90                      | 7           | 10.80          | 12.50               |
| 2       | 69%OPC+31%FA+97.50%MS+2.5%PA             | 665             | 2.73                      | 6.56        | 10.37          | 12.85               |
| 3       | 69%OPC+31%GGBFS+100%MS+0%PA              | 675             | 2.45                      | 6.2         | 11.65          | 11.93               |
| 4       | 69%OPC+31%GGBFS+97.50%MS+2.5%PA          | 680             | 2.2                       | 5.96        | 11.27          | 11.85               |

6.2 **Design Mix Proportion**

The proportioning of the mixture is confirmed based on trial and error method taking into account of EFNARC guidelines. The study is carried out with two SCC mixes developed with FA and GGBFS as replacement of cement at constant level of 31% (144 kg/m$^3$) and PA of 2.5% (24 kg/m$^3$) is additionally utilized as a replacement of M-Sand in other two mixes as mentioned in Table 8. The cementitious content and water/powder ratio is kept constant as 464kg/m$^3$ (in which 320 kg/m$^3$ of OPC and 144 kg/m$^3$ of FA/GGBFS) and 0.42 respectively. Additional water is supplied to the mix in order to ensure the saturated surface dry condition. The ratio of fine aggregate to coarse aggregate is kept minimum to enhance the flow properties. In order to achieve the flow properties 0.8%-1% of superplasticizer and 0.1% of viscosity modifying agent is added, and the chemical admixtures added with respect to the weight of the powder content. The findings from the investigation is verified using the slump flow test, J-ring test and V-funnel tests. The performance of SCC is comparable and satisfies the requirements. Table 8 represents the optimized mix for the developed SCC.
Table 8. Optimized SCC mix in kg/m$^3$

| Mix No. | OPC (kg/m$^3$) | FA (kg/m$^3$) | GGBFS (kg/m$^3$) | M-Sand (kg/m$^3$) | PA (kg/m$^3$) | Coarse Aggregate | Water (kg/m$^3$) | SP (%) |
|---------|----------------|---------------|------------------|-------------------|--------------|-----------------|-----------------|-------|
|         |                |               |                  |                   |              | 10 mm           | 12.5 mm         |       |
| 1       | 320            | 144           | -                | 963               | -            | 520             | 284             | 218   | 0.8  |
| 2       | 320            | 144           | -                | 939               | 24           | 520             | 284             | 218   | 0.9  |
| 3       | 320            | -             | 144              | 963               | -            | 520             | 284             | 218   | 0.9  |
| 4       | 320            | -             | 144              | 939               | 24           | 520             | 284             | 218   | 1    |

6.3 Compressive Strength

The compressive strength test results of all the developed SCC mixes that were tested at 7, 28, 56 and 90 days are presented in Figure 7. The control mixture with FA and GGBFS showed high compressive strength than the mix with 2.5% of PA. The strength reduction with light weight PA can be explained by relating it to the weak adhesion between light weight mineral aggregate to the cement paste due to the shape and size which will act as the weak link in the interfacial Transition Zone (ITZ) which may also affects the consistency of the mixture. The early age strength gain is at lower pace due to the incorporation of the mineral admixtures which delays the cement hydration process. Further, it is recorded that the rate of strength gain and the highest strength value is attained with the mix developed with GGBFS is because of the hydraulic cementitious nature of the mineral pozzolan. However, the varied superplasticizer content reduced the inclusion of high water demand resulting in the reduction in workability and strength parameters. The strength attained is highest in SCC mix developed with GGBFS, it was about 24.03 MPa for the specimen tested at 7 days and to 38.89 MPa for the specimen tested at 90 days. SCC mix developed with GGBFS and 2.5% PA exhibited marginal reduction in strength of about 11.53% as compared to the specimen without PA. The control SCC mix with FA also shown similar high strength like GGBFS utilized SCC mix than the mixes developed with 2.5% PA. The early age strength gain in GGBFS developed SCC mix is higher than FA developed SCC mix which is due to the hydraulic cementing nature of the slag.

Figure 7. Compressive strength of concrete at different age

7. Conclusions

The need for new techniques that introduce waste materials for the manufacture of concrete is essential to substantially reduce the vulnerable effect of wastes on environment and humanity. In this view, the investigation will provide an incentive to the sustainable and environmental friendly concrete production with green materials.
SCC mixes are developed utilizing FA and GGBFS along with PA. The proposed mix reduces the use of cement, that is minimum amount of cement is required for the development of SCC. Workability properties of the developed mix exhibits the EFNARC acceptance limits and the requirement of the superplasticizer was in the same range for both FA and GGBFS. Compressive strength is increased up to 25% for SCC mix with GGBFS instead of cement compared to FA developed SCC mix. The utilization of PA results marginal reduction in strength compared to the control mix due to the paste aggregate interaction in ITZ. The present investigation reveals the possibility of utilization of industrial wastes as SCM upholds the potential of satisfying the fresh and hardened properties with adequate use of superplasticizer, which is an efficient solution to reduce the cost of inventory and to achieve sustainability.

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