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Self-compacting geopolymer concrete: A review

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***Abstract*---**Self-compacting geopolymer concrete (SCGC) is a novel material and a modern high-performance concrete that doesn't require Ordinary Portland cement and additional compaction. SCGC is made up of industrial byproducts, with high Alumina and Silica composition, and uses super plasticizer as a binder for matrix formation and strength. This research examines SCGC, which is prepared with various percentages of Ground Granulated Blast Furnace Slag (GGBFS), Silica Fume (SF) and Metakaolin (MK), activated with various molarities of alkaline solution containing sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). Fresh and hardened characteristics along with microstructural studies are discussed. The beams are analysed using ANSYS software.

***Keywords*---**GGBFS, SF, MK, Fresh and Hardened Properties, Microstructure studies.

Introduction

To meet the growing demand of the construction industry, the usage of cement has expanded. Malhotra et al [1] stated that production of one ton of cement emitted equal amount of CO_2 into the atmosphere. Natural rock reserves are depleted as a result of the raw materials required in cement manufacture. The calcination of lime in cement production requires a temperature of 1500°C, thereby consuming lot of energy. As a result, an alternate binding substance is needed to lessen air pollution and land contamination. The use of cement concrete has expanded to meet the growing demand of the construction industry.

Contamination and loss of vital natural resources must be avoided for long-term growth. The word 'Geopolymer' was coined by Davidovits. J [2] to describe inorganic binders that created concrete without the need of cement, thus lowering

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CO_2 emissions and the energy necessary for calcinations. GGBFS, FA, SF and natural minerals such as MK are used as source materials in Geopolymer concrete, thereby decreasing land pollution and ensuring a sustainable environment.

Nematollahi and J. Sanjayan. [3] established that the quantity of alkaline activators and super plasticizers used in Geopolymer concrete influence its workability. A.A. Aliabdo, et al [4] discovered that adding more water enhances workability upto 200 percent while reducing other qualities by 27 percent. F.U.A. Shaikh et al [5] discovered that due to high viscosity, geo polymer concrete would fail due to lack of compaction.

SCGC (Self-compacting Geo polymer Concrete) is created to solve this problem. SCGC is a ground-breaking concrete that may be placed and compacted without the use of vibration. It may flow under its own weight even in the presence of clogged reinforcement, completely filling the form work and attaining full compaction.

Main Text

Constituents of Scgc

GGBFS

GGBFS is a cementitious substance obtained as a byproduct from blast furnace producing iron. GGBFS improves the resistance of concrete by preventing the damage caused by alkali-silica reaction, sulphates and chlorides, lowers the risk of thermal cracking and making the concrete more durable. Arun B.R. et al. [6] investigated that by increasing the percentage replacement of GGBFS to FA in SCGC enhanced the mechanical strength. Yamini J. et al. [7] discovered that the optimal amount of RHA replacement was 5% in their investigation on the mechanical characteristics of SCGC mixed with GGBFS and RHA. There was 2.81 percent decrease in slump flow value and 3.02 percent gain in compressive strength. Srishaila et al [8] studied that GGBFS gave greater compressive strength than FA in SCGC.

Karthik Swaroop Kumar et.al, [41] produced SCGC with FA, GGBFS and Alcofine with varied binder proportions of 80:10:10, 65:20:15, and 50:25:25. The proportion 65:20:15 gave the optimum mechanical strength and durability. NagarajV.K et.al, [45] examined the impact of FA and GGBFS on flow condition, mechanical strength, and durability attributes of SCGC. GGBFS (0, 25, 50, 75, and 100 percent) was used to replace FA. The findings showed that increasing the GGBFS content in the mix improved the compressive strength and durability. Good results were obtained for SCGC mix made with GGBFS of 75 percent and FA of 25 percent. This blend not only had higher compressive strength and durability, but it also worked well within the EFNARC criteria.

ElsaPaul [49] showed that concrete containing FA and GGBFS had greater compressive strength than concrete with FA, GGBFS and CS. As GGBFS has higher proportion of reactive slag particles than CS, more hydration products are created for FA and GGBFS mix to fill the porous structure.

Metakaolin

Metakaolin is a natural cementitious substance made from Kaolin clay that has been incinerated at temperatures ranging from 650 to 800 degrees Celsius. P. Duan, et.al, [9] found that using MK in concrete results in stronger interfacial transition zone in strength development than using other constituents. Guneyisi E, Gesoglu M [10] found that incorporating Metakaolin of 10-20% into SCGC resulted in improved mechanical characteristics. Mojdeh Mehrinejad Khotbehsara et.al, [39] tested Pumice and MK for their influence on the durability and microstructure of SCC. The microstructure of SCC was studied using images from a scanning electron microscope (SEM). Specimen with a dense micropores combining Pumice and Metakaolin was visible in SEM micrographs, indicating that these mixes were stronger. The results showed that a combination of Pumice of 10% and MK of 10% improved the strength of SCC.

According to Matthew Upshaw and C.S. Cai [40], replacement level of MK with SF enhances the strength, although extra CaO is only beneficial in particular applications. The activator-to-binder ratio, rather than the water-to-binder ratio, had significant impact on strength. It was determined that a geopolymer bond with adequate strength for use in concrete made from recycled materials may be created with some modification. Rahman Madandoust, S.Yasmin Mousair [51] investigated that the flowability and mechanical characteristics can be accomplished by substituting appropriate levels of MK in SCC. Hardened properties of SCC containing Metakaolin gave good outcomes than SCC containing only OPC. MK of 10% was considered a suitable replacement in terms of economic efficiency. Anhad Singh Gill, Rafat Siddique [53] studied that those mixes incorporating MK and RHA increased the compressive strength at all ages. A mix containing MK of 10% and RHA of 10% had the densest structure, resulting in maximum compressive strength.

Silica Fume (SF)

Silica Fume is a cementitious ultrafine powder collected as a residue obtained from the manufacturing of ferro-silicon alloy and silicon. T.G. Ushaa et al. [11] researched about the influence of mineral additives such as GGBFS and silica fume on the fresh and hardened characteristics of SCGC. The strength rose for silica fume replacement of 10%, and then it was reduced with a 15% replacement. N Shafiq, F.A Memon and M F.Nuruddin.[12] found that when low calcium fly ash based SCGC was largely replaced by silica fume, it generated high mechanical strength. Sanghamitra Jena, Ramakanta Panigrahi, and Pooja Salu [13] found that when silica fume of 5 percent was mixed with fly ash in SCGC, the workability and compressive strength were at their best.
Sanghamitra Jena et al [42] prepared GPC of 14M molarity with FA and SF. The addition of silica fume to a geopolymer concrete made of fly ash satisfied M_{40} grade of concrete at 28 days.

Super Plasticizer

In their Fly Ash-based SCGC study, Raijiiwala D.B et al [14] found that superplasticizer dosages up to 5 percentage did not match up to the flowability requirements. However super plasticizer dosages of 6 and 7 percentage enhanced flowability and passing ability according to EFNARC requirements. M. Fadhil Nuruddin, et al [15] found that SP dosage of 6% is ideal because 7% of SP had no meaningful contribution. Ramanathan.P [52] studied that the optimal dose of superplasticizer improved the flow property of concrete.The mineral additive requirements are based on size and shape of particles and surface morphology. By integrating suitable proportions of SF, FA and GGBFS, a cost efficient SCGC design can be created.

Alkaline Solution

Arun.B.R et al [16] on their investigation of SCGC with Fly Ash and Metakaolin, prepared alkaline solution by integrating 1 part of NaOH and 2.5 parts of Na_2SiO_3. Asraf Mohamed Henigal et al [17] investigated that by integrating 1 part of NaOH and 2.75 parts of Na2SiO3 achieved greater strength in compression. Fareed Ahmed Menon et al [18] investigated the impact of NaOH concentration on the flowability and mechanical characteristics of SCGC. He concluded that the concentration variation had least effect on fresh properties and samples with 12 M concentration had maximum compressive strength. In their preliminary investigations on SCGC utilising M Sand, C. Sasidhar et al [19] determined the flowability and strength in compression by altering the concentration of Sodium hydroxide from molarities ranging 8M to 12M and found that increasing the molar concentration of NaOH decreased the flowability characteristics while increasing the strength in compression of SCGC. Koran Salihi, Khaleel H. Younis [43] studied the flowing and passing abilities of SCGC mixtures containing coarse aggregates that are recycled. They conducted experiments with different molar concentrations and alkaline ratios and found that coarse aggregates that are recycled and used in SCGC satisfies EFNARC criterion.

Extra Water

Ashraf Mohamed Henigal et al [17] on their studies on properties of SCGC conducted tests by varying the extra water content by 12%, 14% and 16%. The fresh properties as per EFNARC guidelines were obtained for all mixtures. They showed good workability. R. Siddique et al [20] found that if extra water is used by more than 15 percent, it leads to segregation and bleeding. The strength in compression decreased with increase in water content by more than 12% by mass of binder. To attain the requisite flowability, Nuruddin et al [21] invented that super plasticizer, alkaline activator solution, and additional water should be pre-mixed before introducing to the mix in dry state.

Fine Aggregate

T.G. Ushaa, et al [11] investigated that mix with R-sand of 100% and M-sand of 0% had the least workability and mix with M-sand of 100% and R-sand of 0% had high workability. The sharp edges of the particles in M-sand provided better bond with geopolymer than the rounded particles of natural sand resulting in higher strength. T.G. Ushaa et al [50] studied the endurance of SCGC using various manufactured sand and river sand substitutions and concluded that the strength in compression with manufactured sand of 100 percent replacement and R-Sand of

0 percent replacement produced best results. The workability characteristics of SCGC steadily diminished as the percentage of river sand increased.

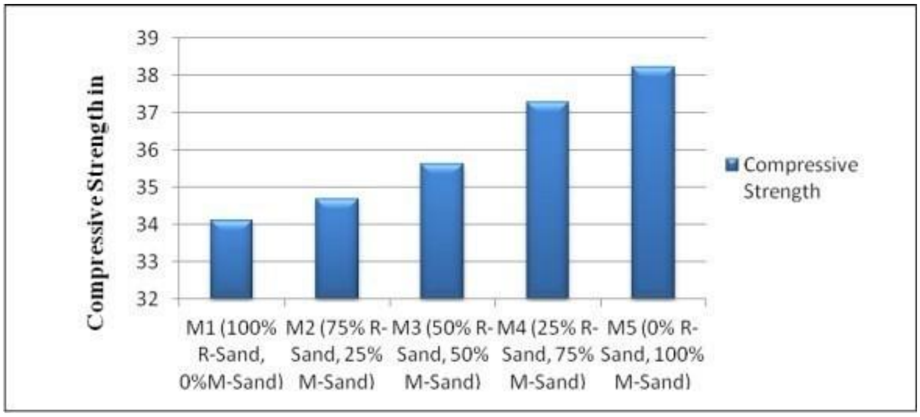


Fig. 1 Compressive strength for various replacement of R-Sand and M-Sand [50]

Coarse Aggregate

T.G. Ushaa et al [11] investigated that the coarse aggregates should be 10 mm down to achieve the required workability and self-compaction.

Mix Proportioning

Muhd Fadhil Nuruddin et al [21] calculated the mix proportions as per EFNARC guidelines. C.Sashidhar et al [19] formulated the mix calculations as per EFNARC guidelines

Casting and Curing

Kasireddy, Mallikarjuna Reddy, G Nagesh Kumar [23] explained the process of casting and curing. The components of SCGC were mixed in dry condition in the pan mixer for 2 minutes followed by 2 min of wet mixing using alkaline activator solution, SP and additional water. The prepared concrete was filled in moulds made of steel and allowed to compact by its own self weight. After casting the specimens were oven cured at 70ºC for 24 hours and then cured for 28 days at ambient temperature.

Palankar and Shankar [24] studied the effect of curing on strength in compression of SCGC and specified that oven curing method is better than room temperature curing method. Memon et al [12] investigated the influence of temperature for curing on the strength in compression of SCGC based on FA and found that the strength in compression increased as the temperature arises from 60° centigrade to 70° centigrade. The strength diminished as the temperature rose over 70° centigrade.

Yamini J. Patel and Niraj Shah [7] studied the influence of temperature setting on the strength in compression of SCGC blended with GGBFS and RHA and concluded that curing at seventy degrees centigrade produces greater strength than curing at room temperature.

Vijai et al. [46] found an increase in mechanical properties of geopolymer concrete at an ideal temperature of 60°C in the oven for 24 hours. In terms of early strength development, curing in oven was shown to be the most suited and effective way.

Heah et al [47] invented that room curing of GPC using MK yields incredibly weak mechanical properties when compared to steam curing. He offered temperature range of forty degree Celsius to hundred degree Celsius for quick enhancement of strength. However, setting at progressively greater temperatures for an extended length of time produces specimen degeneration due to thermo analysis of the sialate –Si–O–Al–O– link. Nuruddin et al.,[48] compared various methods of curing and found that heat curing was the best option to attain more strength, as shown in figure

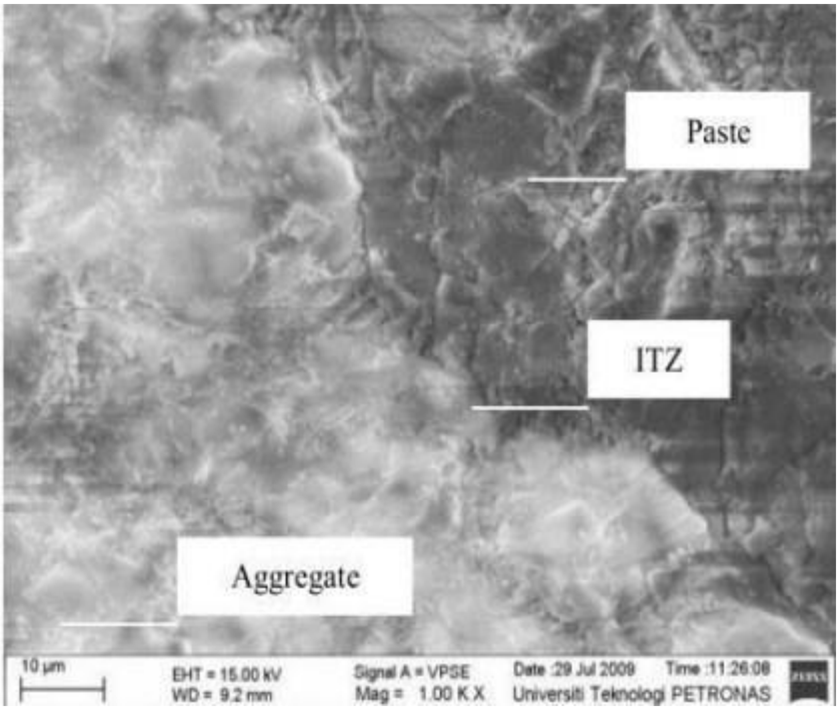


Fig. 2 SEM image for oven curing [48]

Fresh Properties

A freshly made mix was evaluated for workability to determine the characteristic of SCGC. Slump flow, T50cm Slump- flow, V Funnel, and L Box tests were obliged to comply with EFNARC guidelines [22].

Slump flow test

The Slump Flow Test is the most commonly used test to determine the lateral, unrestricted pouring of concrete. All mixes must have a slump value limited to European federation national association representing concrete within sixty-five to eighty centimeters [22].

T50cm- Slump flow test

The T50cm flow in slump measures the duration it takes to attain a diameter of 50 cm. The concrete's ability to bend under its inherent load against surface friction with no external restriction is measured by the slump flow test. According to EFNARC rules [22], the approval criteria are a minimum of 2 seconds and a maximum of 5 seconds.

V Funnel test

The V Funnel test is used to check whether the concrete can fill a confined vent. An upturned conical form slows concrete movement, and the prolonged duration interval shows blockage liability. Duration taken by the concrete to evacuate a V-Funnel box determines the viscosity of the concrete. According to EFNARC rules [22] the duration should be in the range of Six and Twelve seconds respectively.

L Box test

The L Box test assesses the capacity of fresh SCGC to pass through it. The fresh mix is permitted to flow down the vertical barrier and come out of the horizontal extremity of the container. The ratio of the elevation of concrete at the finish of the sloping portion to the elevation of concrete at the beginning of the sloping portion determines its ability to pass. According to EFNARC, acceptable L-Box result ranges from 0.8 to 1.0 [22]

a) V Funnel and L Box Test b) slump flow

Fig. 3 Test on workability [19]

For 8M molarity of NaOH, Nuruddin MF, Samuel D, and Shafiq N [21] reported a slump value of 690 mm. The flow in slump value reduced from sixty-nine to sixty-seven centimeter as the molarity increased from 8M to 12M. This decline was induced by a rise in the viscosity of the mixture. Arun et al [16] found that increasing MK content as a substitute for fly ash in SCGC reduced slump flow as MK particles are amorphous and have greater surface area. The fresh property values for the mix with MK of 30% were found to be out of range from the values given in EFNARC guidelines

Guneyisi and Gesoglu [10] found that increasing MK content improved SCGC cohesion, resulting in a smaller slump flow diameter. According to Yamini J. Patel and Niraj Shah [25], the blend having GGBFS of 100% and RHA of 5% had the optimum workability, while the mix including RHA of 25% failed to meet the

EFNARC's criteria for SCGC. With a high proportion of silica fume replacement for fly ash, Menon et al [12] discovered that there is decrease in slump value and blocking ratio of SCGC. A similar experiment was carried out by Dhiyaneshwaran et al [26]. Habeeb Lateef Muttashara et al. [44] investigated the flowability, passing ability and mechanical characteristics of SCGC by altering the percentage of river sand by waste garnet. With increased use of rejected garnet, the flowability and passing ability improved, but the mechanical properties deteriorated.

Table 1: Trial mixes of different fresh properties [19]

Mix No.	Molarity (M)	Slump flow (mm)	T_{50cm} slump Flow(sec)	V-funnel (sec)	V-funnel at T_{5min} (sec)	L-box ratio (h_2/h_1)
M1	8	690	3.5	9.5	10	1.00
M2	10	690	3.5	10	10.5	0.92
M3	12	670	4.0	11	12	0.90
SCC acceptance criteria as per EFNARC						
Minimum		650	2	6	9	0.8
Maximum		800	5	12	15	1

Hardened Properties

Strength in compression, flexure and split tensile are done for SCGC.
According to Madandoust R, Yasin MS [27] investigated that strength in compression decreases when more than fifteen percent MK was used. B.R. Arun et al [6] carried out studies in which they varied the proportion of FA with MK. They concluded that when the percentage of MK raised from 0 to 30%, the compressive strength decreased regardless of molarity. Menon et al [12] found that the strength in compression of FA improved by increasing NaOH molarity from 8M to 12M and declined at 14M. Naraindas Bheel et al [28]. found that SCGC incorporating wheat straw ash and millet husk ash as a substitute for MK gave best split tensile value at 5 to 15% replacement.Memon et al [12] found that using silica fume upto 15% as an alternative for fly ash enhanced the split tensile strength.

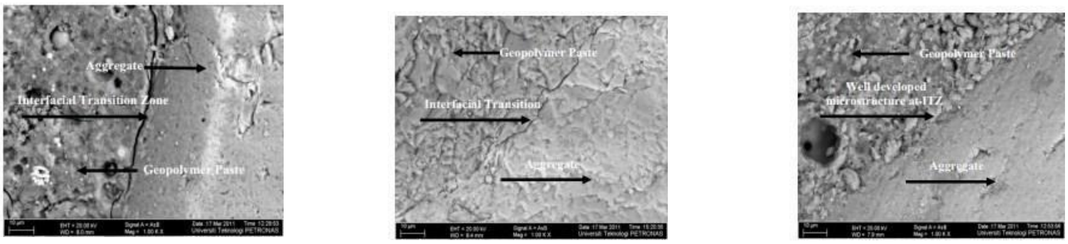
Guneet Saini and Uthej Vattipalli [29] observed that by increasing the molarity, GGBFS content, and adding nano silica by 2% improved the mechanical characteristics. Memon F.A, Nuruddin M.F, and Shaiq N [12] observed that adding up to ten percentage by mass of silica fume to flyash enhanced the mechanical characteristics of SCGC at all ages. The substitution of more than ten percent weight of fly ash by silica fume decreases the mechanical characteristics of concrete.

Naraindas Bheel, et al [30] discovered that using MK and groundnut shell ash separately and combined by weight of fly ash upto ten percentage improved mechanical performance. Sushree Sangita Rautray et al [31] reported that a larger level of GGBFS (70 percent GGBFS and 30 percent flyash) resulted in increased physical and mechanical properties in their investigation on GGBFS, fly ash, and Bacillus Licheniformis.

Saifuddin K.P et al [32] investigated the variation of workability of fly ash and GGBFS-based geopolymers with different percentages of SP and NaOH molarities and discovered that up to six percent SP and sodium hydroxide of 12M gives acceptable results in compressive strength and workability. According to P. S. Deb et al [33], when a large amount of GGBFS is used and the sodium hydroxide to sodium silicate ratio is low, workability is reduced and hardened characteristics are increased.

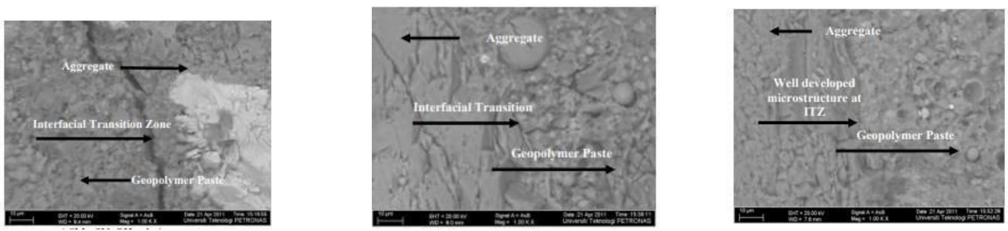
Microstructure Studies

Samuel Demie, et al [34] found that in fly ash-based SCGC a closely packed ITZ is seen between aggregate and binding agent for an SP intake of seven percent which improved the performance of concrete by increasing the strength in compression.



a) 5%SP b) 6%SP c) 7%SP

Fig. 4 SCGC FESEM pictures with varying SP dosage [34]



a) 8M NaOH solution b) 10M NaOH solution c) 12 M NaOH solution

Fig. 5 SCGC FESEM pictures with varying concentrations of NaOH solution [34]

Yamini J.Patel and Niraj Shah [25] discovered that RHA of 15% at 70 °C has a closely packed microstructure compared to RHA of 5% at ambient temperature.

Ansys Software

Using ANSYS software, B Sarath Chandra Kumar and K Ramesh [35] found that at room temperature, beams were treated with NaOH molarity of 10 M and varied doses of GGBFS and Metakaolin. In perspective of ultimate load, the behavior was explored. The findings were achieved to be identical to traditional cement concrete reinforced beams. The geopolymer concrete beams were simulated using ANSYS software by Jammi Nagaraj and Mendu Uday Bhaskar [36]. For OPC and GPC, the stress-strain fluctuation and deflection fluctuation between analytical and experimental values were assessed. In both practical and software applications, the number of failure cracks were shown to be the same.

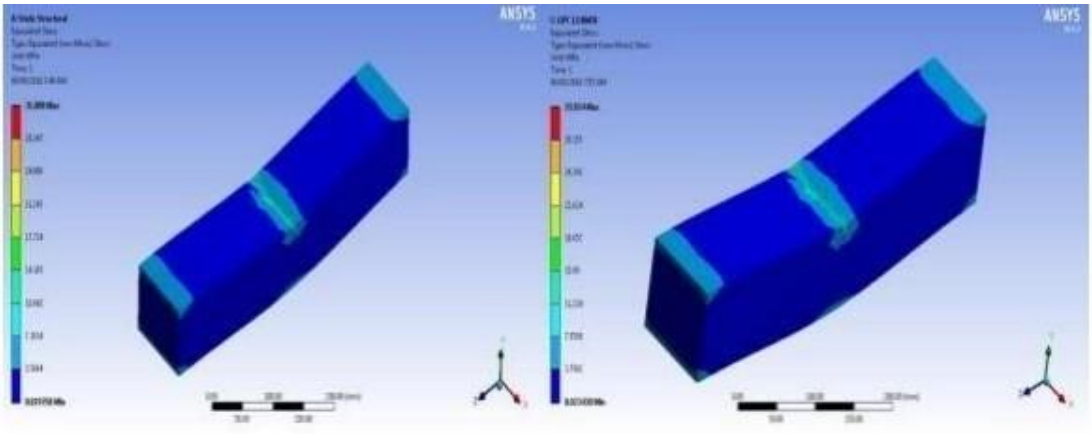


Fig. 6 Variation in stress [36]

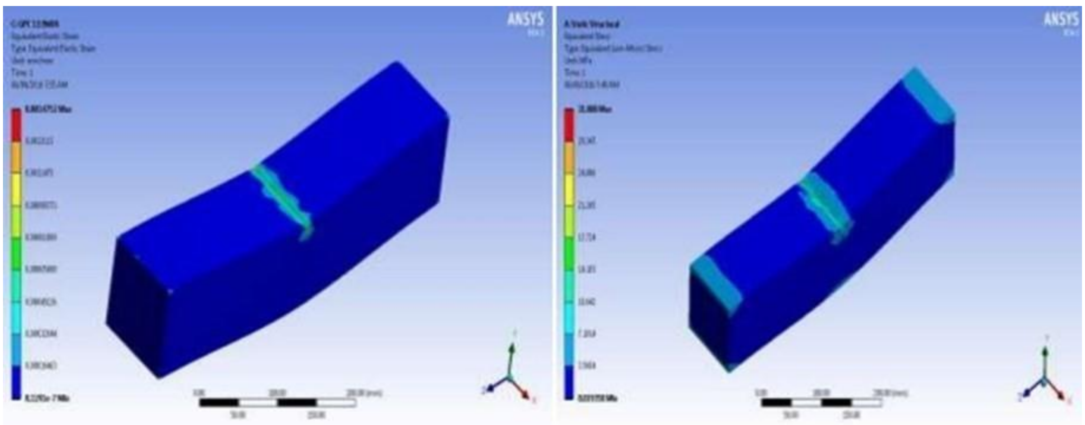


Fig. 7 Variation in strain [36]

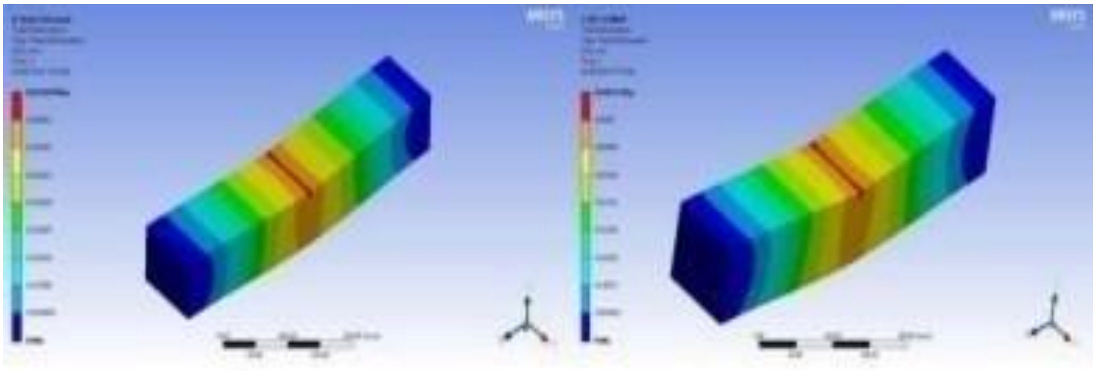


Fig. 8 Variation in Deflection [36]

D. Annapurna et al [37] congregated data on Reinforced Geopolymer Concrete Beams in Flexure during controlled research and utilised it to authenticate the model. The discoveries of theoretical investigations are quite similar to the findings of empirical studies.

Table 2: Theoretical and software result comparison [37]

Beam ID	First crack		Second crack		Third crack		Ultimate load	
GPC	Load (KN)	Def. (mm)	Load (KN)	Def. (mm)	Load (KN)	Def. (mm)	Load (KN)	Def. (mm)
Exp.	6.5	0.255	7	0.269	8	0.302	19.5	0.863
Ana.	7.5	0.2700	8	0.2956	9	0.3446	19	0.836

The rupture characteristics of geopolymer concrete were explored by N. Ganesa, Ruby Abraham, S. Deepa Raj, and Divya Sasi [38]. The efficiency of geopolymer concrete of grade M30 was contrasted to that of normal concrete of the relatively similar grade. Geopolymer concrete outscored normal concrete of the same grade, according to the findings of the test results. The practical findings were matched to those acquired from FEM analysis, and the results were judged to be acceptable.

Conclusion

- The amount of GGBFS enhances the strength in compression, bending, and split tensile strength of SCGC.
- The inclusion of 10-20% metakaolin to the mix increased the mechanical properties.
- Workability and compressive strength rose up to 10% silica fume substitution and declined up to 15% silica fume substitution. According to EFNARC guidelines, SP dosages of 6 and 7% increased workability qualities.
- At 70ºC for 24 hours of oven curing, the strength was higher than at ambient curing. The amounts of the mix were determined using EFNARC norms. An alkaline solution with a molarity of 12M provided the essential fresh properties as well as an improvement in mechanical properties.
- Extra water content of mass of binder of 12% showed good flow properties

and resistance to segregation. Poly carboxylic ether- based SP are utilized as viscosity modifying agents.

- SP dosage of 7% gave dense microstructure in SEM imaging.
- The results obtained from experimental studies and ANSYS software analysis were nearly the same.
- It can be used in chemical resistant bunding and floorings
- It is used in elevator components for passive fire protection in high rise buildings
- It is used in railway sleepers and sewerage pipes
- List of Abbreviations

GGBFS	Ground Granulated Blast Furnace Slag
FA	Fly Ash
SF	Silica Fume
SCGC	Self Compacting Geopolymer Concrete
RHA	Rice Husk Ash
EFNARC	European Federation of National Associations Representing Producers and Applicators of Specialist Building Products for Concrete
SCC	Self compacting concrete
CS	Copper Slag
SEM	Scanning Electron Microscope
M-Sand	Manufactured Sand
R-Sand	River sand
SP	Super Plasticizer
Silate	Silicon-oxo-aluminate
OPC	Ordinary Portland Cement
GPC	Geopolymer Concrete

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