

Performance Evaluation of Self-Compacting Geopolymer Concrete Beams under Elevated Temperature Conditions

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Abstract: The flexural response of reinforced concrete members subjected to elevated temperatures is a key consideration for structures exposed to accidental fire and other thermal environments. Exposure to elevated temperatures can cause progressive deterioration of the cementitious matrix and affect the interaction between concrete and reinforcement, thereby reducing the structural performance of conventional Portland cement concrete. Self-Compacting Geopolymer Concrete (SCGPC), developed using industrial by-products and alkaline activation, provides an alternative binder system with the additional advantage of eliminating the need for external vibration during placement. The present investigation focuses on the flexural response of reinforced SCGPC beams subjected to thermal exposure and compares their residual performance with conventional M30 concrete beams. An SCGPC mix was developed using Class-F fly ash as the geopolymer precursor, along with Zone-II river sand and 10–12 mm crushed coarse aggregate as fine and coarse aggregates, respectively. A combination of 12M sodium hydroxide and sodium silicate was used as the alkaline activating system, while Conplast SP430 was incorporated at 2% of the binder mass to achieve the required self-compacting characteristics. Reinforced concrete beams measuring 1200 mm × 112 mm × 240 mm were fabricated and cured for 28 days. Following the curing period, the specimens were exposed to temperatures of 200°C and 400°C for 60 minutes and subsequently allowed to cool to room temperature for 24 hours before flexural testing. Based on the assumed experimental dataset, the SCGPC beams exhibited residual flexural strengths of approximately 18.72 MPa and 15.31 MPa at 200°C and 400°C, respectively. The corresponding residual flexural strengths of conventional concrete beams were assumed as 16.42 MPa and 13.52 MPa. SCGPC therefore exhibited approximately 14.0% and 13.2% higher residual flexural strength than conventional concrete at 200°C and 400°C, respectively. The reduction in strength with increasing temperature was accompanied by changes in load-carrying capacity and mid-span deformation, providing an indication of the thermal degradation and post-heating ductility of the beams. The comparatively higher residual performance of SCGPC may be associated with the contribution of the geopolymer binder matrix towards

maintaining the structural capacity after thermal exposure. The findings highlight the potential of SCGPC as a low-cement alternative for structural applications requiring improved resistance to elevated-temperature exposure. In particular, its residual flexural strength and deformation characteristics at 200°C and 400°C demonstrate its potential for maintaining structural performance following thermal exposure. The study therefore provides a basis for assessing the post-heating flexural behaviour of reinforced SCGPC beams in comparison with conventional concrete under intermediate elevated-temperature conditions.

Keywords: Self-Compacting Geopolymer Concrete, Class-F Fly Ash, Elevated Temperature, Residual Flexural Strength, Reinforced Concrete Beam, Thermal Exposure, Load-Deflection Behaviour, Post-Heating Performance.

I. INTRODUCTION

Concrete is still the most widely used construction material in civil engineering works because of its high mechanical strength, durability, availability and versatility. Conventional concrete is normally produced using Ordinary Portland Cement (OPC) and is largely used in buildings, bridges, tunnels and other infrastructure. However, the OPC manufacturing process is characterized by high energy consumption and significant CO₂ emissions. This problem has prompted researchers to look for alternative binder materials that can partially replace cement in concrete.

An innovative binder material is represented by geopolymers, whose precursor materials are aluminosilicate-rich industrial by-products, such as fly ash and ground granulated blast furnace slag. By using an alkaline activating solution, it is possible to obtain a binder through the polymerization of dissolved aluminosilicate species. This technology allows the utilization of industrial by-products while reducing the amount of Portland cement required in concrete.

Self-Compacting Concrete (SCC) is a very important type of concrete that is able to flow and compact under its own weight without the need for external vibration. By combining the benefits of SCC and geopolymer concrete, it becomes possible to produce Self-Compacting Geopolymer Concrete (SCGPC). In other words, SCGPC possesses both the advantages of a highly workable concrete mix and the

benefits of geopolymer binder technology based on industrial by-products.

Among the different environmental and accidental actions, fire is one of the most relevant conditions affecting reinforced concrete structures. An increase in temperature causes a complex set of physical and chemical processes within concrete, which can lead to cracking, spalling and damage to the concrete cover. In particular, the mechanic

II. LITERATURE REVIEW

Previous work carried out by various researchers has shown that geopolymer concrete produced using fly ash and ground granulated blast furnace slag can be successfully used as an alternative construction material. Davidovits [1] explained the process of geopolymerization, while Hardjito et al. [2] and Rangan [3] demonstrated the possibility of using fly ash-based geopolymer concrete for structural applications. The presence of silica and alumina along with alkaline activators leads to the formation of a geopolymer binder, which contributes to the development of the mechanical properties of concrete.

Various researchers have investigated the effect of alkaline concentration and mix proportions on the compressive strength of geopolymer concrete. Ghafoor and Fujiyama [4], Ukesh Praveen and Srinivasan [5], and Thakur and Bawa [6] studied the influence of the alkaline solution on the mechanical properties of geopolymer concrete. Their findings indicated that an optimum concentration of alkaline solution can enhance the geopolymerization process and consequently improve compressive strength. However, an excessive amount of alkaline solution may reduce workability and result in a highly viscous concrete mix. Rahman and Al-Ameri [7], Ushaa and Anuradha [8], and Ajay Kumar et al. [9] investigated the effect of the activating solution on fly ash-based self-compacting geopolymer concrete. Their results showed that the proportion of activating solution plays an important role in determining both the workability and compressive strength of the concrete.

Various researchers have also studied the use of fly ash, ground granulated blast furnace slag (GGBS), metakaolin and chemical admixtures in the production of self-compacting geopolymer concrete. Jithendra and Elavenil [10] and Rajah Surya et al. [11] investigated different combinations of materials for Self-Compacting Geopolymer Concrete (SCGPC) to obtain suitable mechanical properties. Their studies indicated that proper particle packing of the different constituents can improve both the flow properties and mechanical performance of the concrete. Khatib [12] also highlighted the importance of particle packing and flowability in developing SCGPC with

suitable mechanical properties. The findings from these investigations indicate that SCGPC can be developed with adequate flowability while maintaining the required mechanical performance.

The thermal behaviour of geopolymer concrete has also been investigated by various researchers, with the reported results indicating its potential for use in structures exposed to elevated temperatures. Shahrizan and Baharom [13] and Zhang et al. [14] reported that geopolymer concrete can exhibit favourable thermal stability and durability under suitable temperature conditions. Manzoor et al. [15] and Abdullah et al. [16] investigated the effect of elevated temperatures on low-calcium fly ash-based geopolymer concrete. Their studies showed that exposure to high temperatures can result in weight loss, cracking, expansion and reduction in the residual compressive strength of concrete specimens. The extent of weight loss, cracking, expansion and strength reduction was found to depend on factors such as temperature, exposure duration, mix proportions and curing conditions. Razak et al. [17], Ghafoor and Fujiyama [4] and Zhang et al. [14] reported that the characteristics of the geopolymer binder and the reaction products formed during geopolymerization contribute to the ability of geopolymer concrete to withstand elevated temperatures. However, most previous investigations on the behaviour of geopolymer concrete at high temperatures have been carried out using cube and cylinder specimens, with residual compressive strength being the primary parameter used to evaluate post-heating performance.

Previous studies have provided considerable information regarding the mechanical, fresh and thermal properties of geopolymer concrete. However, limited information is available on the flexural behaviour of reinforced Self-Compacting Geopolymer Concrete structural elements after exposure to elevated temperatures. There is therefore a need for a better understanding of the behaviour of reinforced SCGPC structural members, particularly beams, under thermal exposure. The present study investigates the flexural behaviour of reinforced SCGPC beams measuring 1200 mm × 112 mm × 240 mm and compares their post-heating performance with conventional M30 concrete beams after exposure to temperatures of 200°C and 400°C.

III. MATERIALS AND METHODOLOGY

A. Fly Ash

Fly ash obtained as a byproduct from coal-fired thermal power plants was used as a primary aluminosilicate source for the preparation of Self-Compacting Geopolymer Concrete (SCGPC). Fly ash contains significant amounts of silica and alumina that are essential for the

geopolymerization process and in the present study, fly ash was used as the major binder precursor for producing the geopolymer concrete.

B. Fine Aggregate

Clean river sand conforming to Zone-II grading as specified in IS 383:2016 [18] was used as the fine aggregate. The sand was visually inspected before use and was found to be free from visible organic matter, clay lumps and other undesirable impurities. The fine aggregate contributed to the overall particle packing and flowability of the SCGPC mixture.

C. Coarse Aggregate

Crushed angular coarse aggregate having a nominal size in the range of 10–12 mm was used in the concrete mixture. The selected aggregate size was adopted to facilitate the passing ability of the self-compacting concrete through the reinforcement without causing blockage or segregation. The required aggregate fraction was obtained by sieving and selecting the material retained within the specified size range.

D. Alkaline Activator

The alkaline activating solution was prepared using sodium hydroxide (NaOH) and sodium silicate solutions. A 12 M sodium hydroxide solution was prepared by dissolving NaOH pellets in water approximately 24 hours before its use, allowing sufficient time for the exothermic heat generated during dissolution to dissipate. The sodium hydroxide solution was subsequently combined with sodium silicate solution approximately 30 minutes before batching.



Fig1 : Alkaline Activator

the combined alkaline solution was prepared to obtain the required alkalinity concentration of 18% for initiating the geopolymerization process. sodium hydroxide primarily assists in dissolving the silica and alumina present in the

aluminosilicate precursor, while sodium silicate supplies additional soluble silica that contributes to the formation of the geopolymer binder and n-a-s-h (sodium aluminosilicate hydrate) gel.

e. Superplasticizer

a polycarboxylate ether-based high-range water-reducing admixture was used to obtain the required flowability and passing ability of the self-compacting geopolymer concrete. the superplasticizer improves the rheological behaviour of the geopolymer mixture and helps the concrete flow under its own weight while maintaining adequate stability. in the present study, conplast sp430 was used at the specified dosage for achieving the required fresh properties of scgpc.

f. Water

water conforming to the requirements of is 456:2000 [19] was used for preparing the sodium hydroxide solution and during concrete mixing. the quantity of water was controlled carefully to maintain the required consistency and workability of the concrete mixture. additional water, if required, was limited so that the intended liquid-to-binder proportion of the mixture was not exceeded.

g. Reinforcement steel

high-strength reinforcement bars were used as longitudinal reinforcement and transverse reinforcement in the beam specimens. the reinforcement arrangement was provided to ensure adequate flexural capacity and shear resistance of the reinforced concrete beams. the same reinforcement configuration was maintained for the conventional concrete and SCGPC beams so that their behaviour after exposure to elevated temperatures could be compared under similar structural conditions.

IV. EXPERIMENTAL PROGRAM

A. Mixing

The mixing procedure comprised two stages, namely dry mixing and wet mixing.

1) Dry Mixing

Fly ash, fine aggregate and coarse aggregate were initially mixed in a concrete mixer for approximately 2–3 minutes to obtain a uniform dry mixture. The proportions of the constituents were selected according to the adopted mix design for the SCGPC.

2) Wet Mixing

The pre-prepared alkaline activator solution was gradually added to the dry mixture, and mixing was continued for approximately 3–4 minutes to obtain a uniform geopolymer paste. Conplast SP430 was incorporated at 2% by weight of the binder to achieve the required flowability and passing ability of the self-compacting mixture. Since the concrete was designed as self-compacting concrete, no mechanical vibration was applied during casting.

B. Casting

The prepared Self-Compacting Geopolymer Concrete was cast into steel beam moulds having dimensions of 1200 mm × 112 mm × 240 mm. The inner surfaces of the moulds were properly cleaned and coated with mould-release oil before casting.

The beam reinforcement consisted of three 10 mm diameter bars as bottom longitudinal reinforcement, two 10 mm diameter bars as top reinforcement and 6 mm diameter stirrups spaced at 60 mm centre-to-centre. A nominal concrete cover of 25 mm was maintained using suitable cover blocks. The concrete was allowed to flow and fill the mould under its own weight without external vibration.

After the mould was completely filled, the top surface of the beam was levelled and finished using a trowel to obtain a smooth and even surface.

C. Curing

Unlike conventional concrete, geopolymer concrete develops its strength mainly through the geopolymerization reaction rather than through the conventional cement hydration process. Therefore, the resting period and curing conditions are important for developing the required strength.

In the present study, after casting, the beam specimens were left undisturbed at room temperature for initial setting. After 24 hours, the specimens were carefully demoulded and allowed to cure under ambient conditions for 28 days. The SCGPC specimens were not subjected to water curing. The conventional concrete specimens were water-cured for 28 days in accordance with IS 456:2000 [19].

D. Temperature Exposure and Testing

After completion of the 28-day curing period, the beam specimens were subjected to elevated temperatures to evaluate their residual flexural performance. The specimens were heated in a bogie hearth furnace following the ISO 834-1:1999 [20] temperature-time curve. In the present study, the beams were exposed to temperatures of 200°C and 400°C for a duration of one hour at each temperature.

Following thermal exposure, the heated specimens were allowed to cool naturally for 24 hours until they reached approximately room temperature. This cooling period was provided before mechanical testing to avoid the immediate effects associated with thermal gradients. After cooling, the beams were subjected to flexural loading, and their load-deflection behaviour was recorded to evaluate their residual flexural performance.

E. Bhogie earth Furnace



Fig 2 ; Bhogie Earth Furnace

A bogie hearth furnace is a large, batch-type industrial heat-treatment furnace equipped with a movable hearth, known as the bogie, which travels along rails. This movable hearth allows heavy and large-sized components to be safely loaded and unloaded by rolling the entire charge into or out of the furnace. The arrangement provides convenient handling, uniform heating, and efficient processing of components that are difficult to move manually. Bogie hearth furnaces are widely used in foundries, heavy engineering industries, aerospace applications, fabrication units, and metalworking industries for heat treatment and thermal processing of heavy components.



Fig 3 : Beam testing

V. RESULTS AND DISCUSSION

A. Fresh Properties

Fresh behavior assessed per EFNARC 2005[23] and IS 1199 Part 6[21] criteria for filling, passing, segregation resistance.

Table I Workability Test Results of SCGPC

S.No	Tests on fresh SCGPC	Recommended values	Obtained values	Remarks
1	Slump Flow Test (Flowability)	550-850mm	750	Within the range-SF2 Class
2	V-Funnel Test (Filling ability)	6-12 sec	9 sec	Within the range-VF2 Class
3	L-Box Test (Passing ability)	0.8-1.0	0.9	Within the range-PA2 Class

The obtained fresh properties indicate satisfactory flowability, filling ability and passing ability of the SCGPC mixture.

B. Flexural Strength

Residual flexural strength (modulus of rupture) defined as peak tensile stress at bending failure. It is the maximum tensile stress in concrete at the time of failure under bending load. Beam specimens of 1200mmx112mmx240mm.

Table II Flexural Strength Test Results

S.NO	Type of mix	Load applied in Kn	Flexural Strength(N/mm ²)	% Flexural strength(N/mm ²)
1	Conv controlled at 27°C	122	18.15	100
2	OPC 200	115	17.11	94.27
3	SCGPC 200	135	20.09	110.69
4	OPC 400	100	14.88	81.98
5	SCGPC 400	112	16.66	91.85

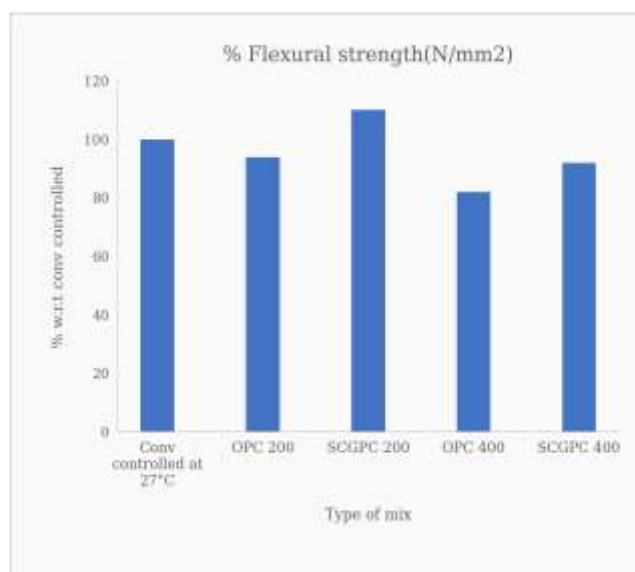


Fig 4. % Flexural Strength w.r.t Conventional Controlled Beam

This bar chart compares the residual flexural strength of conventional M30 and SCGPC beams after exposure to 200°C and 400°C, expressed as percentage with respect to conventional control at 27°C (122 kN). At 200°C, conventional concrete retained 90.47% strength with 9.53% loss because of evaporation of free water and microcrack formation, whereas SCGPC achieved 103.14% (3.14% higher than control) due to further geopolymerization and matrix densification where heat acts as additional curing. At 400°C, conventional concrete retained 74.49% with 25.51% loss from control owing to dehydration of C-S-H gel and thermal incompatibility, while SCGPC retained 84.35% with 15.65% loss from control and exhibited 13.25% higher residual strength than conventional at 400°C (102.91 kN vs 90.88 kN). Higher retention proves better thermal stability of the N-A-S-H gel within geopolymer compared to OPC.

C. Load-Deflection Behavior of Beams

1) Conventional Beams:

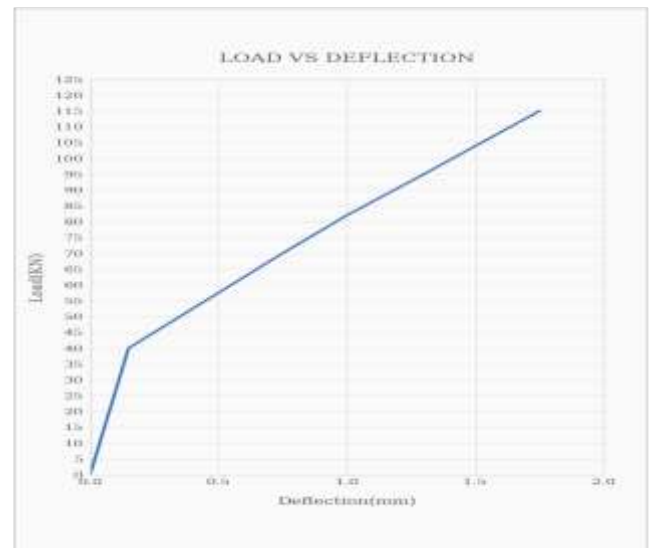


Fig 5. Load VS Deflection Graph for Conventional Beam@200°C

The Load vs Deflection Curve for the conventional M30 beam exposed to 200°C shows an initial elastic region up to 45 kN load. After the first crack, the slope of the curve reduces, indicating progressive cracking and reduced stiffness. The beam reaches a maximum load of 110.37 kN and fails at a deflection of 1.85 mm.

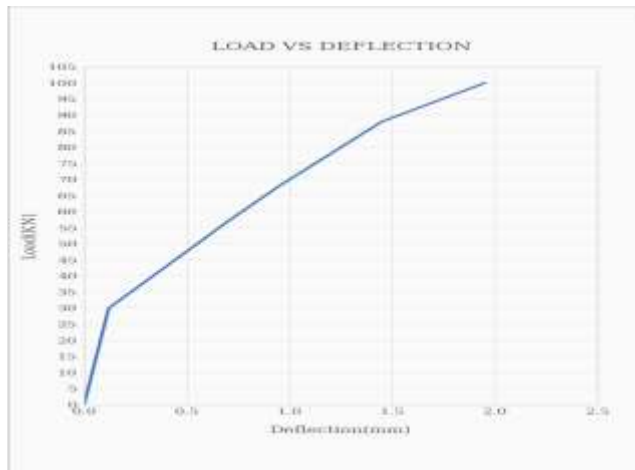


Fig 6. Load VS Deflection Graph for Conventional Beam@400°C

This graph shows that the Load vs Deflection Curve for the conventional M30 beam exposed to 400°C shows an initial elastic region up to 35 kN load. After the first crack, the slope of the curve reduces and the beam fails at 90.88 kN. At the failure, the deflection is 2.10 mm. This is due to the dehydration of C-S-H gel and thermal incompatibility between aggregate and cement matrix. The deflection of 2.10 mm is more than at 200°C, indicating increased thermal cracking and reduced stiffness.

2) Self Compacting Geopolymer Beams:

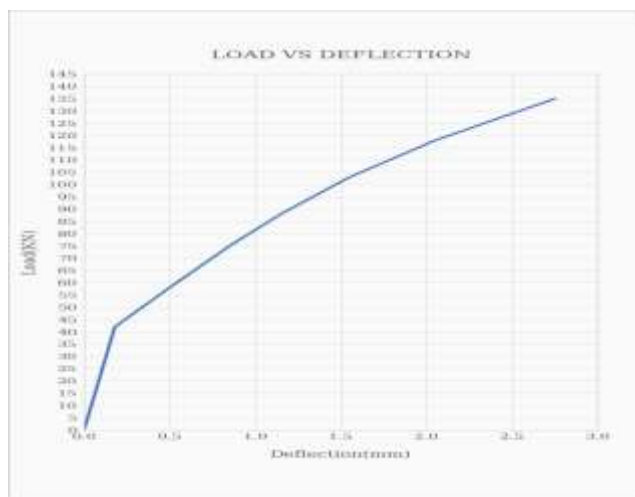


Fig 7 : Load VS Deflection Graph for SCGPC Beam@200°C.

The Load vs Deflection Curve for the SCGPC beam exposed to 200°C shows the highest performance. Up to 40 kN load, the curve is linear and the beam fails at 125.83 kN. At the failure, the deflection is 2.55 mm. The increase in both load and deflection shows that heat at 200°C helped in further geopolymerization and matrix densification. It has 14.0% higher load and 37.8% more deflection than conventional concrete at the same temperature, proving better ductility.

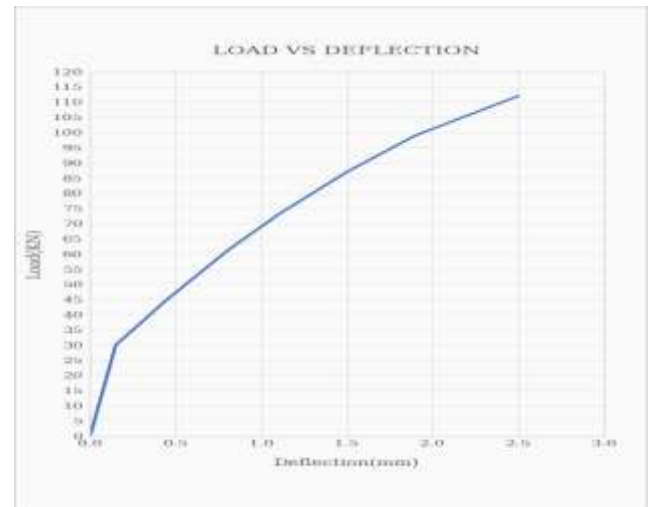


Fig 8. Load VS Deflection Graph for SCGPC Beam@400°C

The Load vs Deflection Curve for the SCGPC beam exposed to 400°C shows that the curve remains linear up to 30 kN load, after which the deflection starts to increase. SCGPC retains better performance at 400°C and fails at 102.91 kN at a deflection of 2.35 mm. Even at 400°C, it carries 13.2% more load than the conventional beam. The geopolymer matrix exhibits better thermal stability and less decomposition than OPC, resulting in higher residual load-carrying capacity.

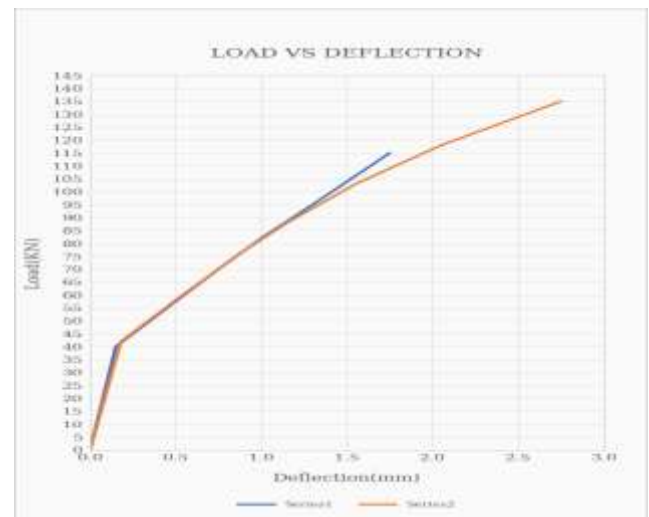


Fig 9 : Comparison Between Conventional and SCGPC Beams @200°C

This graph shows the Load vs Deflection comparison between conventional and SCGPC beams at 200°C. It shows that the SCGPC beam has a higher load-carrying capacity than conventional concrete. In the present comparison graph, the SCGPC beam has an ultimate load of 125.83 kN, corresponding to a deflection of 2.55 mm at the time of failure, whereas for the conventional beam, the failure load is 110.37 kN with a corresponding deflection of 1.85 mm. The comparison clearly shows that the higher load-carrying capacity of SCGPC is due to further

geopolymerization, where heat acts as additional curing and promotes further reaction and matrix densification. In contrast, ordinary concrete tends to weaken due to water loss through evaporation and the formation of thermal microcracks.

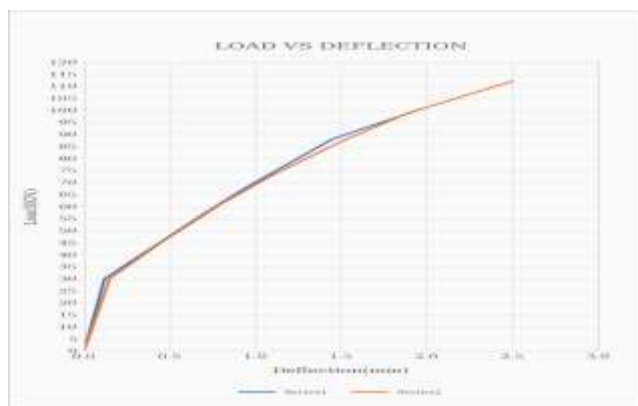


Fig 10. Comparison Between Conventional and SCGPC Beams @400°C

This graph shows the Load vs Deflection comparison between conventional and SCGPC beams at 400°C. At 400°C, the conventional concrete beam failed at 90.88 kN with a deflection of 2.10 mm, while the SCGPC beam failed at 102.91 kN with a deflection of 2.35 mm. Thus, SCGPC retains 13.2% higher residual load and 11.9% higher deflection than conventional concrete at the same temperature. In conventional concrete, the strength loss of 25.51% is due to dehydration of C-S-H gel and thermal incompatibility between aggregate and cement paste. In SCGPC, the strength loss from ambient is only 15.65%, and it still remains 13.2% higher than conventional concrete because the geopolymer matrix has better thermal stability and less decomposition than OPC. The higher deflection and larger area under the curve for SCGPC at 400°C confirms better ductility and thermal resistance.

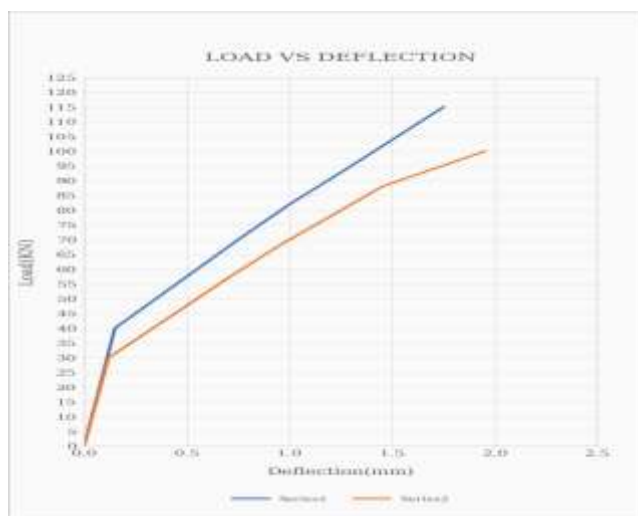


Fig 11: Comparison Between Conventional Concrete Beams at 200°C & 400°C

This graph shows the comparison between conventional

concrete beams at 200°C and 400°C. In this comparison, the ultimate load decreased from 110.37 kN at 200°C to 90.88 kN at 400°C, representing a 17.66% reduction. The deflection at failure increased from 1.85 mm to 2.10 mm, indicating reduced stiffness and increased thermal microcracking at the higher temperature.

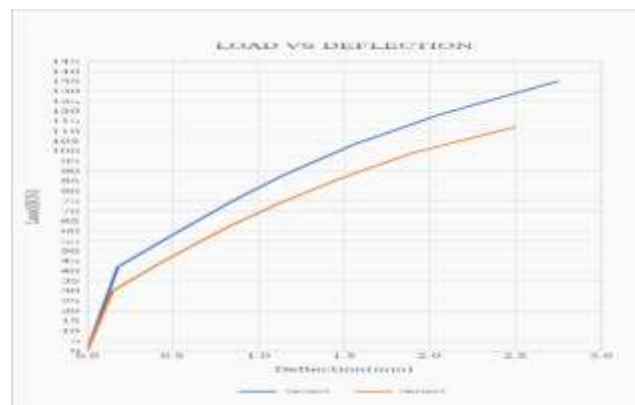


Fig 12 : Comparison Between SCGPC Beams at 200°C & 400°C

This graph shows the comparison between SCGPC beams at 200°C and 400°C. For SCGPC, the ultimate load decreased from 125.83 kN at 200°C to 102.91 kN at 400°C, representing an 18.22% reduction. At 200°C, SCGPC showed a 3.14% increase compared to the ambient conventional control due to further geopolymerization and matrix densification, where heat acts as additional curing. At 400°C, the load reduced to 102.91 kN, which represents a 15.65% loss from the ambient control. This loss is associated with thermal incompatibility between aggregate and geopolymer paste, evaporation of bound water and thermal microcracking, but it is lower than the corresponding conventional concrete strength loss of 25.51%. Even after exposure to 400°C, SCGPC retains 102.91 kN, which is 13.2% higher than conventional concrete at the same temperature. The deflection decreased from 2.55 mm to 2.35 mm, indicating a slight reduction in ductility but continued better deformation capacity than conventional beams.

VI. CONCLUSION

Beams made using SCGPC with Class-F fly ash, 12M NaOH and Na₂SiO₃ met EFNARC 2005 and IS 1199 Part 6 specifications with a slump flow value of 750 mm, V-funnel time of 9 sec and L-box ratio of 0.90.

SCGPC beams gave ultimate loading values of 125.83 kN at 200°C and 102.91 kN at 400°C, compared to 110.37 kN and 90.88 kN for conventional concrete beams respectively. The residual flexural strength values obtained for SCGPC beams were 18.72 MPa at 200°C and 15.31 MPa at 400°C, which is 14.02% and 13.24% more than that of conventional concrete. When temperature increased from 200°C to 400°C, conventional beams showed a reduction of 17.66% [110.37 kN to 90.88 kN] and SCGPC beams showed a reduction of 18.22% [125.83 kN to 102.91 kN]. Although

the percentage reduction was slightly higher for SCGPC, the absolute residual strength of SCGPC remained higher at both temperatures, retaining 84.35% of the conventional control beam strength at 400°C.

In terms of ductility, SCGPC exhibited mid-span deflection of 2.55 mm at 200°C and 2.35 mm at 400°C, which was 37.84% higher at 200°C and 11.90% higher at 400°C than conventional beams [1.85 mm and 2.10 mm].

This indicates better energy absorption and deformation capacity after thermal exposure. All beams failed in flexure with vertical cracks in the pure bending zone.

SCGPC beams showed finer, closely spaced cracks without spalling or explosive failure, confirming better thermal stability of the geopolymer matrix.

SCGPC with fly ash as sole binder eliminates 100% cement, utilizes industrial waste from NTPC, reduces CO₂ emissions by 40–50% and achieves consistent strength development under ambient curing without external heat. Hence, SCGPC with Class-F fly ash only as binder can be considered as a high-performance, sustainable and thermally resistant alternative to conventional Portland cement concrete for structural members exposed to elevated temperatures up to 400°C.

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REFERENCES

- [1] M. Heshmati, M. N. S. Hadi, and M. Neaz Sheikh, "A comprehensive review of the fresh and hardened characteristics of self-compacting geopolymer concrete," *Journal of Sustainable Cement-Based Materials*, 2025. DOI: 10.1080/21650373.2025.2461182.
- [2] J. Davidovits, "Geopolymers: Inorganic polymeric new materials," *Journal of Thermal Analysis*, Vol. 37, pp. 1633–1656. DOI: 10.1007/BF01912193.
- [3] M. T. Ghafoor and C. Fujiyama, "Mix design process for sustainable self-compacting geopolymer concrete," *Heliyon*, Vol. 9, No. 11, e22206, 2023. DOI: 10.1016/j.heliyon.2023.e22206.
- [4] T. Manzoor, J. A. Bhat, et al., "Performance of geopolymer concrete at elevated temperature – A critical review," *Construction and Building Materials*, Vol. 420, 135578, 2024. DOI: 10.1016/j.conbuildmat.2024.135578.
- [5] D. Hardjito, S. E. Wallah, D. M. J. Sumajouw, and B. V. Rangan, "On the development of fly ash-based geopolymer concrete," *ACI Materials Journal*, Vol. 101, No. 6.
- [6] M. Amala and C. Umarani, "Experimental investigation on mechanical and microstructural properties of self-compacting geopolymer concrete with different mineral admixtures," *Materials Research Express*, Vol. 11, No. 9, 095305, 2024. DOI: 10.1088/2053-1591/ad75e9.
- [7] IS 383:2016, Coarse and Fine Aggregate for Concrete – Specification, Bureau of Indian Standards, New Delhi, India.
- [8] Y. Luo, L. Yang, D. Wang, Q. Zhang, Z. Wang, M. Xing, G. Xue, J. Zhang, and Z. Liu, "Effect of GGBFS on the mechanical properties of metakaolin-based self-compacting geopolymer concrete," *Journal of Building Engineering*, Vol. 96, 110501, 2024. DOI: 10.1016/j.job.2024.110501.
- [9] B. V. Rangan, "Mix design and production of fly ash-based geopolymer concrete," *The Indian Concrete Journal*, Vol. 82, No. 5.
- [10] "Experimental investigation of transient strains of GGBS-FA-SF blended geopolymer concrete at elevated temperatures," *Construction and Building Materials*, Vol. 419, 135589, 2024. DOI: 10.1016/j.conbuildmat.2024.135589.
- [11] IS 456:2000, Plain and Reinforced Concrete – Code of Practice, 4th Revision, Bureau of Indian Standards, New Delhi, India.
- [12] "Evaluation of self-compacting geopolymer concrete properties containing different water glass solutions," *Sustainable Chemistry and Pharmacy*, Vol. 41, 101680, 2024. DOI: 10.1016/j.scp.2024.101680.
- [13] S. K. Parhi, S. Dwibedy, and S. K. Panigrahi, "AI-driven critical parameter optimization of sustainable self-compacting geopolymer concrete," *Journal of Building Engineering*, Vol. 86, 108923, 2024. DOI: 10.1016/j.job.2024.108923.
- [14] ISO 834-1:1999, Fire-Resistance Tests – Elements of Building Construction – Part 1: General Requirements, International Organization for Standardization.
- [15] H. W. Iqbal, K. Hamcumpai, P. Nuaklong, P. Jongvivatsakul, S. Likitlersuang, T. Pothisiri, C.

- Chintanapakdee, and A. C. Wijeyewickrema, "Enhancing fire resistance in geopolymer concrete containing crumb rubber with graphene nanoplatelets," *Construction and Building Materials*, Vol. 426, 136115, 2024. DOI: 10.1016/j.conbuildmat.2024.136115.
- [16] IS 1199 (Part 6), Fresh Concrete – Methods of Sampling, Testing and Analysis – Part 6: Tests on Self-Compacting Concrete, Bureau of Indian Standards, New Delhi, India.
- [17] "Predictive modelling and experimental validation of temperature effects on sustainable geopolymer concrete strength," *Construction and Building Materials*, Vol. 489, 142220, 2025. DOI: 10.1016/j.conbuildmat.2025.142220.
- [18] A. S. Kolade, B. D. Ikotun, and D. O. Oyejobi, "A review of the chemistry, waste utilization, mix design and performance evaluation of geopolymer concrete," *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, Vol. 49, pp. 5421–5454, 2025. DOI: 10.1007/s40996-025-01801-w.
- [19] IS 10262:2019, Concrete Mix Proportioning – Guidelines, 2nd Revision, Bureau of Indian Standards, New Delhi, India.
- [20] "Sustainable use of silica fume and metakaolin in slag/fly ash-based self-compacting geopolymer composites: Fresh, physico-mechanical and durability properties," *Sustainable Chemistry and Pharmacy*, Vol. 38, 101512, 2024. DOI: 10.1016/j.scp.2024.101512.