

Experimental Assessment of the Residual Flexural Strength of Self-Compacting Geopolymer Concrete Beams after Elevated Temperature Exposure

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Abstract: Concrete is commonly used in construction of chimneys, blast furnace lining, nuclear shielding, rocket launching pads and industrial structures subjected to high temperatures. Production of Ordinary Portland Cement consumes a lot of energy and results in large carbon emissions in the atmosphere. Geopolymer concrete made of Class-F fly ash is a low-carbon concrete that exhibits improved thermal stability. The SCGPC is a sustainable material that combines sustainability properties with self-compacting ability that is useful for congested reinforcement and no mechanical vibration. This study involved preparation of SCGPC mix containing Class-F fly ash as primary binder, Zone-II river sand as fine aggregates, crushed angular aggregates of sizes 10mm and 12mm as coarse aggregate, 12M sodium hydroxide with sodium silicate solution having 18% alkalinity as an activator and polycarboxylate ether based super plasticizer Conplast SP430 in 2% dose by binder weight. Beams of size 1200mm x 112mm x 240mm were cast. After 28 days ambient curing of SCGPC and conventional water curing of M30, beams were subjected to 100°C and 300°C in electric furnace for 60 minutes, allowed to cool down for 24 hours and loaded. Test results indicated SCGPC beams achieved residual flexural strength of 20.09 MPa at 100°C and 16.66 MPa at 300°C, exhibiting 17.04% reduction and 82.96% retention between temperatures. Conventional beams showed 17.11 MPa at 100°C and 14.88 MPa at 300°C with 13.04% reduction and 86.96% retention. SCGPC retained 17.39% higher strength at 100°C and 12.0% higher at 300°C compared to conventional beams. In terms of ductility, SCGPC exhibited 54.28% higher mid-span deflection at 100°C and 28.20% higher at 300°C than conventional beams, confirming superior deformation capacity. Therefore, SCGPC can be considered sustainable thermally resilient alternative offering improved strength and ductility with reduced carbon footprint.

Keywords: Self-Compacting Geopolymer Concrete, Fly Ash, Sodium Hydroxide, Sodium Silicate, Elevated Temperature, Flexural Strength, Load-deflection behavior.

I. INTRODUCTION

The most popular material for constructions all over the world is concrete because of high strength, durability and widespread distribution. The most common kind of this material is ordinary Portland cement concrete that is widely used in buildings, bridges, tunnels and many other infrastructure projects. But at the same time cement production consumes many energy resources and leads to carbon dioxide emission into the atmosphere. Thus, nowadays the scientists are looking for the alternatives that could make this process more ecological.

The first example is geopolymer concrete that is made of alumino-silicate-rich materials such as fly ash, ground granulated blast furnace slag and other wastes of different plants. This mixture is activated by an alkaline solution, which leads to creation of a binder that replaces Portland cement or decreases its usage.

Another innovative direction in concrete is self-compacting concrete. Its main advantage is the ability to flow under its own weight and fill the formwork without any mechanical vibration. Combining these two technologies results in self-compacting geopolymer concrete. It provides the flowability of self-compacting concrete and the environmental advantages of geopolymer concrete.

One of the accidental situations that may have an effect on reinforced concrete construction is fire. The presence of high temperature causes water movements, thermal expansion and changes in chemical composition. Such effects lead to cracking, spalling and reduction in mechanical properties.

However, most researches consider the compressive strength after heating. But it is important to remember that the flexural resistance of constructions is also a matter for investigation since beams are normally loaded in flexion.

II. LITERATURE REVIEW

Different authors have explored the use of industrial by-

products in combination with alkaline activation to improve the properties of concrete. The results of various experiments on Class-F fly ash and ground granulated blast furnace slag show that these raw materials contain high amounts of amorphous silica and alumina that help in enhancing the strength of concrete through the process of geopolymerization reactions by Sodium Aluminosilicate Hydrate [N-A-S-H] gel formation [Davidovits, 1991 [1]; Hardjito et al., 2004 [2]; Rangan, 2008 [3]].

Various experimental studies on fly ash based geopolymer concrete used as partial and full replacement of cement material reported improvement in compressive and split tensile strength up to an optimal molarity ratio and then degradation in strength due to increasing viscosity and brittleness [Ghafoor & Fujiyama, 2023[4]; Ukesh Praveen & Srinivasan, 2017[5]; Thakur & Bawa, 2022[6]]. Likewise, improvement in the workability and strength of M30 grade self-compacting geopolymer concrete having Class-F fly ash from NTPC was found at controlled activator ratio [Rahman & Al-Ameri, 2020[7]; Ushaa & Anuradha, 2015[8]; Ajay Kumar et al., 2018[9]].

The investigations carried out using fly ash in combination with GGBS, metakaolin and superplasticizer revealed that better packing and microstructure densification results in improved performance in terms of strength and durability of self-compacting geopolymer concrete [Jithendra & Elavenil, 2017[10]; Rajah Surya et al., 2021[11]; Khatib, 2008[12]]. Nevertheless, the increased value of NaOH from 8M to 16M and higher values of workability due to increased stickiness with increased activator were noticed by many researchers.

Studies carried out to investigate the durability aspect indicated that geopolymer concrete had better thermal resistance and lower chloride permeability when compared with ordinary Portland cement concrete up to optimum temperature conditions [Shahrizan & Baharom, 2021[13]; Zhang et al., 2020[14]]. Similarly, ambient-cured low calcium fly ash geopolymer concrete had improved thermal stability, but excessive exposure to high temperatures above 600°C was detrimental to its residual strength and resulted in micro-cracking [Manzoor et al., 2024[15]; Abdullah et al., 2024[16]]. There was mass loss of 2% to 10.2% and strength reduction of 15% to 60% at high temperatures ranging between 100°C to 1000°C.

According to recent studies, the high-temperature performance can be improved through the presence of alkaline media and stable N-A-S-H gel as these will promote the formation of products with thermal stability [Razak et al., 2022[17]; Ghafoor & Fujiyama, 2023[4]; Zhang et al., 2020[14]]. There is much research done regarding the compressive strength of geopolymer cubes

subjected to high temperature but little research has been carried out on the reinforced beams at a structural level subjected to two-point loadings.

From the reviewed literature, it can be seen that despite considerable amount of work done in relation to mix design of self-compacting geopolymer concrete and their compressive strength at high temperature levels, not much research has been carried out in relation to residual flexural strength of reinforced self-compacting geopolymer concrete beams of size 1200 mm × 112 mm × 240 mm subjected to 100°C and 300°C for 60 minutes. Comparative studies regarding performance of self-compacting geopolymer concrete beams and normal M30 beams under similar curing and heating conditions along with load deflection behaviour have also not been extensively studied.

III. MATERIALS AND METHODOLOGY

A. Fly Ash

Fly ash is the by-product that is derived from coal-fired thermal power plants. It has a high quantity of silica and alumina content that can be utilized in geopolymerization process. In the current experiment, Fly Ash has been used as one of the major sources for preparing Self-compacting geopolymer concrete

B. Fine Aggregate

Clean river sand of Zone-II gradation (IS 383-2016)[18] was employed. Visual inspection confirmed absence of organic matter and clay lumps.

C. Coarse Aggregate

Angular crushed stone of 10-12mm nominal dimension was chosen to satisfy passing ability. Fraction retained between 12mm and 10mm sieves was used.

D. Alkaline Activator

The activating solution used for alkaline activation was prepared by adding solutions of sodium hydroxide and sodium silicate. 12 M NaOH solution (pellets dissolved 24 hours earlier to dissipate the exothermic heat) and sodium silicate solution. Mixed 30 minutes prior to batching to facilitate the dissolution and cool off the solution because of the exothermic reactions. The prepared NaOH solution was then mixed with sodium silicate solution 30 minutes before batching, to obtain the final activating solution having an alkalinity concentration of 18%, needed to trigger geopolymerization process. The role of sodium hydroxide is to dissolve the silica and alumina from the aluminosilicates precursors, while the sodium silicate provides the extra silica which contributes in forming Sodium Aluminosilicate Hydrate [N-A-S-H] gel.

E. Superplasticizer

An appropriate polycarboxylate ether superplasticizer, which is a type of HRWRA, was employed for ensuring the

flowability and passing ability of the self-compacting geopolymer concrete. This water-reducing admixture enhances the rheological behavior of the geopolymer mixture without influencing the geopolymerization reaction.

F. Water

Water that met the standards laid out by IS 456 2000[19] was utilized during the preparation of the 12M sodium hydroxide solution and for the maintenance of the consistency of the concrete mixture. Water was added to the mix only if there was need to increase its workability, but without exceeding the required liquid to binder ratio.

G. Reinforcement Steel

High-strength reinforcement bars are used for the longitudinal reinforcement and stirrups of the beam specimens.

IV. EXPERIMENTAL PROGRAM

A. Mixing

Here, the mixing process consists of two stages: dry mixing and wet mixing

1) Dry Mixing: Fly ash, sand and coarse aggregate were mixed dry in a concrete mixer for 2-3 minutes. The proportions of mix are based on Sample-15: G-0.63-16-2-40N.

2) Wet Mixing: The pre-prepared alkaline activator solution was mixed slowly with the dry mix for 3-4 minutes and uniform geopolymer paste was obtained. Superplasticizer Conplast SP430 was used in 2% content by weight of binder to obtain required slump flow properties. Since it is a self-compacting mixture, there was no need for any mechanical vibration.

B. Casting

Self-compacting geopolymer concrete was cast into steel beam mould of dimension 1200 x 112 x 240 mm, which was greased with mould release oil before casting. Reinforcement bars of three numbers of 10 mm dia at bottom, two bars of 10 mm dia at top and stirrups of 6 mm dia at 60 mm c/c were placed with a 25 mm cover from edges. This was done with the help of cover blocks.

Finishing: After complete filling, the top surface of the beams was levelled and finished smoothly using a trowel to obtain an even surface.

C. Curing

The geopolymer concrete does not get its strength from hydration like traditional concrete but through polymerization; hence the importance of the resting time and curing of the concrete.

In the current study, after the pouring of concrete into moulds, the specimens were left undisturbed to set initially at room temperature. After 24 hours, the specimens were carefully demoulded and allowed to cure for 28 days at

room temperature. The specimens of SCGPC were not water-cured, while the specimens of conventional concrete were water-cured for 28 days as per IS 456:2000[19].

D. Temperature Exposure and Testing

After completing the 28-day ambient curing period, the beams were subjected to increased temperature conditions to determine the residual flexural strength. These beams were heated in bogie hearth furnace according to ISO 834-1:1999[20] Curve at a temperature exposure of 100°C and 300°C respectively, and the exposure is one hour for each temperature.

Once heated, these beams were cooled for 24 hours until room temperature was reached to prevent any shock due to thermal effects. After this, they were tested for load deflection after 28 days.

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 as per IS 1199 (Part 6)[21] & IS 10262[22] / EFNARC 2005[23]	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

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. Here a total of 4 beam specimens for OPC & SCGPC.

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 100	115	17.11	94.27
3	SCGPC 100	135	20.09	110.69
4	OPC 300	100	14.88	81.98
5	SCGPC 300	112	16.66	91.80

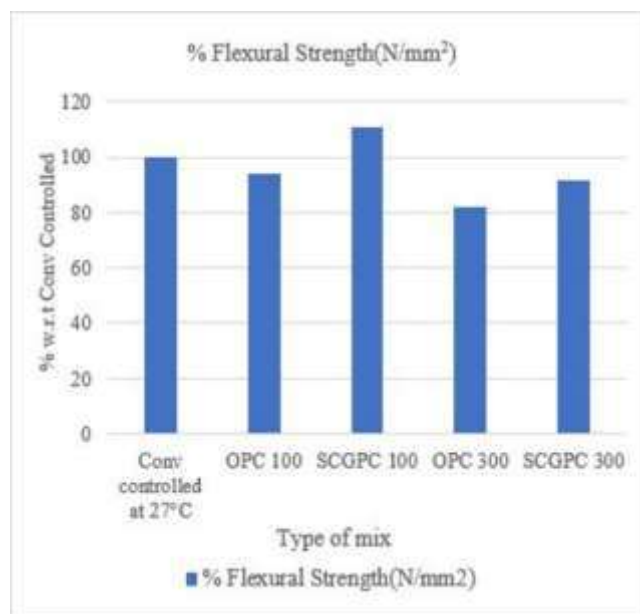


Fig 1. % Flexural Strength w.r.t Conventional Controlled Beam

This bar chart compares the residual flexural strength of conventional M30 and SCGPC beams after exposure to 100°C and 300°C, expressed as percentage with respect to conventional control at 27°C (122 kN). At 100°C, conventional concrete retained 94.27% strength with 5.73% loss because of evaporation of free water and microcrack formation, whereas SCGPC achieved 110.69% (10.69% higher than control) due to further geopolymerization and matrix densification where heat acts as additional curing. At 300°C, conventional concrete retained 81.98% with 18.02% loss from control owing to dehydration of C-S-H gel and thermal incompatibility, while SCGPC retained 91.8% with only 8.10% loss from control and exhibited 12.0% higher residual strength than

conventional at 300°C (112 kN vs 100 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:

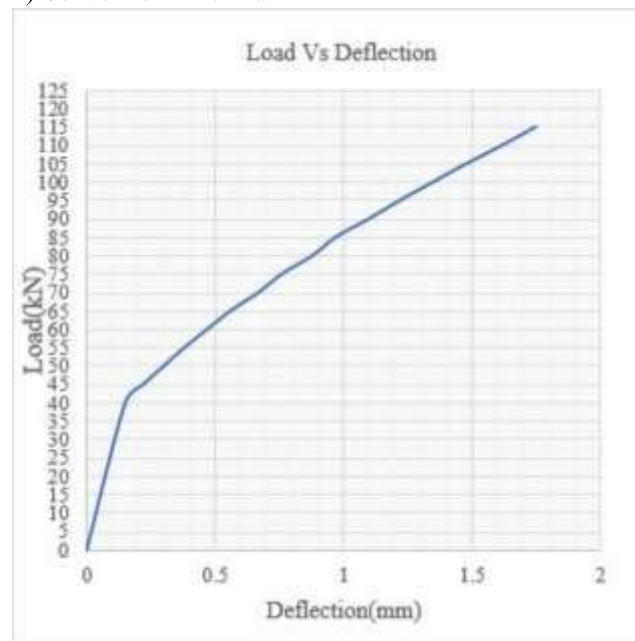


Fig 2. Load VS Deflection Graph for Conventional Beam@100°C

The Load vs Deflection Curve for the conventional M30 beam exposed to 100°C the curve shows initial elastic region up to 45 kN load after first crack slope reduces and the beam fails at 115 kN. At the failure the deflection should be 1.75mm.

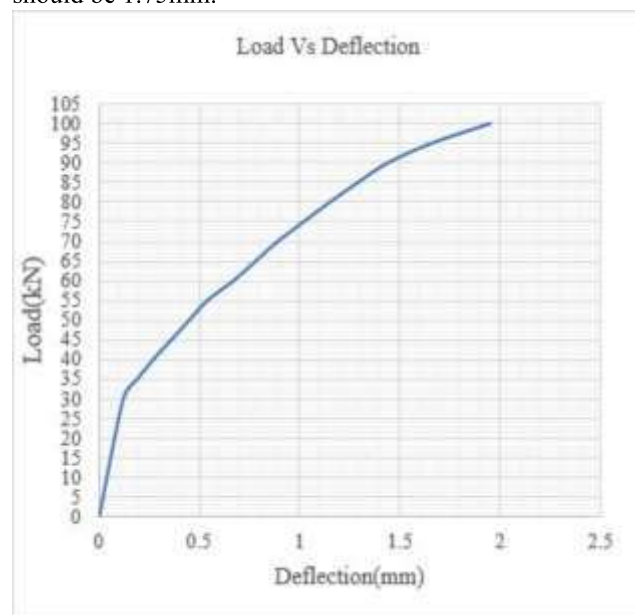


Fig 3. Load VS Deflection Graph for Conventional Beam@300°C.

This graph shows that the Load vs Deflection Curve for the conventional M30 beam exposed to 300°C the curve shows initial elastic region up to 35 kN load after first crack slope

reduces and the beam fails at 100 kN. At the failure the deflection should be 1.95mm. This is due to the dehydration of C-S-H gel and thermal incompatibility between aggregate and cement matrix. The deflection of 1.95 mm is more than at 100°C, indicating more brittle microcracking.

2) Self Compacting Geopolymer Beams:

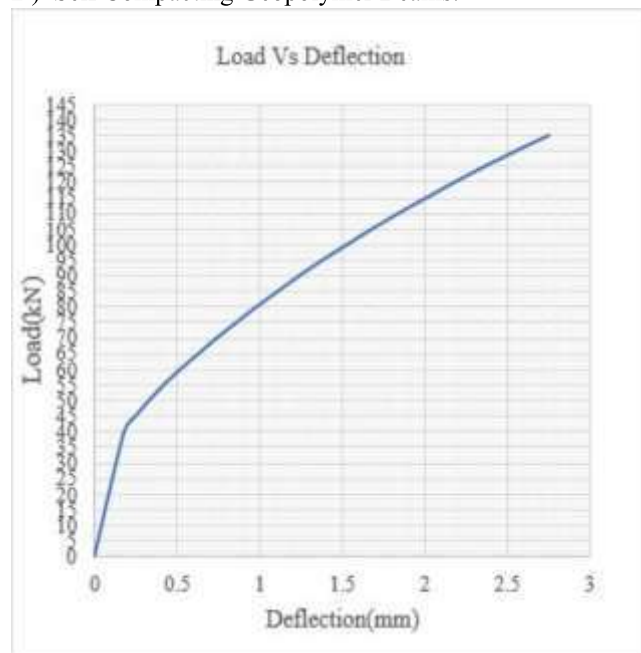


Fig 4. Load VS Deflection Graph for SCGPC Beam@100°C.

The Load vs Deflection Curve for the SCGPC beam exposed to 100°C this curve shows highest performance. Up to 40kN load the curve is linear and the beam fails at 135 kN. At the failure the deflection should be 2.75mm. The increase in both load and deflection shows that heat at 100°C helped in further geopolymerization and it has 17.4% higher load and 54% more deflection than conventional at same temp, proving better ductility.

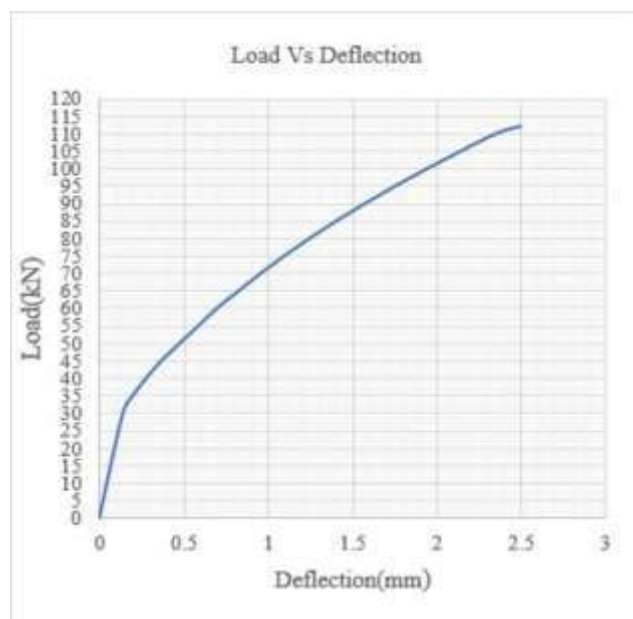


Fig 5. Load VS Deflection Graph for SCGPC Beam@300°C

The Load vs Deflection Curve for the SCGPC beam exposed to 300°C, in this the curve shows up to 30kN it is linear after that deflection starts. SCGPC retains better performance at 300°C. It fails at 112 kN at 2.5 mm deflection. Even at 300°C, it carries 12% more load than conventional beam. The geopolymer matrix has better thermal stability and less decomposition than OPC, hence higher residual load

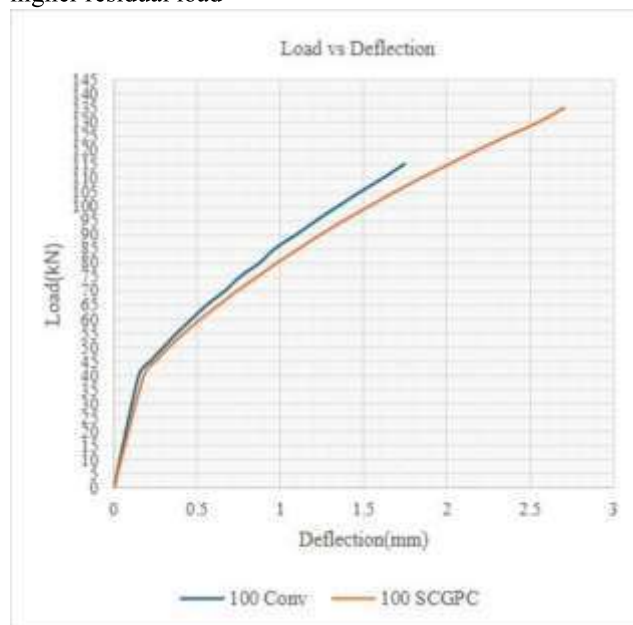


Fig 6. Comparison Between Conventional and SCGPC Beams @100°C

This graph shows that load vs deflection comparison between conventional and SCGPC beams at 100°C, it shows that SCGPC beam has higher load carrying capacity than conventional concrete, in the present comparison graph

SCGPC has ultimate load of 135kN corresponding deflection is 2.75mm at the time of failure, for conventional at the time of failure load is 115kN corresponding deflection is 1.95mm. The comparison clearly shows that higher load in SCGPC is due to further geopolymerization in this heat acts as additional curing and completes the reaction. While ordinary concrete tends to weaken as a result of water loss through evaporation and cracking.

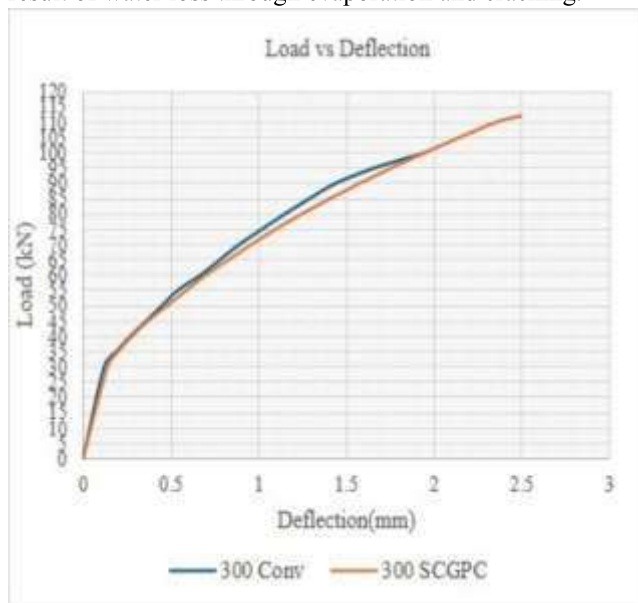


Fig 7. Comparison Between Conventional and SCGPC Beams @300°C

This graph shows that load vs deflection comparison between conventional and SCGPC beams at 300°C. At 300°C, conventional concrete beam failed at 100 kN with 1.95 mm deflection, while SCGPC beam failed at 112 kN with 2.50 mm deflection. Thus SCGPC retains 12% higher residual load and 28.2% higher deflection than conventional concrete at the same temperature. In conventional concrete, the strength loss of 18.47% is due to dehydration of C-S-H gel, decomposition of Ca(OH)_2 and thermal incompatibility between aggregate and cement paste. In SCGPC, the strength loss from ambient is only 8.66%, and it still remains 12% higher than conventional because the geopolymer matrix has better thermal stability, less decomposition and no C-S-H degradation like OPC. The higher deflection and larger area under the curve for SCGPC at 300°C confirms better ductility and fire resistance.

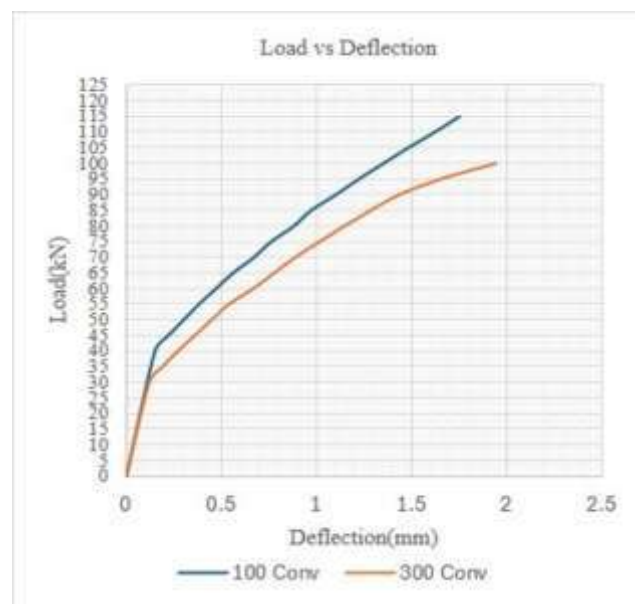


Fig 8. Comparison Between Conventional Concrete Beams at 100°C & 300°C

This graph shows that comparison between conventional concrete beams at 100°C & 300°C, in this the ultimate load decreased from 115kN at 100°C to 100kN at 300°C, which has 13.04% reduction. The deflection at failure increased from 1.75mm to 1.95mm indicates reduced stiffness and more microcracking at higher temperatures.

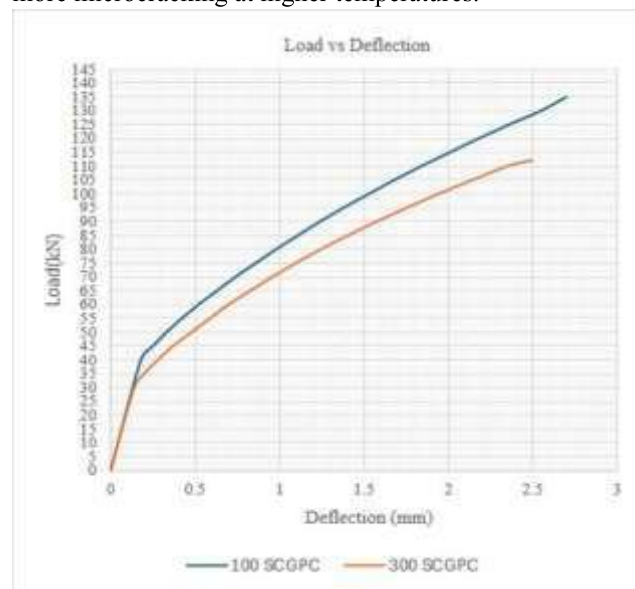


Fig 9. Comparison Between SCGPC Beams at 100°C & 300°C

This graph shows that comparison between SCGPC beams at 100°C & 300°C, for SCGPC ultimate load decreased from 135kN at 100°C and 112kN at 300°C, which has a 17.03%. At 100°C, SCGPC showed a 10.08% increase compared to ambient control due to further geopolymerization where heat acts as additional curing. At 300°C, the load reduced to 112 kN, which is an 8.66% loss from ambient. This loss is due to thermal incompatibility

between aggregate and geopolymer paste, evaporation of bound water and minor microcracking, but it is much less than conventional concrete loss of 18.47%. Even after exposure to 300°C, SCGPC retains 112 kN, which is 12% higher than conventional at same temperature. The deflection reduced from 2.70 mm to 2.50 mm, indicating slight reduction in ductility but still higher energy absorption 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 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 135 kN at 100°C and 112 kN at 300°C, compared to 115 kN and 100 kN for conventional concrete beams respectively. The residual flexural strength values obtained for SCGPC beams were 20.09 MPa at 100°C and 16.66 MPa at 300°C, which is 17.39% and 12.0% more than that of conventional concrete. When temperature increased from 100°C to 300°C, conventional beams showed a reduction of 13.04% [115 kN to 100 kN] and SCGPC beams showed a reduction of 17.03% [135 kN to 112 kN]. Although percentage reduction was slightly higher for SCGPC, absolute residual strength of SCGPC remained higher at both temperatures, retaining 82.96% of its strength at 100°C.

In terms of ductility, SCGPC exhibited mid-span deflection of 2.75 mm at 100°C and 2.50 mm at 300°C, which was 54.28% higher at 100°C and 28.20% higher at 300°C than conventional beams [1.75 mm and 1.95 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 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 recommended as a high-performance, sustainable and thermally resistant alternative to conventional Portland cement concrete for structural members exposed to elevated temperatures up to 300°C.

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