Revista Ingeniería de Construcción RIC
Vol 38 Nº2 2023
www.ricuc.cl
DOI: 10.7764/RIC.00075.21

ENGLISH VERSION...

Fracture behavior of slag & flyash-based geopolymer concrete in comparison with OPC-based conventional concrete including the effect of steel and hybrid fibers

Comportamiento de fracturas del hormigón geopolímero en base de escoria y cenizas volantes en comparación con el hormigón convencional en base de OPC, incluido el efecto del acero y las fibras híbridas

Singh, Pranay * [1] http:// orcid.org/0000-0003-1754-4488
Singh, Brijesh * http://orcid.org/0000-0002-6512-1968
Ojha, P.N. * http://orcid.org/0000-0003-1754-4488
Singh, Abhishek * http:// orcid.org/0000-0001-6169-9482
Trivedi, Amit * http://orcid.org/0000-0002-2594-4679

* National Council for Cement and Building Materials, Ballabgarh, INDIA

Fecha de Recepción: 16/09/2022
Fecha de Aceptación: 02/02/2023
Fecha de Publicación: 02/08/2023
PAG: 361-381

Abstract:
The study presents an experimental investigation of the fracture behavior of hardened slag and fly ash-based alkali-activated normal and high-strength geopolymer concrete compared with conventional Ordinary Portland Cement (OPC) based concrete with steel and hybrid fibers. The fracture parameters considered in the experimental investigation include fracture energy, stress intensity factor, energy release rate, and characteristic length. The study concludes that the observed differences in the fracture and mechanical performance of the conventional and geopolymer concrete agree with the microstructural differences between these concrete systems reported in past literature. The slag-based geopolymer concrete is marginally inferior to the O.P.C.-based concrete with similar compressive strength in fracture performance. Also, hybrid fiber reinforcement improves the fracture performance of geopolymer concrete more than the steel fiber alone. Contrary to geopolymer concrete, steel fiber reinforced conventional concrete is superior to hybrid fiber reinforced conventional concrete in terms of fracture behavior.
Keywords: *Geopolymer concrete; Fracture energy; CMOD; Notched-Beam; Characteristic length; Fiber reinforced geopolymer concrete.*

Resumen
El estudio presenta una investigación experimental del comportamiento de fractura del hormigón de geopolímero normal y de alta resistencia activado con álcali a base de escoria endurecida y cenizas volantes en comparación con el hormigón convencional a base de cemento Portland ordinario (OPC) con acero y fibras híbridas. Los parámetros de fractura considerados en la investigación experimental incluyen energía de fractura, factor de intensidad de tensión, tasa de liberación de energía y longitud característica. El estudio concluye que las diferencias observadas en la fractura y el desempeño mecánico del concreto convencional y geopolimérico concuerdan con las diferencias micro estructurales entre estos sistemas de concreto reportadas en la literatura anterior. El hormigón de geopolímero a base de escoria es marginalmente inferior al hormigón en base de O.P.C. con una resistencia a la compresión similar en el comportamiento de fractura. Además, el refuerzo de fibra híbrida mejora el rendimiento de fractura del hormigón geopolímero más que la fibra de acero sola. A diferencia del hormigón geopolímero, el hormigón convencional reforzado con fibras de acero es superior al hormigón convencional reforzado con fibras híbridas en términos de comportamiento de fractura.
Palabras Claves: Hormigón geopolímero; energía de fractura; CMOD; *Notched-Beam; Longitud Características; Hormigón Geopolimérico reforzado con fibras.*

[1] *Corresponding author:*
Professor, National Council for Cement and Building Materials, Ballabgarh, INDIA
author: vighneshr@skcet.ac.in

DOI: 10.7764/RIC.00075.21

1. Introduction

The rising concern for adopting a circular economy (Benachio et al., 2020) worldwide has also revolutionized the construction industry (Ojha et al., 2021), (Ojha et al., 2022), (Ojha et al 2021a). Various efforts are being made to reuse the mineral waste from the industry as a viable construction material. Along with this, the production of Ordinary Portland Cement (OPC) is an energy-intensive process. It is estimated that about one tonne of carbon dioxide is produced in the manufacturing process of one tonne of OPC (Trivedi et al., 2022). This makes OPC an unsustainable construction material and a significant source of greenhouse gas emissions. Concerning these issues, replacing OPC with pozzolanic mineral waste is quite popular. But the replacement level is still significantly less to cause any significant change in demand and production of OPC. The need of the hour is cement-free concrete with similar mechanical, fracture, seismic, and durability performance as conventional cement-based concrete. The alkali-activated materials (AAMs), popularly called geopolymers, are being looked at as the alternative for cement-based concrete and as a potential material for achieving sustainability and circular economy in the construction sector. Contrary to conventional concrete, these geopolymers can be made almost entirely from industrial mineral wastes using lesser energy. Among different variations of the geopolymers, the blast furnace slag and fly ash-based blends are the most popular and have been extensively studied in the past. The methodology and the mix design for the production of the geopolymer concrete having similar strength to conventional concrete is readily available in the literature. (Trivedi et al., 2022) presents two mixes with slag and fly ash in the ratio of 70:30 (by weight) activated by sodium hydroxide and sodium silicate and evaluated its mechanical properties. The study achieved similar compressive strength in geopolymer concrete as in conventional concrete. Comparing the other properties of the comparable strength geopolymer concrete and traditional concrete, the split tensile strength, flexural strength, and drying shrinkage were comparable. However, the modulus of elasticity of the geopolymer mix was lower in the geopolymer concrete than the conventional concrete.

The variation in the properties of the geopolymer and conventional O.P.C.-based mixes arise from the microstructural variations, the variation in the number and size of the pores, and different intrinsic properties of varying gel systems produced in these concrete systems. The microstructure of the geopolymer concrete depends on the ingredients used in its preparation. For a Slag based hardened geopolymer (High-Calcium system), C-A-S-H (Calcium Aluminosilicate Hydrate) gel with crosslinking and non-cross-linking structure is the primary constituent in the gel matrix (Myers et al., 2013). This gel system is different from the C-S-H (Calcium Silicate Hydrate) gel produced as a hydration product of O.P.C.-based conventional concrete. The crosslinking in the geopolymer concrete due to polymerization gives it an improved mechanical strength at lower binder content (Hassan et al., 2020). The crosslinking among different layers in C-A-S-H gel can be seen in (Figure 1), which is not present in the C-S-H gel system (Marvilla et al., 2021).

Revista Ingeniería de Construcción RIC
Vol 38 Nº2 2023
www.ricuc.cl
DOI: 10.7764/RIC.00075.21

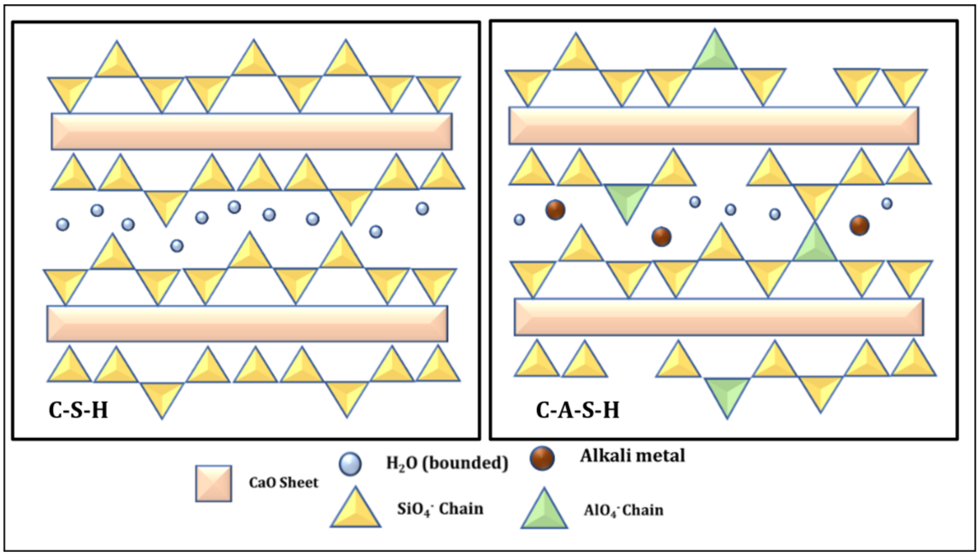

Figure 1. *Schematic representation of C-S-H and C-A-S-H gel systems*

A fly ash-based geopolymer (Low-calcium system) primarily constitutes N-A-S-H (Sodium Aluminosilicate Hydrate) gel as a reaction product in concrete. N-A-S-H gel consists of randomly distributed and crosslinked Silicon and Aluminium tetrahedral. Based on literature (Lahoti et al., 2019), (Criado et al., 2007), (Criado at al., 2008), a schematic 2-dimensional representation of 3-dimensional N-A-S-H gel is presented in (Figure 2).

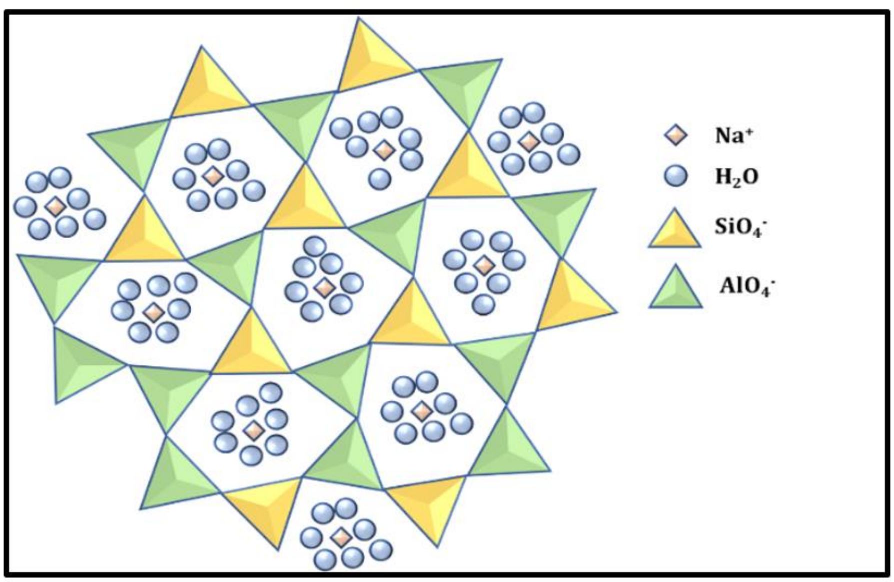

Figure 2. *2-dimensional Schematic representation of 3-dimensional N-A-S-H gel*

As shown in (Figure 1) and (Figure 2), C-A-S-H and N-A-S-H gel consist of crosslinking, which is absent in the C-S-H get. These crosslinks make the microstructure of hardened geopolymer concrete much denser than conventional OPC concrete. Past studies (Provis et al., 2012), (Garboczi, 1990), (Yang et al., 2020) also indicate the variation in the pore size and pore distribution in the geopolymer concrete and conventional OPC concrete. Various studies found that the pore size in the slag-based geopolymer concrete is less than 50nm, with most of the pores below 20nm. On the contrary, the pore size in conventional concrete ranges from 10nm

DOI: 10.7764/RIC.00075.21

to 100nm. The number of pores in the OPC concrete is also higher than in the geopolymer concrete (Hassam et al., 2020). Some past studies highlight the properties of high and very-high-strength conventional OPC-based concrete and the effect of fly ash and silica fume in the mix (Ojhaet al 2022), (Singh, 2020), (Singh, 2018), (Arora et al.,m 2016), (Ojha et al., 2021), (Arora et al., 2019), (Arora et al., 2017), (Singh et al., 2021). The silica fume helps get a much better packing density in the OPC concrete mix, thereby improving its mechanical properties.

The addition of steel fiber prevents sudden catastrophic failure in concrete by improving its tensile and flexural performance. Polypropylene fiber can bend around the aggregates, and a hybrid mix of steel and polypropylene fiber has been investigated for conventional concrete systems. In high-strength concrete with higher packing density, polypropylene fiber also helps improve fire resistance by providing a passage for moisture once the temperature exceeds the melting point of polypropylene fibers (Patel et al., 2021). The effect of fiber addition in geopolymer concrete has also been studied (Asrani et al., 2019), ([24], (Aisheh et al., 2022) and the findings suggest a considerable improvement in the fracture performance of the geopolymer concrete with fiber reinforcement. For bridging the microcracks in geopolymer concrete, a mix of steel fiber with polypropylene or glass fiber is found to be most effective.

Besides the mechanical properties and microstructural arrangements, investigating the fracture parameters is essential for developing a constitutive model of newer material. These parameters define the crack arresting properties of the material. The fracture parameters considered in the present study include Fracture energy, Stress intensity factor, characteristic length, and energy release rate. Fracture energy is defined as the energy required to produce a unit crack in the material. The stress intensity factor represents the maximum stress level accommodated in an existing crack's neighbourhood without forming a newer crack. The characteristic length is the maximum possible zone of strain hardening in the material. And the energy release rate is the rate of decrease in the material's potential energy with the formation of new cracked surfaces.

The present study evaluates these parameters using Load-deflection and load-CMOD (Crack Mouth Opening Displacement) curves obtained from the experimental investigation on beams of 100mm x 100mm x 500mm size under a three-point bend test (Ojha et al., 2022), (R.T.-50 F.M.C., 1985), (Shah, 1990), (Alwesabi, 20221), (Bureau, 2020), (Bureau, 2016), (Bureau, 2004), (ASTM, 2014), (Patel et al., 2020), (Bazant and Pijaudier-Cabot, 1989), (Sahin and Köksal, 2011), (Taha et al., 2008), (Ojha et al., 2021), (Arora and Singh, 2016), (Singh et al., 2021), (Ojha et al., 2021). The fracture parameters for the geopolymer concrete have been compared with the fracture performance of the similar strength conventional concrete. The possible explanation for the observed trend has been established based on the microstructural investigations presented in past literature.}

2. Materials and Mix proportion

s

As cementitious material in the OPC-based conventional concrete Ordinary Portland Cement of 53 grade as per IS 269:2015 (Ojha et al., 2021), Fly-ash and silica fume are used. The geopolymer concrete mix is prepared using granulated blast furnace slag (GGBS) and fly ash as a source of reactive alumino-silicates in a proportion of 70:30 by weight. A combination of Sodium hydroxide and sodium silicate and potable water is used as a chemical activator in the mix. For conventional and geopolymer concrete, crushed coarse aggregates with a maximum nominal size of 20 mm and crushed fine aggregates confirming Zone II specifications of IS 383:216 (Bureau of Indian Standards, 2016) are used. The physical and chemical characteristics of the materials used in the study are given in (Table 1), (Table 2), (Table 3), (Table4).

Table 1. *Physical and Chemical Characteristics of GGBS and fly ash used in geopolymer*

DOI: 10.7764/RIC.00075.21

Characteristics	GGBS	Fly Ash
Physical Tests:		
Blaine's Fineness (m^2/Kg)	335	330
Specific Gravity	2.90	2.33
Lime reactivity (N/mm^2)	Not applicable	6.40
Chemical Tests:		
Calcium Oxide (%)	37.66	5.80
Silica (%)	34.60	48.66
Reactive Silica (%)	33.96	23.52
Alumina (%)	18.38	26.72
Iron Oxide (%)	0.98	8.87
Magnesium Oxide (%)	5.15	1.43
Na_2Oeq (%)	0.60	0.74
Loss on Ignition (%)	0.40	4.76
Total Sulphur as SO_3 (%)	0.05	0.75
Sulphide Sulphur (%)	0.39	0.56
Chloride (%)	0.024	0.026
Manganese Oxide (%)	1.32	0.13

Table 2. *Physical &Chemical Characteristics of Cement, silica fume and fly ash used in conventional concrete*

Characteristics	OPC -53 Grade	Silica Fume	Fly Ash
Physical Tests:			
Fineness Blaine's (m^2/kg)	320.00	22000	403
Soundness Autoclave (%)	00.05	-	-
Soundness Le Chatelier (mm)	1.00	-	-
Setting Time Initial (min.) & (max.)	170.00 & 220.00	-	-
Specific gravity	3.16	2.24	2.2
Chemical Tests:			
Loss of Ignition (LOI) (%)	1.50	1.16	0.4
Silica (SiO_2) (%)	20.38	95.02	60.95
Iron Oxide (Fe_2O_3) (%)	3.96	0.80	5.70
Aluminium Oxide (Al_2O_3)	4.95	-	26.67
Calcium Oxide (CaO) (%)	60.73	-	2.08
Magnesium Oxide (MgO) (%)	4.78	-	0.69
Sulphate (SO_3) (%)	2.07	-	0.29
Chloride (Cl) (%)	0.04	-	0.009
IR (%)	1.20	-	-
Moisture (%)	-	0.43	-

Table 3. *Properties of Sodium Silicate gel*

S. No.	Parameter	Results Obtained
1	Appearance	Light Grey Colour
2	Matter Insoluble in water, %	< 0.01
3	Relative Density (at 27° C)	1.55
4	Total Soluble Silicates (%)	48.10

Table 4. *Properties of Aggregate*

DOI: 10.7764/RIC.00075.21

Property		Granite		Fine Aggregate
		20 mm	10 mm	
Specific gravity		2.83	2.83	2.65
Water absorption (%)		0.3	0.3	0.59
Sieve Analysis Cumulative Percentage Passing(%)	20mm	98	100	100
	10 mm	1	68	100
	4.75 mm	0	2	99
	2.36 mm	0	0	89
	1.18 mm	0	0	64
	600 µ	0	0	43
	300 µ	0	0	26
	150 µ	0	0	14
	Pan	0	0	0
Abrasion, Crushing & Impact		19,19,13	-	-
Flakiness % & Elongation %		29, 25	-	-

Sodium hydroxide (NaOH), used as the activator in the geopolymer mix, was 97.16 percent pure. Sodium Silicate Gel (Na2SiO3) was also utilized as an activator in addition to sodium hydroxide. (Table 3) summarises the properties of the used sodium silicate gel. And (Table 4) presents the properties of Coarse and Fine aggregates used in the mix. The study presents two mixes for the conventional OPC-based concrete and two for alkali-activated concrete. The mixed proportions are adopted from the past literature. (Table 5) and (Table 6) give the ratio of the materials used in the mixes of geopolymer and conventional concrete, respectively.

Table 5. *Mix details of geopolymer concrete*

Mix Parameter	GC1	GC2
Total cementitious Binder (Kg/m^3)	350	380
The ratio of water to total cementitious binder	0.50	0.40
Na2O (% by weight of total cementitious binder)	7	8
Activator Modulus (SiO_2/Na_2O)	1	1
GGBS (Kg/m^3)	245	266
Fly ash (Kg/m^3)	105	114
NaOH (Kg/m^3)	17.24	21.39
Na_2SiO_3 gel (Kg/m^3)	74.20	92.12
Fine Aggregate (Kg/m^3)	690	660.80
Coarse Aggregate – 10 mm (Kg/m^3)	514.50	540
Coarse Aggregate – 20 mm (Kg/m^3)	631	662
Water (after correction) (Kg/m^3)	132.48	107.58

Table 6. *Mix Proportion of Conventional Concrete*

Id	w/b	Total Cementitious Content [Cement C + Flyash (FA) + Silica Fume(SF)] (Kg/m^3)	Water Content (Kg/m^3)	Admixture % by weight ofCement	Fine Aggregateas % of Total Aggregate by weight
CC1	**0.36**	**417 (334+83+0)**	150	0.45	39
CC2	**0.27**	**525 (400+75+50)**	140	.70	39

The mentioned mixes were prepared in three different variations –(i) Control or Plain mix – P, (ii) With 1% Steel fiber by volume – S, and (iii) With 1% of hybrid fiber by volume containing 75% steel fiber and 25% Polypropylene fiber by volume -H. The Steel fibers used are 0.55 mm in diameter and 35 mm in length and have an aspect ratio of 63. The tensile strength of the fibers as per the manufacturer is 1486.99 N/mm^2. The polypropylene triangular fiber of 6 mm length has been used in the hybrid fiber mix. The density of SF is 7860 Kg/m^3, and the density of PPF is 910 Kg/m^3. (Figure 3) shows the steel and Polypropylene fiber used in the study.

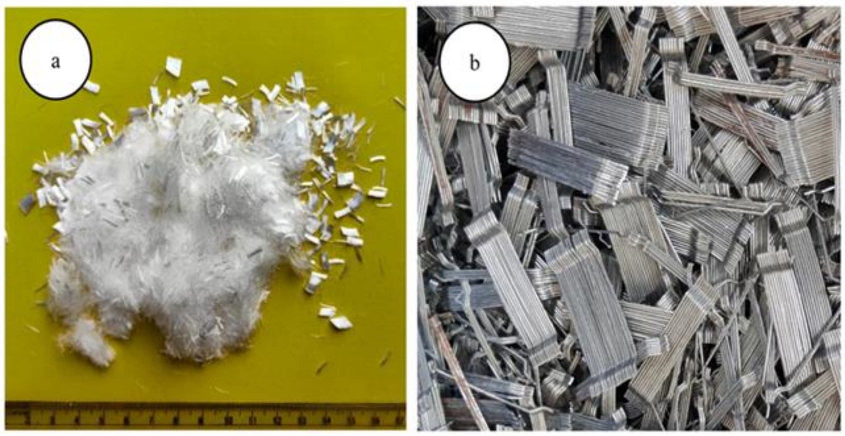

Figure 3 (a) Polypropylene fiber and (b) steel fiber used in the study

3. Experimental Setup and Test Procedure

This section discusses the compressive strength test, split tensile strength test, and 3-Point bend test on notched beams, based on the approved methods by the standards and the literature.

3.1 Compressive strength, Split Tensile Strength, MOE, and Poisson's ratio

This compressive strength was measured at 28-day per IS: 516 (Bureau of Indian Standards, 2004). The split tensile strength test was performed on cylindrical concrete specimens after a 28-day curing period according to IS:516 (Bureau of Indian Standards, 2004). ASTM-C469 (ASTM, 2014) was used to determine the samples' MOE and Poisson ratio. The investigation reported average value for a group of three specimens for each of these tests.

3.2 Three-point bend test on Notched beam

The test procedure of the 3-Point bending test described by RILEM and literature (Ojha et al., 2022), (R.T.-50 F.M.C., 1985), (Shah, 1990), (Alwesabi et al., 2021) was used to assess various fracture parameters for a notched beam specimen. (Figure 4) and (Figure 5) depicts a schematic design of the 3-Point bend test and the laboratory equipment setup for the test performed. The test specimen is a notched beam with a 35 mm notch at the mid-span. The dimensions of the beam are 100mm x 100mm x 500mm. It is simply supported on two smooth rollers and bears a clear span of 400 mm, as illustrated in (Figure 4b).

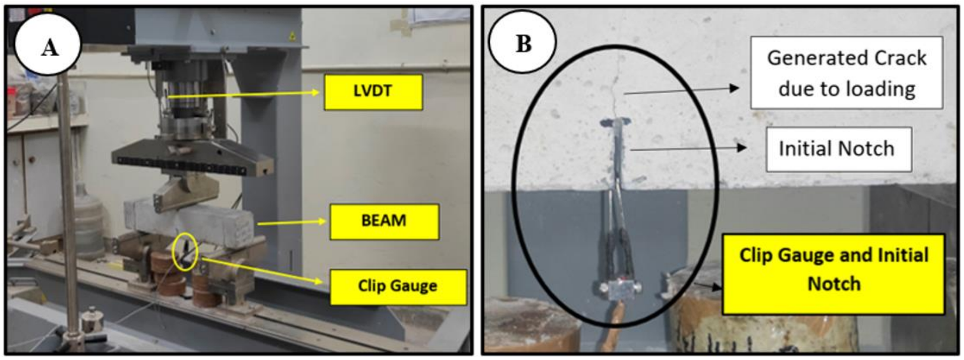

Figure 4. *(a) Setup for three-point bend test, (b) Initial Notch, generated crack due to loading and clip gauge measuring CMOD during the test*

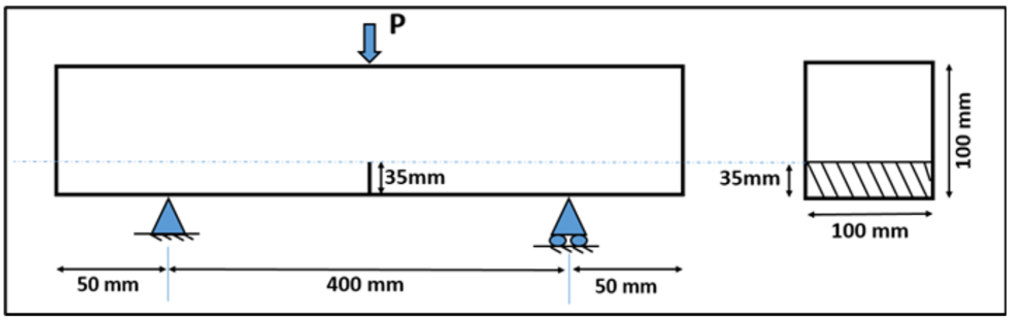

Figure 5. *Beam dimensions and notch depth for the test*

The deflection at mid-span was measured with an LVDT, and the Crack Mouth Opening Displacement (CMOD) was measured using a clip gauge that was supported by two steel knife edges. The load was applied on the beam at the rate of 0.40 µm/sec using a displacement control machine having a load capacity of 30kN.

4. Results and Discussions

4.1 Compressive strength, Split Tensile Strength, and density

The findings on the compressive and split tensile strength along with the hardened density is presented in (Table 7). The mixes considered bears two different strength ranges. The normal strength (CC1 and GC1) has an approximate cube compressive strength of 50 MPa at 28 days and The high strength mix (CC2 and GC2) has cube strength of approximately 70 MPa at 28 days. The addition of fibers does not have significant effect on the compressive strength of both conventional and geopolymer concrete. The split tensile strength and density also varies marginally in different mixes. The spilt tensile strength values for the normal strength conventional concrete with and without fiber is approximately 4 MPa and similar split tensile strength is observed in normal strength geopolymer concrete. However, for higher strength range the split tensile strength of the conventional cement concrete is marginally higher than the split tensile strength of geopolymer concrete. The reason for the variation can be attributed to the presence of silica fume in the higher strength conventional concrete which is known to improve the mechanical properties of the concrete in past literatures. The variations in the hardened density of different samples are marginal and is approximately 2500 Kg/m^3.

Table 7. *Compressive strength, Split Tensile Strength, and density of the mix considered*

Id	Type	28-day strength (MPa)		Split Tensile strength (MPa)	Hardened Density (Kg/m^3)
		Cube Strength	Cylindrical Strength		
CC1_P	Normal Strength Cement Concrete	54.10	39.30	4.04	2517
CC1_S	Normal Strength Cement Concrete with steel fibers	53.20	44.87	4.73	2540
CC1_H	Normal Strength Cement Concrete with hybrid fibers	45.40	27.80	3.82	2502
GC1_P	Normal Strength Geopolymer Concrete	54.20	45.56	4.09	2505
GC1_S	Normal Strength Geopolymer Concrete withSteel Fibers	65.30	62.45	5.32	2533
GC1_H	Normal Strength Geopolymer Concrete with hybrid fibers	50.30	51.50	3.93	2466
CC2_P	High Strength Cement Concrete	71.30	62.4	5.05	2463
CC2_S	High Strength Cement Concrete 2 with steel fibers	83.10	75.29	7.15	2517
CC2_H	High Strength Cement Concrete with hybrid fibers	75.00	57.56	6.14	2554
GC2_P	High Strength Geopolymer Concrete	72.17	64.38	4.50	2482
GC2_S	High Strength Geopolymer Concrete with steel fibers	65.33	65.37	5.48	2546
GC2_H	High Strength Geopolymer Concrete with Hybrid Fibers	62.33	70.30	5.26	2471

4.2 Modulus of Elasticity and Poisson's ratio

The experimentally determined values of the modulus of elasticity (M.O.E.) and the Poisson's ratio is given in (Table 8). The trend of variation of M.O.E. of the concrete samples has been shown in (Figure 6).

Table 8. *M.O.E. and Poisson's ratio*

		CC1	**CC2**	**GC1**	**GC2**
M.O.E. (GPa)	Control	32.64	43.131	22.92	33.374
	SF	32.94	43.381	33.854	36.821
	HF	31.41	43.536	33.398	37.05
Poisson's ratio	Control	0.16	0.137	0.175	0.139
	SF	0.165	0.137	0.141	0.15
	HF	0.17	0.157	0.179	0.189

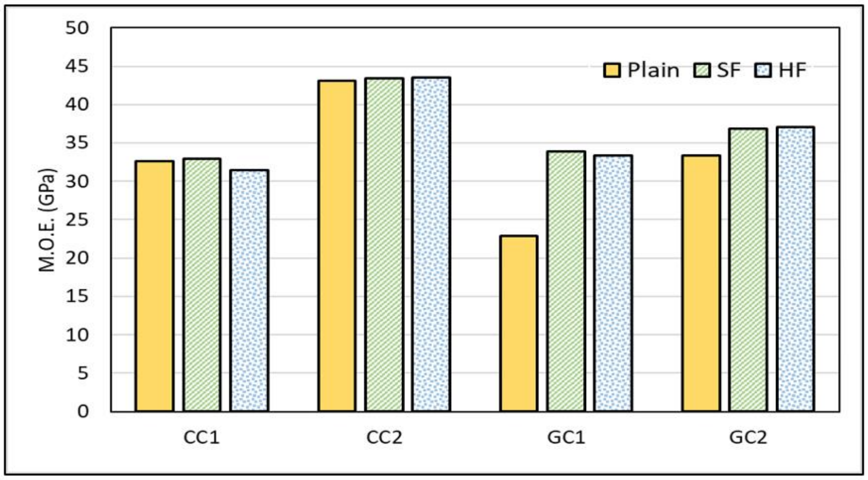

Figure 6. *Modulus of elasticity*

The plot shows a lower modulus of elasticity of geopolymer concrete compared to the conventional cement concrete. Past literature validates the trend of present finding. Past study by (Trivedi et al., 2022) suggests that geopolymer concrete exhibits a drop in elastic modulus values when compared to conventional concrete of the same compressive strength. In slag-based geopolymer concrete, C-A-S-H gel has an intrinsic modulus similar to that of C-S-H gel formed in cement. However, the intrinsic modulus of the N-A-S-H gel produced in low-calcium fly ash gel-based geopolymer concrete is significantly lower than that of the C-S-H gel produced in cement. Due to the low intrinsic modulus of the N-A-S-H gel and the formulation of micro cracks in the slag based geopolymer concrete, the elastic modulus for geopolymer concrete is lower than that of conventional concrete. Comparing the modulus of elasticity of the plain and fiber reinforced concrete it is observed that for conventional cement concrete the difference in M.O.E. values are not significant after the addition of fibers. But for geopolymer concrete the M.O.E. values improve significantly after the fiber addition. The increase in M.O.E. value can be attributed to the interlocking provided by the fibers which limits the micro cracks formation in the geopolymer concrete, thereby improving the elasticity of the concrete. However due to the prevailing lower intrinsic modulus in geopolymer concrete, the M.O.E. values of fiber reinforced geopolymer concrete is lower than their convention concrete counterparts.

4.3 Load-CMOD and load-deflection behaviour

(Figure 7), (Figure 8) and (Figure 9) shows the Load-CMOD and Load-deflection curves for different mix designs considered in the study.

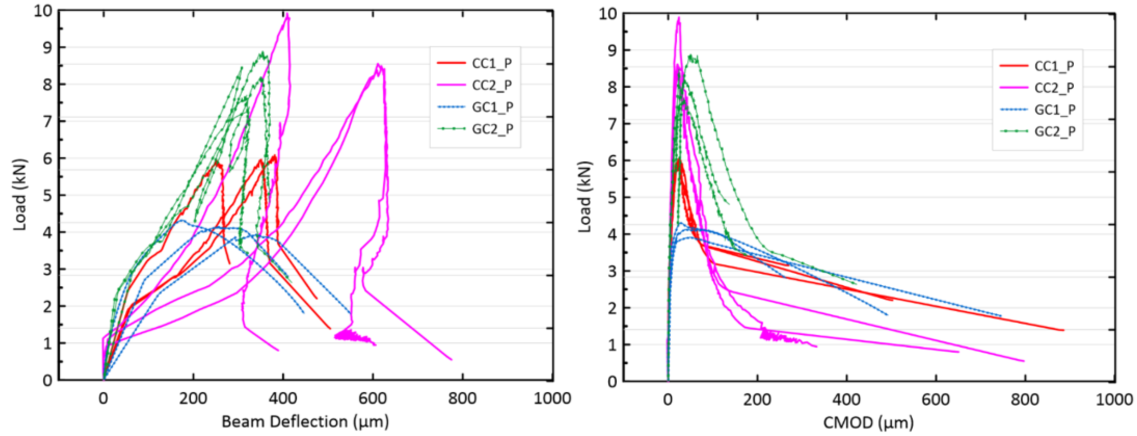

Figure 7. *Load-deflection and Load-CMOD behaviour of Mixes without fiber*

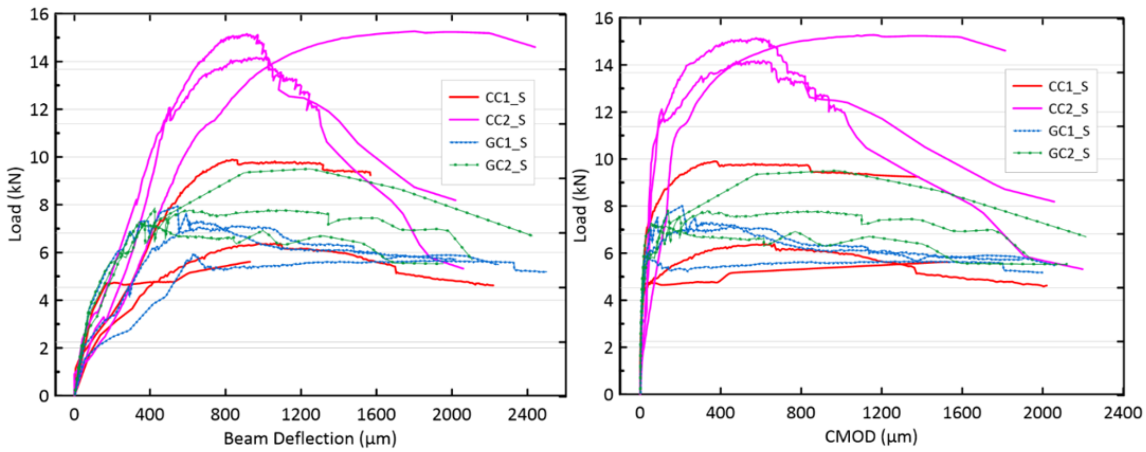

Figure 8. *Load-deflection and Load-CMOD behaviour of Mixes with 1% steel fiber*

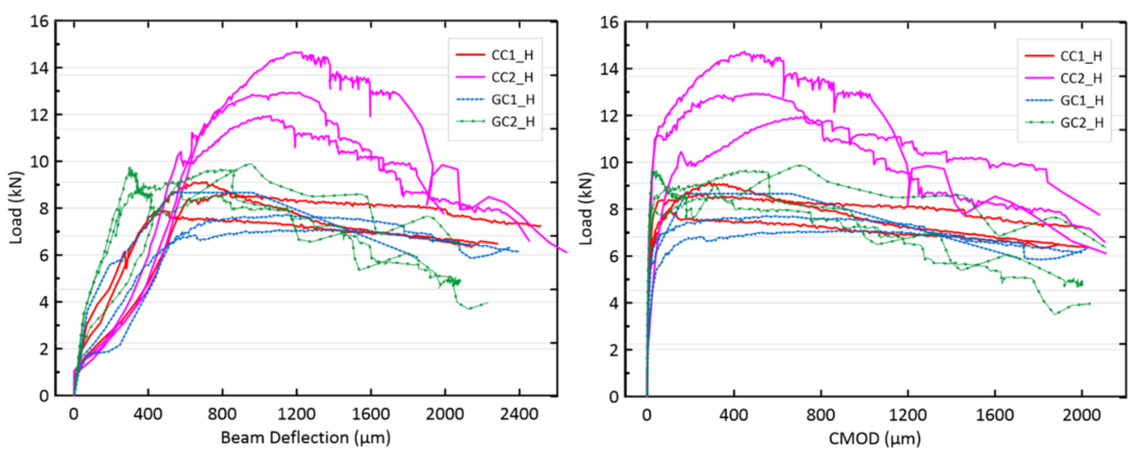

Figure 9. *Load-deflection and Load-CMOD behaviour of Mixes with 1% Hybrid fiber (0.75% F + 0.25% PP) S*

As seen in the plots the peak of the curves depends primarily on the grade of the concrete samples. Also, the curve peaks does not change significantly after the addition of fibers, however the post peak behaviour of the curves improved massively and will be reflected in the fracture parameters. The high strength conventional concrete with fibers shows an exceptional behavior and has the highest peaks. Also the peak in these samples were seen at higher CMOD level suggesting comparatively better ductility. The reason can be attributed to the action of the silica fume present in these mixes.

4.4 Peak load Capacity and flexural strength

Peak load is the maximum flexural load taken by the specimen during the tree point bend test and the Flexural strength is calculated from the Peak load using the (Equation 1) as given below (Patel et al., 2020):

$$Flexural\ strength\ (MPa) = \frac{3P_{max}L_{eff}}{2b(h-a_0)^2} \qquad (1)$$

Where P_{max} is the peak load, L_{eff} is the effective length of the beam, b is the width of the beam, h is the height and a_0 is the notch depth. The values for these dimensions are given with the experimental details in previous sections. The dimension of the beams for all the samples are similar, therefore the flexural strength plot represents a factored peak load plot. For the reason, the comparative trend for the flexural strength follows the trend of the peak load.

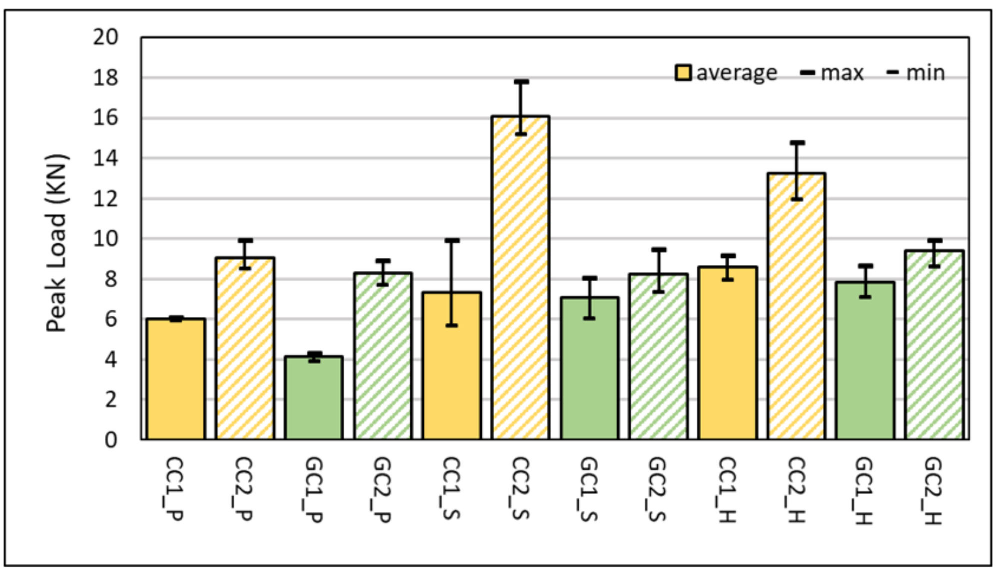

Figure 10. *Peak load*

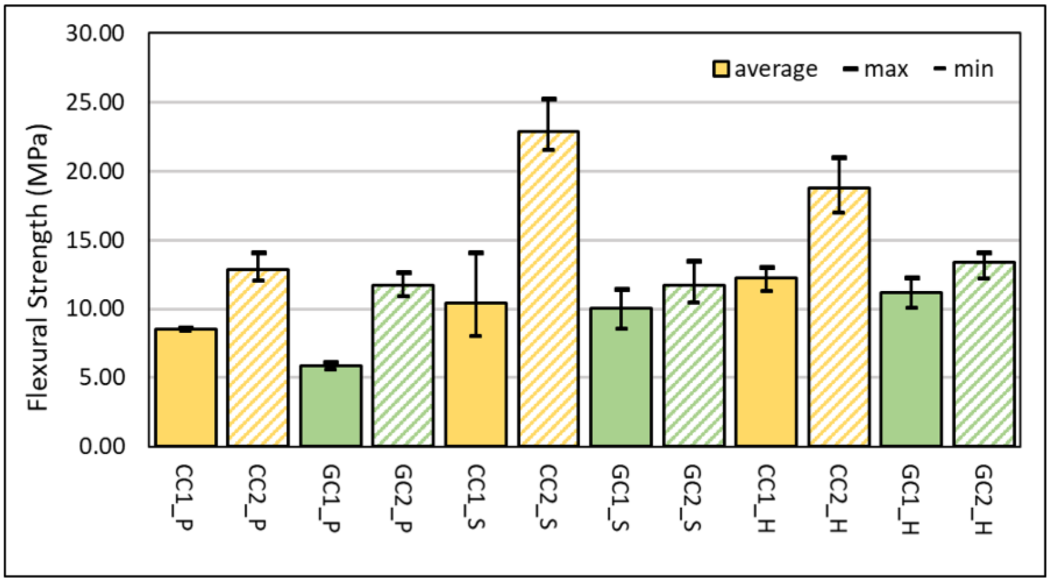

Figure 11. *Flexural strength*

(Figure 10) and (Figure 11) shows the peak load and the flexural strength values for the samples tested in three-point bend test. Comparing the load capacities and flexural strength of the plain conventional (CC1_P, CC2_P) and geopolymer concrete (GC1P, GC2P) of similar strength ranges, the geopolymer concrete shows lower value than the conventional concrete. Literature suggests that the slag bases geopolymer concrete shows a higher compressive strength with increase in the activator modulus and the activator solution concentration, but the rise in the compressive strength is not reflected proportionally as increase in the flexural strength. The reason is attributed to the formation of micro cracks in slag based geopolymer gels. Therefore, although the plain geopolymer concrete has achieved the equivalent compressive strength as the conventional concrete the peak load and flexural strength values are lower than the conventional concrete. However, except for the case of high strength conventional concrete, after the addition of steel or hybrid fibers the peak load capacities and the flexural strength of normal strength convention concrete is comparable with those of normal strength geopolymer concrete. High strength conventional concrete (CC2_P, CC2_S, CC2_H) bears exceptional properties in terms of increase in load capacity and flexural strength increase with addition of steel fibers. This exceptional improvement can be attributed to the presence of silica fume in high strength conventional concrete mix which tends to significantly improve the flexural capacity of the concrete thereby improving the peak load in the high strength conventional concrete.

4.5 Fracture Energy

One of the basic properties of the material which is useful in analysing and determining crack resistance, brittleness and toughness is termed as Fracture energy (Gf) which can be defined as the energy required to create a unit crack in a given specimen (R.T.-50 F.M.C., 1985). This energy can be calculated using (Equation 2).

$$G_f(N/m) = (W_o + mg\delta_o)/A_{lig} \tag{2}$$

The above equation for calculating G_f uses W_o as the area under the load-deflection curve for the tested beam., g is acceleration due to gravity, i.e., 9.81 m/s^2, m as total weight which includes total weight of the loading arrangement not attached to beam and total weight of the beam between the support, Alig as area of ligament representing area of projection of fractural zone on the plane perpendicular to the axis of the beam.

DOI: 10.7764/RIC.00075.21

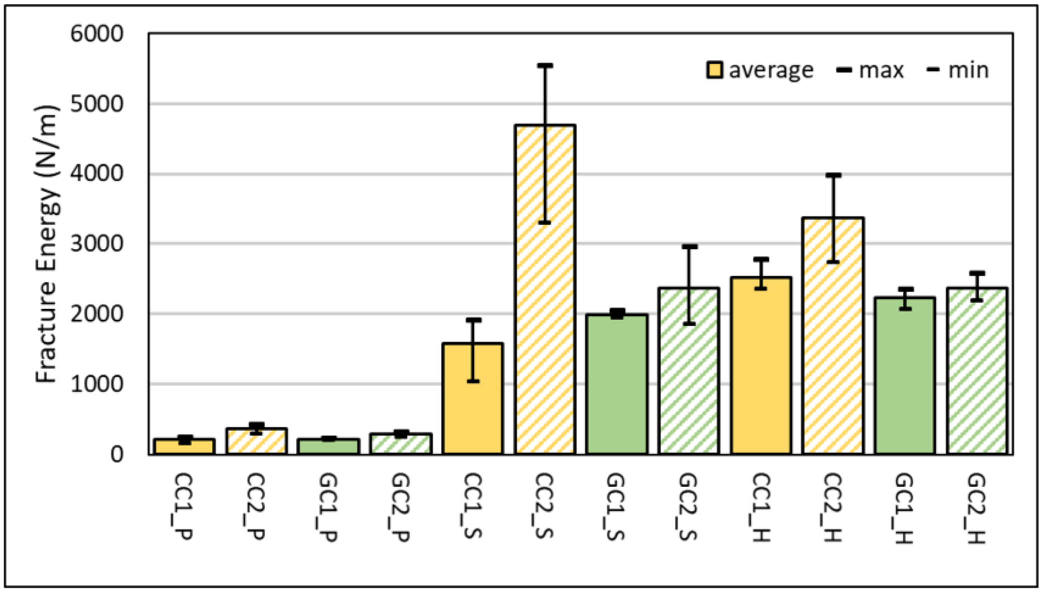

Figure 12. *Fracture energy*

As shown in (Figure 12) the highest fracture energy is shown by high strength conventional concrete with steel fibre (CC2_S) followed by high strength conventional concrete (CC2_H) with hybrid fibers. As explained earlier, the high strength concrete shows exceptional flexural properties due to the presence of silica fume in the mix. Along with this the improvement in the fracture performance of the concrete after the addition of fibers is related to the interlocking provided by the fibers by in the concrete. Well established literatures suggest that the geopolymer concrete consists of less pores than the conventional concrete made with OPC. The pores are crucial for achieving the optimum benefit from the fiber addition in the mix. With increase in the strength of the geopolymer mix the pores decreases drastically therefore the fibers added in the mix is not able to shows the similar interlocking effect as visible in high strength conventional concrete. Along with having number of pores the size of and individual pore in the geopolymer concrete is smaller. Literature suggests that the geopolymer concrete consist of mesopores with size ranging from 2 nm to 50 nm, with maximum pores below 20 nm. On contrary the pore size of conventional ordinary Portland cement concrete ranges between 10 to 100 nm. The size of this nano-scale pores significantly affects the performance of hybrid fibers which consists of 25% polypropylene fibers. The polypropylene fibers can bend and get into these pores more effectively than the steel fibers. Comparing the geopolymer samples with steel fibers (GC1_S, SC2_S) and with hybrid fibers (GC1_H, GC2_H), the samples with hybrid fibers shows slightly better fracture energy. This is contrary to the trend in the conventional concrete where the steel fiber reinforced concrete shows a superior behaviour than the hybrid fiber reinforced concrete. Because in conventional concrete there are enough pores for the steel fibers that the action of hybrid fiber is not that significant.

4.6 Stress intensity Factor

Stress Intensity Factor (K_{IC}) is a factor which quantifies the stress in the surrounding of a crack, and is useful in comparing the brittleness of two separate materials. As the values of K_{IC} increases the ability of concrete to bear higher stresses around the crack increases showing less brittle behaviour. This factor can be calculated using the following (Equation 3) as given in RILEM TC 89-FMT (Shah, 1990):

$$K_{IC}\ (MPa\sqrt{m}) = 3(P_{Nmax} + 0.5mg)\frac{S\sqrt{\pi a}}{2d^2\, b} f(\alpha) \qquad \textbf{(3)}$$

In the above equation, S is used as span of the beam in m, α is used as ratio of a and d which is α = a/d = 0.35, PNmax is given as maximum load that is applied on the notched prism in Newton, and f(α) is used for geometry correction for bending load and is given by (Equation 4) as follows:

$$f(\alpha) = \frac{1.99 - \alpha(1-\alpha)(2.15 - 3.9\alpha + 2.7\alpha^2)}{\sqrt{\pi}(1+2\alpha)(1-\alpha)^{3/2}} \quad (4)$$

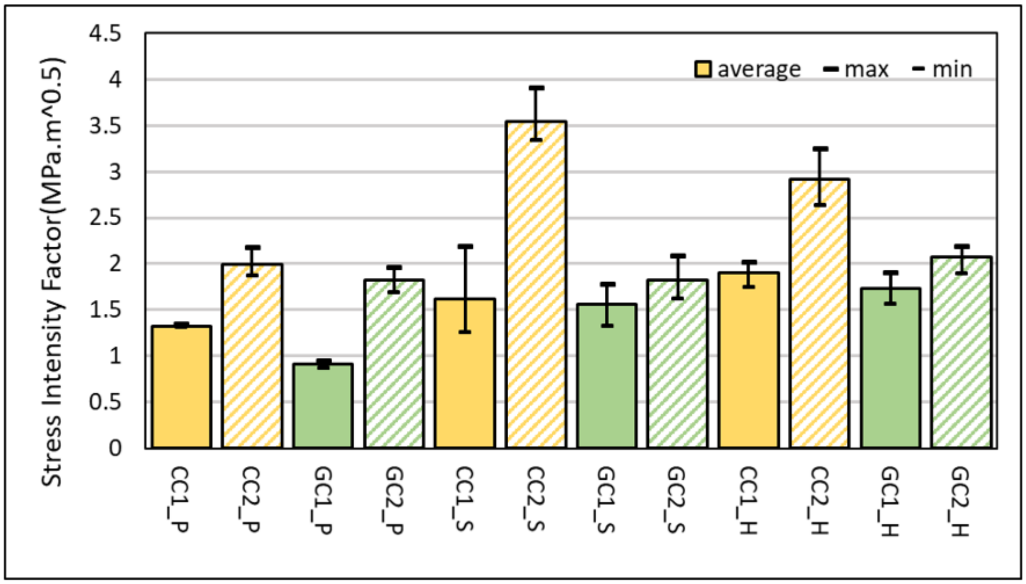

***Figure 13.** Stress Intensity Factor*

Stress intensity factor is directly linked with the initiation of newer crack in the concrete. Past literature suggests that the grade of the concrete is more important factor for stress intensity factor than the fiber reinforcement for conventional concrete. The same is observed here also, the higher strength concrete has higher stress intensity factor than the normal strength concrete for both the conventional and geopolymer concrete. With addition of steel fibers, the stress intensity factor increases further when compared to the plain concrete. Also, similar to the fracture energy the high strength conventional concrete with steel and hybrid fibers shows exceptional behaviour due to the presence of silica fume. The stress intensity factor for the hybrid fiber reinforced geopolymer concrete is greater than that of the steel fiber reinforced geopolymer concrete, depicting an opposite trend to the conventional concrete. Similar to fracture energy, the reason can be attributed to the presence of finer pores in the geopolymer concrete which is more suitable for the polypropylene fibers than the steel fibers, present in the hybrid fiber mix.

4.7 Characteristic length

In nonlocal continuum formulations, characteristic length is a material parameter that indicates the smallest possible breadth of a zone of strain-softening damage (Bazant and Pijaudier-Cabot, 1989). In discrete fracture models, it may be thought of as the smallest feasible fracture length. Characteristic length is a measure brittleness of two materials in terms of the the beginning of early fractures. Smaller characteristic length materials are more brittle; therefore, fracture propagation is easier in these materials. It can be evaluated using (Equation 5) based on literature (Sahin and Köksal, 2010) as given below.

$$L_{ch}(mm) = \frac{EG_f}{{f_{st}}^2} \quad (5)$$

In (Equation 4) E is young's modulus, G_f is the fracture energy and f_{st} is the split tensile strength for the mix. The calculated values for the characteristic length is presented in (Figure 14).

The characteristic length of concrete depends mathematically on the modulus of elasticity, fracture energy and the split tensile strength of the concrete. Since, the plain geopolymer concrete has smaller modulus of elasticity than the conventional concrete the same has been reflected in the characteristic length.

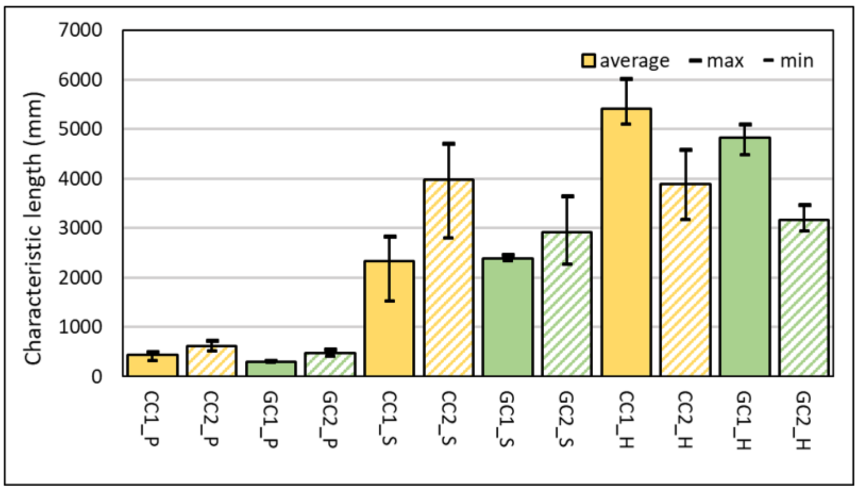

***Figure 14.** Characteristic Length*

The reason for lower characteristic length can be attributed to the lower intrinsic modulus of the N-A-S-H gel produced in geopolymer concrete compared to the C-S-H gel produced in cement. Due to the low intrinsic modulus of the N-A-S-H gel and the formulation of micro cracks in the slag based geopolymer concrete, the elastic modulus and elasticity for geopolymer concrete is lower than that of conventional concrete. Due to lower elasticity the geopolymer is more brittle and therefore possess smaller characteristic length than conventional concrete. Also, similar to the findings of the past studies, with addition fibers in the concrete the characteristic length of the concrete increases significantly. Due to presence of more pores, bigger in size than the pores in geopolymer concrete, the fiber reinforced conventional concrete shows better characteristic length than the geopolymer concrete of comparable strength. In the case of hybrid fiber reinforcement, the Polypropylene fibers gives a better interlocking of the concrete in the smaller pores of the geopolymer concrete than the steel fibers. As a result, the characteristic length of the hybrid fiber reinforced concrete is greater than the steel fiber reinforced concrete.

4.8 Energy Release rate

The energy release rate is the rate at which energy is changed as a material fractures and a new surface emerges. It is expressed quantitatively as the reduction in total potential energy per increase in fracture surface area. The energy release rate is a critical component in determining material properties linked to fracture and fatigue. It can be evaluated using (Equation 5) as presented by literature (Taha et al., 2008).

$$G_{IC}(N/m) = \frac{{K_{IC}}^2}{E}$$

(5)

In (Equation 5) KIC the stress intensity factor and E is the modulus of elasticity of the specimen. The comparative graphs for the energy release rate are shown in (Figure 15). The energy release rate shows a similar trend to other fracture parameters. With increase in the grade of concrete the energy release rate increases. Also with addition of the fibers the energy release rate increases due to the interlocking provided by the fibers in the mix. The highest energy release rate is given by the high strength conventional concrete with steel fibers followed by the same mix with hybrid fibers. Also, the trend of variation of the energy release rate is opposite between the conventional and geopolymer concrete when steel and hybrid fiber reinforcement are compared. Due to dominant presence of meso-scale pores in geopolymer concrete the hybrid reinforcement is more effective in geopolymer concrete which is opposite to the conventional concrete where the steel fiber reinforcement shows the superior performance.

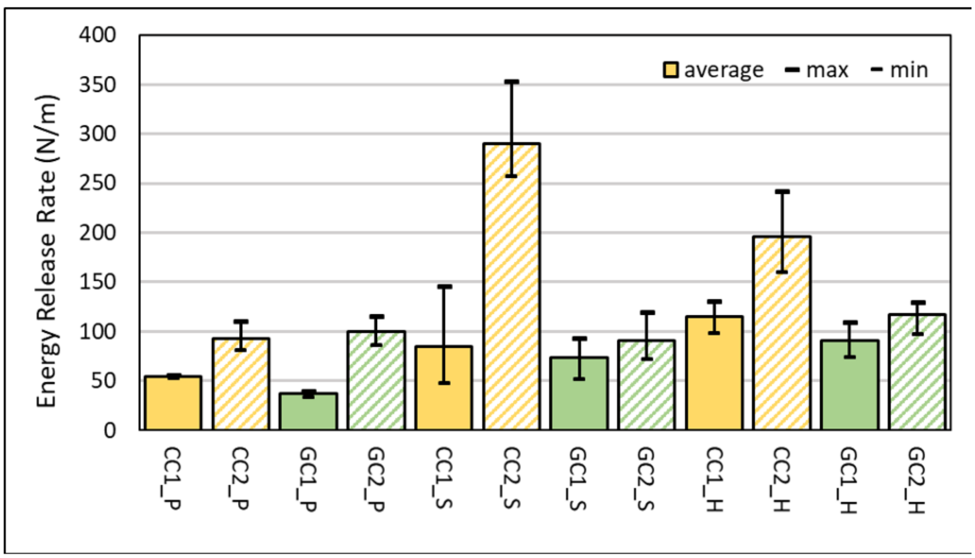

Figure 15. *Energy release rate*

4.9 Comparative analysis on the mechanical and fracture performance of geopolymer concrete and conventional concrete.

The ratio of the observed properties of the geopolymer and conventional concrete mixes are summarized in (Table 9).

DOI: 10.7764/RIC.00075.21

Table 9. *Comparison of properties of geopolymer concrete with comparable strength conventional concrete*

Parameters	**Ratio of geopolymer to Conventional (without fibers)**		**Ratio of geopolymer to Conventional (with steelfibers)**		**Ratio of geopolymer to Conventional (with hybrid fibers)**	
	Normal Strength	High Strength	Normal Strength	High Strength	Normal Strength	High Strength
Binder Content	0.84	0.72	0.84	0.72	0.84	0.72
Compressive Strength	1.00	1.01	1.23	0.79	1.11	0.83
Modulus of Elasticity	0.70	0.77	1.03	0.85	1.06	0.85
Peak Load/FlexuralStrength	0.69	0.91	0.96	0.51	0.91	0.79
FractureEnergy	1.01	0.79	1.26	0.51	0.89	0.86
Stress Intensity factor	0.69	0.91	0.96	0.51	0.91	0.79
Characteristic Length	0.69	0.77	1.03	0.73	0.89	1.00
Energy release rate	0.68	1.08	0.86	0.31	0.79	0.73

Table shows that instead of having a lower binder content the geopolymer concrete achieved the similar compressive strength as conventional concrete. Also, the other facture parameters with some exceptions which are lower than the comparable compressive strength conventional concrete is in comparable range considering the ratio of the binder content in the mix. Table shows a possibility of having some correlation between binder content and fracture performance of the OPC and the geopolymer concrete. The details and the possible explanation for the variations shown in the table has already been discussed in earlier sections.

5. Conclusion

• Past studies suggest that the differences between the mechanical and fracture performance of the Conventional OPC concrete and geopolymer concrete primarily originate from the variations in their microstructure, intrinsic properties of different gel systems, pore size and number, and developed microcracks in the concrete types. The experimental findings affirm the propositions in the literature.
• The geopolymer concrete achieved a similar compressive strength to conventional OPC concrete at a lower binder content. This can be attributed to the crosslinking in the C-A-S-H and N-A-S-H gel presents the hardened geopolymer concrete, which is not observed in the C-S-H gel of conventional OPC concrete.
• The modulus of elasticity of geopolymer concrete is lower than that of conventional OPC concrete. The possible reasoning for the observed behavior is the lower intrinsic modules of the gel system and the presence of microcracks in the geopolymer concrete, as suggested by past researchers. The N-A-S-H gel formed in the geopolymer concrete has a lower intrinsic modulus than the C-S-H gel found in hardened OPC concrete. Also, slag-based geopolymer concrete has microcracks which significantly reduces its modulus of elasticity.
• Additionally, it was found that with the addition of fibers, the MOE values increased in geopolymers which can be credited to bridging action provided by the steel and hybrid fibers, which limited the microcrack formation to some extent in the geopolymer concrete.
• The geopolymer concrete's fracture performance is marginally lower than the conventional OPC concrete with comparable compressive strength. But the comparison considering the ratio of binder content suggests that with lower binder content the geopolymer concrete shows fracture performance at par with conventional concrete. With increase in grade of the concrete an improvement in the fracture parameters is observed in both conventional and geopolymer concrete. The conventional concrete mix with silica fume presented the best fracture performance among the considered mixes.
• With the addition of steel and hybrid fibers, the fracture performance of both concrete types improved significantly. However, adding fibers presented opposite improvement trends in conventional and geopolymer concrete. In conventional concrete, steel fibers performed much better than the hybrid fiber reinforcement. Whereas, for geopolymer concrete the hybrid fiber resulted in superior behaviour than the steel fiber alone. The observation affirm the findings in past which suggest the presence of finer pores in the geopolymer concrete

than conventional concrete. Due to the finer pore in geopolymer concrete, the Polypropylene fibers in hybrid fiber mix provided a better interlocking than the steel fiber alone.

6. References

Benachio, G.; Freitas, M.; Tavares, S. (2020). Circular economy in the construction industry: A systematic literature review. Journal of Cleaner Production. 260. 121046. 10.1016/j.jclepro.2020.12104

Ojha, P. N.; Singh, B.; Kaura, P.; Singh, A. (2021). Lightweight geopolymer fly ash sand: an alternative to fine aggregate for concrete production. Research on Engineering Structures and Materials. 10.17515/resm2021.257ma0205.

Ojhaa, P.N.; Prakash, S.; Singh, P.; Mandre, M.K.; Kumar, S. (2022). Effect of high ratio fly ash on roller compacted concrete for dam construction. Research on Engineering Structures and Materials, 8(2): 233-251.

Ojha, P. N.; Arora, V.V.; Trivedi, A.; Singh, A.; Singh, B.; Kaushik, N. (2021). Experimental Investigations on Use of C&D Waste as an Alternative to Natural Aggregates in Concrete. Sustainable Structures and Materials, Vol. 4, (1), 58-70

Trivedi, A.; Ojha, P.N.; Singh, A.; Singh, B.; S. Bansal, S.; Sengupta, L. (2022). "Experimental investigations on mechanical properties of normal and high strength high calcium geopolymer concrete," Journal of Asian Concrete Federation, 8(1), pp. 16–25, Jun. 2022, doi: 10.18702/acf.2022.6.8.1.16.

Myers, R.; Bernal Lopez, S; Provis, J. (2013). Generalized Structural Description of Calcium–Sodium Aluminosilicate Hydrate Gels: The Cross-Linked Substituted Tobermorite Model. Langmuir, 29 (17). 5294 - 5306. ISSN 0743-7463 https://doi.org/10.1021/la4000473 **Hassan, A.; Arif, M.; Shariq, M. (2020).** "Influence of Microstructure of Geopolymer Concrete on Its Mechanical Properties—A Review," LNCE, volume 35. pp. 119–129. doi: 10.1007/978-981-13-7480-7_10.

Teixeira Marvila, M.; Rangel Garcez de Azevedo, A.; Barbosa de Oliveira, L.; de Castro Xavier, G.; Fontes Vieira, C. (2021). "Mechanical, physical and durability properties of activated alkali cement based on blast furnace slag as a function of %Na_2O," Case Studies in Construction Materials, vol. 15, p. e00723, doi: 10.1016/j.cscm.2021.e00723.

Lahoti, M.; Tan, K.H.; Yang, E.H. (2019). "A critical review of geopolymer properties for structural fire-resistance applications," Construction and Building Materials, vol. 221, pp. 514–526, Oct. 2019, doi: 10.1016/j.conbuildmat.2019.06.076.

Criado, M.; Fernández-Jiménez, A.; Palomo, A. (2007). "Alkali activation of fly ash: Effect of the SiO_2/Na_2O ratio. Part I: FTIR study," Microporous and Mesoporous Materials, 106(1–3), doi: 10.1016/j.micromeso.2007.02.055.

Criado, M.; Fernández-Jiménez, A.; Palomo, A.; Sobrados, I.; and J. Sanz, J. (2008). "Effect of the SiO_2/Na_2O ratio on the alkali activation of fly ash. Part II: ^{29}Si MAS-NMR Survey. Microporous and Mesoporous Materials, 109(1–3), doi: 10.1016/j.micromeso.2007.05.062.

Provis, J.L.; Myers, R.J.; White, C.E.; Rose, V.; Deventer, J.S.J. (2012). "X-ray micro tomography shows pore structure and tortuosity in alkali-activated binders," Cement and Concrete Research, 42(6), doi: 10.1016/j.cemconres.2012.03.004.

Garboczi, E. J. (1990) "Permeability, diffusivity, and microstructural parameters: A critical review," Cement and Concrete Research, 20(4), doi: 10.1016/0008-8846(90)90101-3.

Yang, M.; Paudel, S.R.; Asa, E. (2020). "Comparison of pore structure in alkali activated fly ash geopolymer and ordinary concrete due to alkali-silica reaction using micro-computed tomography," Construction and Building Materials, vol. 236, p. 117524, doi: 10.1016/j.conbuildmat.2019.117524.

Ojha, P.N.; Singh, P.; Singh, B.; Singh, A.; Mittal, P. (2022). . Fracture behavior of plain and fiber-reinforced high strength concrete containing high strength steel fiber. Research on. Engineering. Structural. Materials 8(3): 583-602. http://dx.doi.org/10.17515/resm2022.377ma1228

Singh, B.; Patel, V.; Ojha, P.N.; Arora, V. (2020). "Analysis of stress block parameters for high strength concrete," Journal of Asian Concrete Federation, 6(1), pp. 1–9, doi: 10.18702/acf.2020.6.6.1.

Singh, B.; Arora, V.; Patel, V. (2018). "Study on stress strain characteristics of high strength concrete," Indian Concrete Journal, 92(6) pp. 37–43.

Arora, V.; Singh, B.; Jain, S. (2016). "Experimental studies on short term mechanical properties of high strength concrete," Indian Concrete Journal, 90(10) pp. 65–75.

Ojha, P.N.; Singh, B.; Singh, A.; Patel, V.; Arora, V. (2021). "Experimental study on creep and shrinkage behaviour of high strength concrete," Indian Concrete Journal, 95(2), pp. 30–42.

Arora, V.; Singh, B.; Patel, V.; Trivedi, A. (2019)."Stress–Strain Behaviour and Performance Evaluation of High Strength Steel Fibre Reinforced Concrete," Indian Concrete Journal, 93(12), pp. 54–61.

Arora, V.; Singh, B.; Jain, S. (2017). "Effect of indigenous aggregate type on mechanical properties of high strength concrete," Indian Concrete Journal, 91(1) pp. 34–44.

Singh, B.; Ojha, O.P.; Patel, V.; Trivedi, A.; Singh, A. (2021). "Empirical equation and experimental validation of shear parameters for high strength concrete (HSC)," The Journal of Asian Concrete Federation, 7(2), pp. 46–55, doi: 10.18702/acf.2021.12.7.2.46.

Patel, V.; Singh, B.; Ojha, P.N.; Adhikari, S. (2021). "Mechanical Properties of Polypropylene Fiber Reinforced Concrete under Elevated Temperature," Journal of Architectural Environment and Structural Engineering Research, 4(2), doi: 10.30564/jaeser.v4i2.3296.

Asrani, N.P.; Murali, G.; Abdelgader, H.S.; Parthiban, K.; Haridharan, M.K.; Karthikeyan, K. (2019). "Investigation on Mode I Fracture Behavior of Hybrid Fiber-Reinforced Geopolymer Composites," Arabian Journal for Science and Engineering, 44(10), doi: 10.1007/s13369-019-04074-4.

Aisheh, Y.; Atrushi, D.; Akeed, M.; Qaidi, S.; Tayeh, B.A. (2022). "Influence of steel fibers and microsilica on the mechanical properties of ultra-high-performance geopolymer concrete (UHP-GPC)," Case Studies in Construction Materials, vol. 17, p. e01245, doi: 10.1016/j.cscm.2022.e01245.

R. T.-50 F. M. C. (1985) (Draft Recommendation) (1985)., "Determination of the fracture energy of mortar and concrete by means of three-point bend tests on notched beams," Mater. Struct., vol. 18, no. 106, pp. 285–290, 1985.

S. P. Shah, (1990) "Determination of fracture parameters (K Ic s and CTODc) of plain concrete using three-point bend tests," Materials and Structures, vol. 23, no. 6, pp. 457–460, Feb. 1990, doi: 10.1007/BF02472029.

E. A. H. Alwesabi, B. H. A. Bakar, I. M. H. Alshaikh, A. M. Zeyad, A. Altheeb, and H. Alghamdi, (2021) "Experimental investigation on fracture characteristics of plain and rubberized concrete containing hybrid steel-polypropylene fiber," Structures, vol. 33, pp. 4421–4432, Oct. 2021, doi: 10.1016/j.istruc.2021.07.011.

B. of Indian Standards, (2020) "Ordinary Portland cement - Specification (Sixth Revision)," IS 269 : 2015 (Reaffirmed Year : 2020), 2020.

B. of Indian Standards,(2016) "Coarse and Fine Aggregate for Concrete - Specification (Third Revision)," IS 383-2016, 2016.

I. S. 516:2014, (2014) "Method of Tests for Strength of Concrete," IS : 516 - 1959 (Reaffirmed 2004), 2004.

A. S. for Testing and Materials, "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression (ASTM C 469)," ASTM International. 2014.

V. Patel, B. Singh, and V. v Arora, (2020) "Study on fracture behaviour of high strength concrete including **effect of steel fiber," Indian Concrete Journal, vol. 94, no. 4, pp. 1–9, 2020.**

Z. P. Bažant and G. (1989) Pijaudier-Cabot, "Measurement of Characteristic Length of Nonlocal Continuum," Journal of Engineering Mechanics, vol. 115, no. 4, 1989, doi: 10.1061/(asce)0733-9399(1989)115:4(755).

Y. Şahin and F. Köksal, (2011) "The influences of matrix and steel fibre tensile strengths on the fracture energy of high-strength concrete," Construction and Building Materials, vol. 25, no. 4, 2011, doi: 10.1016/j.conbuildmat.2010.11.084.

M. M. R. Taha, A. S. El-Dieb, M. A. A. El-Wahab, and M. E. Abdel-Hameed, (2008) "Mechanical, Fracture, and Microstructural Investigations of Rubber Concrete," Journal of Materials in Civil Engineering, vol. 20, no. 10, 2008, doi: 10.1061/(asce)0899-1561(2008)20:10(640).

P. N. Ojha, A. Trivedi, B. Singh, A. K. N. S, V. Patel, and R. K. Gupta, (2021) "High performance fiber reinforced concrete – for repair in spillways of concrete dams," Research on Engineering Structures and Materials, 2021, doi: 10.17515/resm2021.252ma0128.

V V Arora & Brijesh Singh, (2016), Durability Studies on Prestressed Concrete made with Portland Pozzolana Cement, Indian Concrete Journal, Vol.90, No.8, 41-48

Singh, B., Ojha P.N., Trivedi A., Patel, V., & Arora V V, (2021) "Development Of Empirical Equations For Prediction Of Flexural And Split Tensile Strength For Normal & High Strength Concrete With Granite And Calc-Granulite Aggregate, Indian Concrete Journal, Vol.95, No.11, pp 36-46

PN Ojha, B Singh, A Singh, V Patel, VV Arora (2021) Experimental study on creep and shrinkage behaviour of high strength concrete for application in high rise buildings. Indian Concrete Journal. 2021; 95(2) 30-42.