scientific reports

OPEN

Resilient and green structural potential of steel fiber reinforced geopolymer concrete

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This study investigates the environmental sustainability and long-term durability of structural grade geopolymer concrete, comparing it with conventional cement concrete of similar strength grades. A comprehensive experimental investigation was conducted, optimising geopolymer concrete mix design by varying molar concentrations and incorporating fibers. Mixes incorporating 1% fibers were prepared and tested at 8, 10, 12, and 14 molarities, with a constant sodium hydroxide to sodium silicate ratio of 2.5, to evaluate performance enhancement. Results indicate that the addition of fibers and increasing molarity decreased slump values by up to 41%, reflecting reduced workability. However, compressive strength increased by 11%, showcasing enhanced mechanical properties. Geopolymer concrete also exhibited excellent resistance to long-term durability challenges when exposed to acidic and alkaline environments. Although the cost of geopolymer concrete with 14 M concentration at a laboratory scale is higher than ordinary Portland cement concrete, primarily due to the transportation of materials in small quantities, its environmental benefits are notable. The embodied energy and carbon emissions of geopolymer concrete were found to be 47.84% and 57.62% lower, respectively, compared to Portland cement concrete.

Keywords Structural geopolymer concrete, Steel fiber, Durability studies, Embodied energy, Embodied carbon

The present scenario in the production of ordinary Portland cement (OPC) is a carbon intensive process that generates a substantial amount of greenhouse gas which accounts for approximately 8% of global CO_2 emissions, significantly contributing to global climate change due to its greenhouse gas effects[1,2]. Concrete made from Portland cement is an extremely versatile building material that requires minimal upkeep throughout its lifespan. However, exposure to extreme temperatures can compromise its durability, raising concerns about its ability to withstand chemical assaults, particularly from alkaline and acid environments[3–6]. Furthermore, it has been claimed that the alkaline properties of ordinary Portland cement concrete (OPC) impact the sustainability and longevity of buildings in acidic surroundings[7,8]. During its lifetime, concrete is exposed to various severe conditions depending on its intended use and environmental factors. Researchers have highlighted that acid and alkaline environments, such as those containing sulfuric acid, hydrochloric acid, and magnesium and sodium sulfate, cause detrimental effects on concrete properties. These conditions substantially shorten the service life of concrete structures and negatively affect the environment[9–12].

On the other hand, geopolymers are an alternative to Portland cement, which is made from alkali activated precursor materials. Geopolymers are inorganic materials rich in silicon and aluminium that react with strong alkaline activators, typically a combination of sodium or potassium hydroxide and sodium or potassium silicate[13]. Sodium hydroxide (SH) and sodium silicate (SS) are the most commonly used due to their superior performance, cost-effectiveness, and availability[13,14]. Geopolymer concrete (GPC) offers many environmental benefits along with outstanding mechanical properties and better long term durability properties. It is produced using aluminosilicate rich materials selected from industrial by-products as precursors. Incorporating these byproducts like fly ash (FA), ground granulated blast furnace slag (GGBS), silica fume (SF) and rice husk ash (RHA) into concrete reduces the demand for OPC, thereby promoting environmental sustainability[15–17].

From the various literature, it is observed that significant improvements in the mechanical and long term durability properties of geopolymer concrete (GPC) with the use of various precursor materials, including

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fly ash, ground granulated blast furnace slag, silica fume, rice husk ash, and metakaolin[15–19]. Additionally, incorporating nanoparticles into geopolymer also significantly enhances strength and durability[20,21]. Given the increasing demand for GPC alongside conventional OPC concrete, assessing their resistance to acid and alkaline environments presents a promising area for the present research. Previous studies have indicated that GPCs exhibit superior durability characteristics compared to conventional OPC concrete[22,23]. Many researchers have reported that previous studies assessing the resilience of fly ash (FA) and slag based GPC against acid and alkaline environments have yielded relatively positive results[24–27].

The performance of GPC is significantly influenced by the kinds and attributes of the raw materials, the curing conditions, and a few activator parameters, such as the mass ratio of the NaOH solution to the Na_2SiO_3 solution, the modulus of the NaOH solution, and the concentration of the NaOH solution[26,28–32]. Adding discrete fibers as reinforcement in GPC is a popular technique to increase the ductility of concrete without compromising its compressive strength[33–36]. The construction industry has been very interested in GPC Fiber Reinforced Concretes over the past decade since it has been witnessed that the addition of fiber enhances certain characteristics of ordinary GPC[37]. Researchers have reported that an optimum dosage of steel fibers in concrete is around 1%, which improves mechanical properties without adversely affecting other concrete properties[32,38].

Embodied energy and carbon emissions of concrete are critical metrics in evaluating its environmental impact. These measures account for the total energy consumption and CO_2 emissions from material extraction to construction[39–41]. Indirect transport has the greatest environmental impact, with raw material transport accounting for approximately 80% of the embodied energy and 79% of CO_2 emissions[41]. Understanding these factors is essential for developing sustainable concrete solutions that minimise ecological footprints. Further, carbon emission equivalent (ECO_2-e) in concrete assessments evaluates the environmental impact by quantifying CO_2 emissions during production. Understanding these metrics is crucial for assessing sustainability and optimising eco-friendly concrete solutions. Researchers have chosen various parameters to estimate the CO_2 equivalent (ECO_2-e) more accurately, enhancing the precision of environmental impact assessments for concrete production[42].

In this context, the present experimental investigation addresses the research gap by evaluating the long term durability and ecological aspects of geopolymer concrete with varying sodium hydroxide concentrations. It also provides a comparative assessment of cost, embodied energy and carbon emissions between geopolymer concrete and ordinary Portland cement of a similar grade. The research also aims to use industrial by products which promotes resource efficiency and waste utilisation. The main objective is to estimate the structural viability of GPC as a durable, low carbon alternative to OPC by optimising the mix ingredients and evaluating the performance of acid and alkali conditions. The findings aim to support the broader adoption of GPC in sustainable construction by demonstrating its potential to significantly reduce the carbon footprint while maintaining structural performance.

Significance of the study

This study is significant as it highlights the potential of geopolymer concrete to reduce carbon footprints and improve environmental sustainability in the construction industry. By utilising industrial by-products such as FA and GGBS, geopolymer concrete offers a viable alternative to conventional cement concrete. The comprehensive investigation into mix proportion optimisation and long-term durability demonstrates that geopolymer concrete not only enhances mechanical properties but also provides excellent resistance to acidic and alkaline environments. This research underscores the importance of geopolymer concrete in promoting sustainable construction practices and reducing embodied energy and carbon emissions.

Materials and methodology

Materials

In this section, all materials used in the present study are characterised for their basic properties. Detailed descriptions and specifications of each material, including their physical and chemical properties, are provided to ensure a comprehensive understanding of their roles and contributions to the concrete mix designs. This characterisation is crucial for evaluating the performance and sustainability of both the cement and geopolymer concretes investigated in this study.

The precursor materials used were Class F fly ash (FA) from KPTCL Bellary, and ground granulated blast furnace slag (GGBS) sourced from JSW Steel Plant, Thorangalu, Karnataka. The locally available ordinary Portland cement of 53 grade was used in the present study, in compliance with IS 269[43]. Table 1 provides the details of the physical properties and chemical composition of the materials used in this study.

The chemicals, sodium hydroxide (SH) and sodium silicate (SS) were procured from Om Sanvi Enterprise, Bangalore, India. For this study, the alkali activators were prepared by mixing sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) in the required quantity as per mix details. The mass ratio of sodium silicate solution to sodium hydroxide solution was maintained at 2.5 based on previous studies and literature[10,19,21]. Table 2 provides the properties of NaOH and Na_2SiO_3.

The M-sand utilised in this investigation was bought from the nearby quarry industry. The coarse aggregates of downsize 20 mm were obtained by pulverising hard rock stones locally market. Table 3 gives the physical characteristics of aggregates characterised as per IS 2386[44] and IS 383[45]. The particle size distribution of aggregates is presented in Fig. 1.

In this study, crimped steel fiber was selected for investigation. The steel fiber used in this study has a length of 30 mm, a diameter of 0.5 mm, and an aspect ratio of 60. In this investigation, 1% fiber by mass of the binder was utilised based on previous literature[32,38]. In this study, normal potable tap water was used for the production and curing of cement concrete, while deionised water was used for the production of geopolymer concrete to minimize the influence of external alkalis on the mix composition.

Material	FA	GGBS	Cement
Physical properties			
Specific gravity	2.35	2.91	3.10
Specific Surface area (m^2/kg)	410	500	310
LOI (%)	0.1	0.3	4.0
Colour	Grey	Whitish	Grey
Chemical composition (%)			
SiO_2	61.47	31.31	22.4
Al_2O_3	31.46	18.37	6.5
Fe_2O_3	2.08	0.36	3.75
CaO	0.91	41.94	60.2
SO_3	0.45	2.7	2.14
MgO	0.57	4.37	1.61
Na_2O	0.39	0.1	0.08

Table 1. Properties of materials used in the study.

Properties	Sp. gravity	Molarity	Na_2O	SiO_2	Water
SH (NaOH)	1.53–1.55	8, 10, 12, 14	–	–	–
SS (Na_2SiO_3)	2.11	–	14.7	29.4	47.5

Table 2. Properties of alkaline activators.

Property	Sp. Gr	Bulk Density (kg/m^3)	Water absorption (%)	Finesse modules	Silt content (%)	Aggregate Impact value	Aggregate Crushing value	Elongation index	Flakiness index
M-sand	2.9	1702	1.02	2.13	4.3%	–	–	–	–
C-A	2.7	1456	0.5	6.9	–	26.21	22	13.5	12.6

Table 3. Physical properties of aggregates.

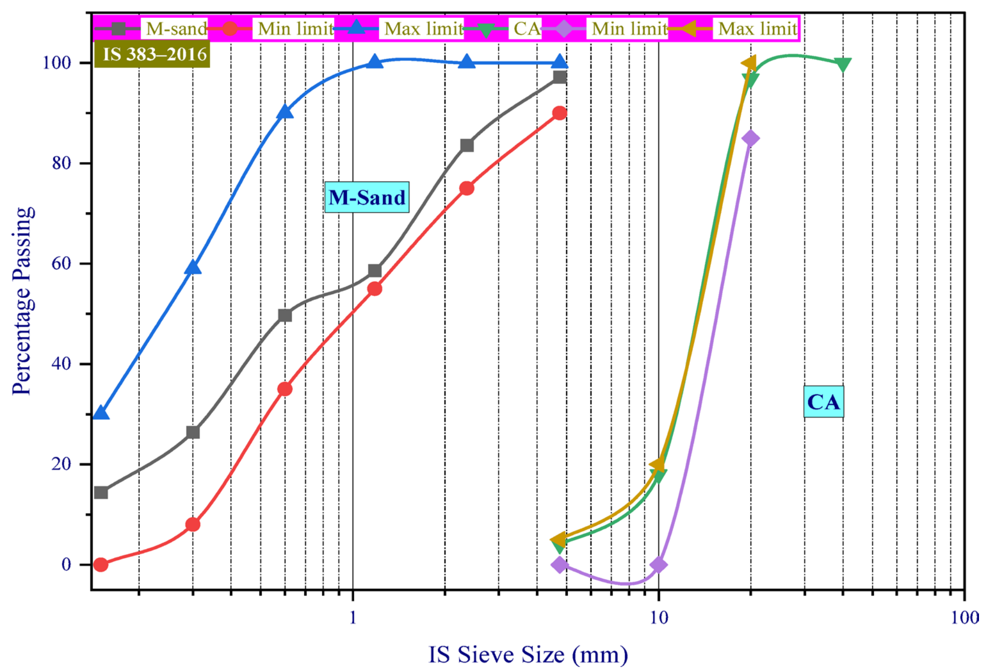


Fig. 1. Particle size distribution of aggregates with limits.

Mix design and Mix designation.

The concrete mix design was carried out according to IS 10262-2009[46] for cement concrete, with details presented in Table 4 for M40 grade concrete with a w/c ratio of 0.35 and geopolymer concrete mix design was selected based on previous studies. Several mixes were prepared with steel fibers (SF) and without steel fibers (NF) for both cement concrete and geopolymer concrete. For example, CCMS indicates a cement concrete mix (control concrete), while CCMSF represents cement concrete with steel fibers. Geopolymer concrete mixes are denoted as follows: M08SF for an 8 molar concentration of sodium hydroxide solution with steel fibers, M10SF, M12SF, and M14SF for 10, 12, and 14 molar concentrations, respectively. Similarly, M08NF denotes an 8-molar concentration of sodium hydroxide solution without steel fibers, with M10NF, M12NF, and M14NF for 10, 12, and 14 molar concentrations without steel fibers.

Preparation of specimens

As presented in Table 4, the materials were proportioned according to the requirements for the preparation of required specimens and mixed in a laboratory mixer. The alkaline solution was prepared at least 24 h before mixing with the solid components and must be used within 36 h to avoid turning into a semi-solid state. The binder and aggregates were dry-mixed in the mixer for 2–3 min before gradually adding the premixed alkaline solution. Mixing then continued for an additional 4–6 min until a stable mix was achieved. The samples were cast into moulds and were then kept in a room with temperatures ranging between 25 ± 2 °C. The samples were demoulded after 24 h and left in the same room to cure until testing for geopolymer concrete specimens. However, the cement concrete specimens were cured in the normal water bath.

Tests on concrete

All the mixes were evaluated for slump in the fresh state according to the guidelines of IS 1199[47]. The compressive strength of the hardened concrete was assessed as per IS 516–1959[48] at 7, 14, 28, 90, and 180 days. Additionally, all concrete mixes were subjected to long-term durability studies in strong acid and alkaline environments, including HCl, H_2SO_4, and Na_2SO_4 solutions. The solutions for these studies were prepared as defined in standards and previous research studies[21,30,49,50]. Specimens were selected after 28 days of curing to perform these durability studies. The deterioration of the specimens subjected to acid and alkaline environments was evaluated by assessing the percentage of weight loss and comparing their residual compressive strength (RCS). The performance of all mixes was evaluated by measuring weight loss and strength loss at 28, 90, and 180 days.

Results and discussion

Workability

Placing fresh geopolymer concrete in structural applications can be more challenging than placing conventional cement concrete of equivalent slump. This is primarily due to the high viscosity of the alkaline activators used, particularly the sodium silicate solution. The increased viscosity imparts higher cohesiveness to the geopolymer concrete, making it more resistant to flow. The results of this study, presented in Fig. 2, found that fresh geopolymer concrete was highly cohesive compared to cement concrete and became relatively stiffer as the molarity increased. This behaviour aligns with the findings in the literature, where elevated molarity decreases the fluidity and workability of the mixture[10,19,21]. Furthermore, the addition of steel fibers further intensified the reduction in workability. Fibers increase the surface area within the mix, which leads to additional water absorption, further reducing the flowability of the concrete. High fiber content in the mix can lead to a harsh, dry consistency, making it challenging to handle, place, and compact the concrete effectively[32,38].

Compressive strength

Figure 3 demonstrates the impact of concrete age on the compressive strength of both cement concrete and geopolymer concrete (GPC), with varying concentrations (8, 10, 12, and 14 molars) of sodium hydroxide (SH) solution, both with and without fibers. The data clearly illustrates that as the molarity of sodium hydroxide increases, the strength of geopolymer concrete also increases. This trend aligns with previous research findings, indicating a positive correlation between the concentration of sodium hydroxide and the compressive strength of geopolymer concrete[51]. The maximum compressive strength at 28 days for 14 molar geopolymer concrete is 8.34% higher compared to cement concrete. Adding steel fibers to the mix further improves the strength by 9.11%. In geopolymer concrete, increasing the SH concentration from 8 to 14 molar results in a 6.38% increase in strength. Additionally, the inclusion of steel fibers in the geopolymer concrete leads to a further strength increase of up to 7.32%. Figure 4 shows that the rate of strength development in geopolymer concrete is comparable to that of cement concrete, with the strength gain rate being similar across all mixes. It is noteworthy that

	Binder		Alkaline solution		Filler material	
Grade	FA	GGBS	NaOH	Na_2SiO_3	M- Sand	CA
M-40	260	173.94	66.4	161	696	1043
For cement concrete						
Grade	Cement	Water	M-Sand	CA		
M-40	416	142	648	1235		

Table 4. Mix proportion for cement concrete and geopolymer concrete.

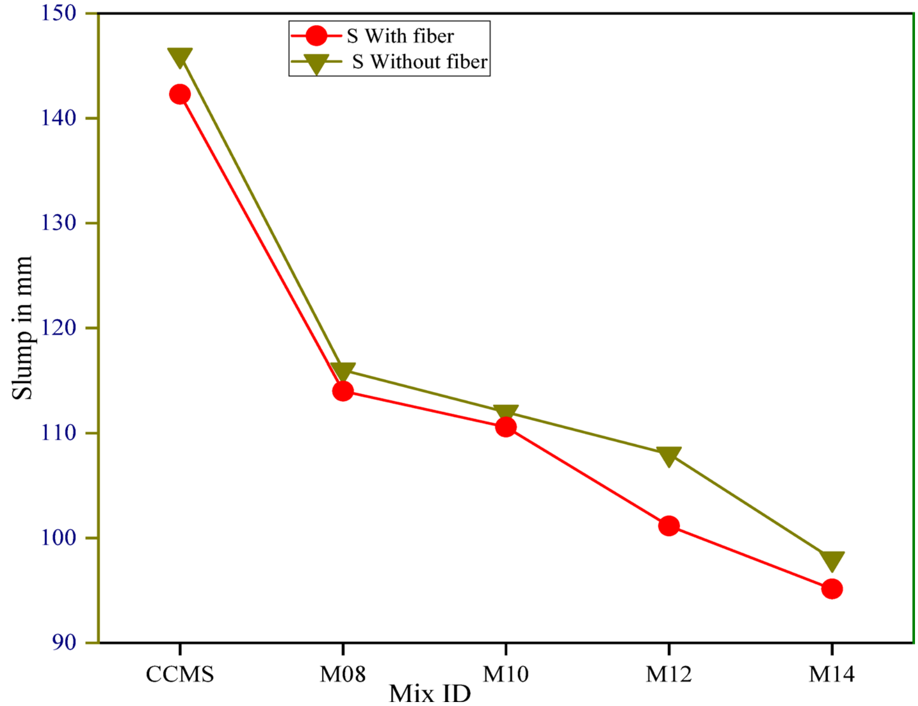


Fig. 2. Effect of fiber and alkali activator on the workability of concretes.

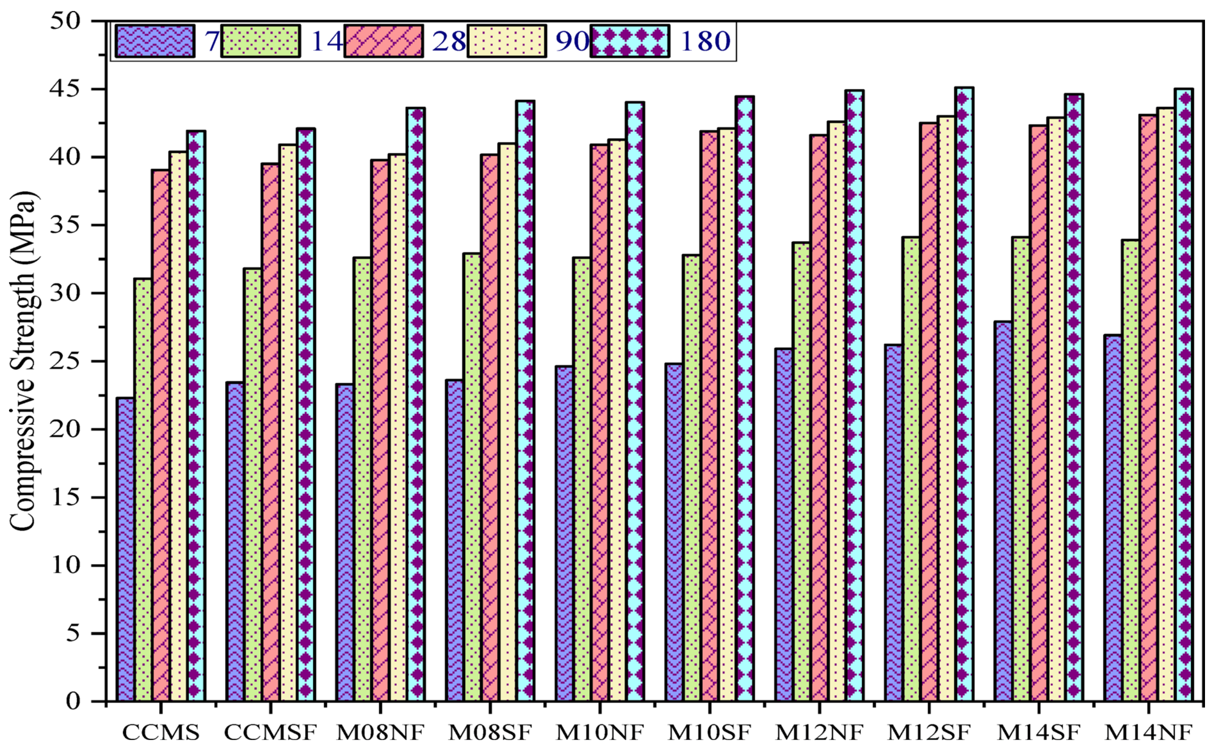


Fig. 3. Compressive strength at different curing ages (MPa).

increasing the SH concentration in geopolymer concrete results in early strength gain due to the early surface hydrolysis of the precursor materials[52,53]. Geopolymer concrete with an 8 molar SH concentration exhibited better strength even after 90 days, likely due to the slow rate of reaction, which leads to strength gain at later ages. Furthermore, the data illustrates that the addition of fibers and the proper selection of SH concentration can increase concrete strength by up to 10%. This improvement is due to the fibers restricting the propagation

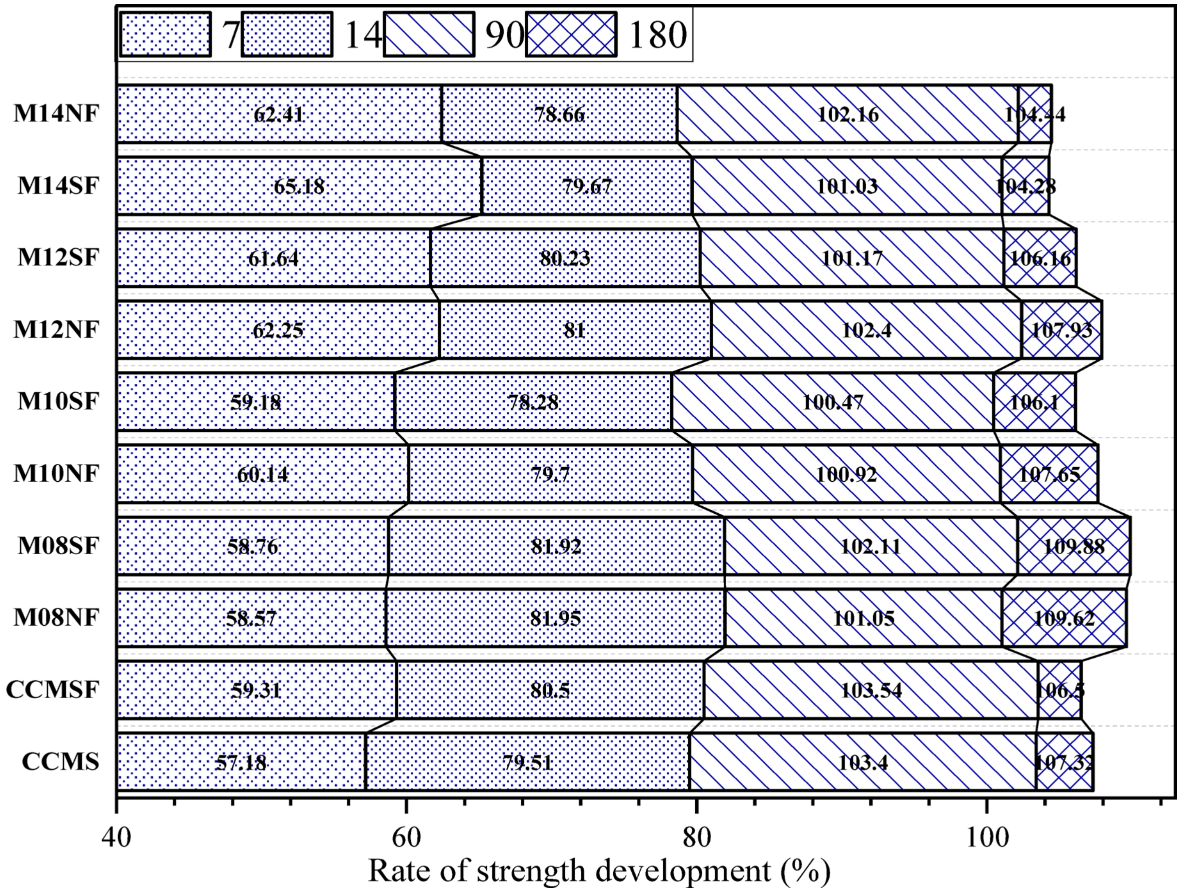


Fig. 4. Compressive strength growth rate compared to 28 days of strength.

of micro-cracks and the proper surface hydrolysis of precursor materials, thereby increasing the load-carrying capacity of the specimens[52,53].

Long term durability tests

Resistance to H_2SO_4 environment

The weight loss of GPC samples after 180 days in H_2SO_4 solution ranged from 9.89% to 18.69%, whereas cement concrete cubes exhibited a higher weight loss of 20.59%. When the molarity increased from 8 M, the resistance improved by 13%, 32%, and 41.27%, respectively. Adding steel fibers (SF) in GPC further enhanced acid resistance in mixes by 1.35%, 4.18%, 9.43%, and 4.69% with respect to the concentration of SH, respectively. The mixes CCMS and CCMSF had residual compressive strength (RCS) of 63.1% and 69.18% respectively. The deterioration of RCS in H_2SO_4 decreased with higher molarity and the addition of fibers. In geopolymer concrete, the highest RCS recorded was 81.23% for M14SF with 1% SF at 180 days. Figure 5 shows a dramatic drop in compressive strength for all concrete types exposed to H_2SO_4, with a slower rate of reduction over time. The susceptibility of OPC concrete to acid attack can be attributed to the presence of C-S-H and $Ca(OH)_2$ gel, which react with acid solutions, causing tensile stress and ultimately leading to cracks in the concrete matrix[54]. In contrast, the alumina and silica compounds in the GPC matrix react with $Ca(OH)_2$ to form more stable C-A-S-H and N-A-S-H gels. These gels reduce acid diffusion, leading to a lower percentage of weight loss. Additionally, N-A-S-H and C-A-S-H gels have a high filler effect in the GPC pores, resulting in a denser matrix[30]. The superior performance of GPC in sulfuric acid solution compared to OPC concrete can be attributed to differences in reaction mechanisms and phase composition. The deterioration of GPC samples in an acidic environment occurs due to the disintegration of the geopolymer gel, damaging the aluminosilicate bonds and releasing silicic acid, resulting in a reduction in residual compressive strength[50].

Resistance to Na_2SO_4 environment

From Fig. 6 it is evident that the weight loss due to Na_2SO_4 in all the mixes, where GPC exhibited lower weight loss in Na_2SO_4 for instance a mix CCMS had an overall weight loss of 6.64% for immersion 180 days, and GPC with mix M14SF had only 2.19% of weight loss which is 70% lesser than OPC. However, there was a noticeable strength loss of about 22.2% in cement concrete whereas the strength loss in GPC specimens reduced as the concentration of SH increased from 8 to 14 M, along with the concentration and addition of fibre showed that the concrete performing very well in Na_2SO_4 environment even after 180 days. Researchers indicate that sodium sulfate attack progresses in stages: the outer skin expands and cracks the interior, which remains chemically

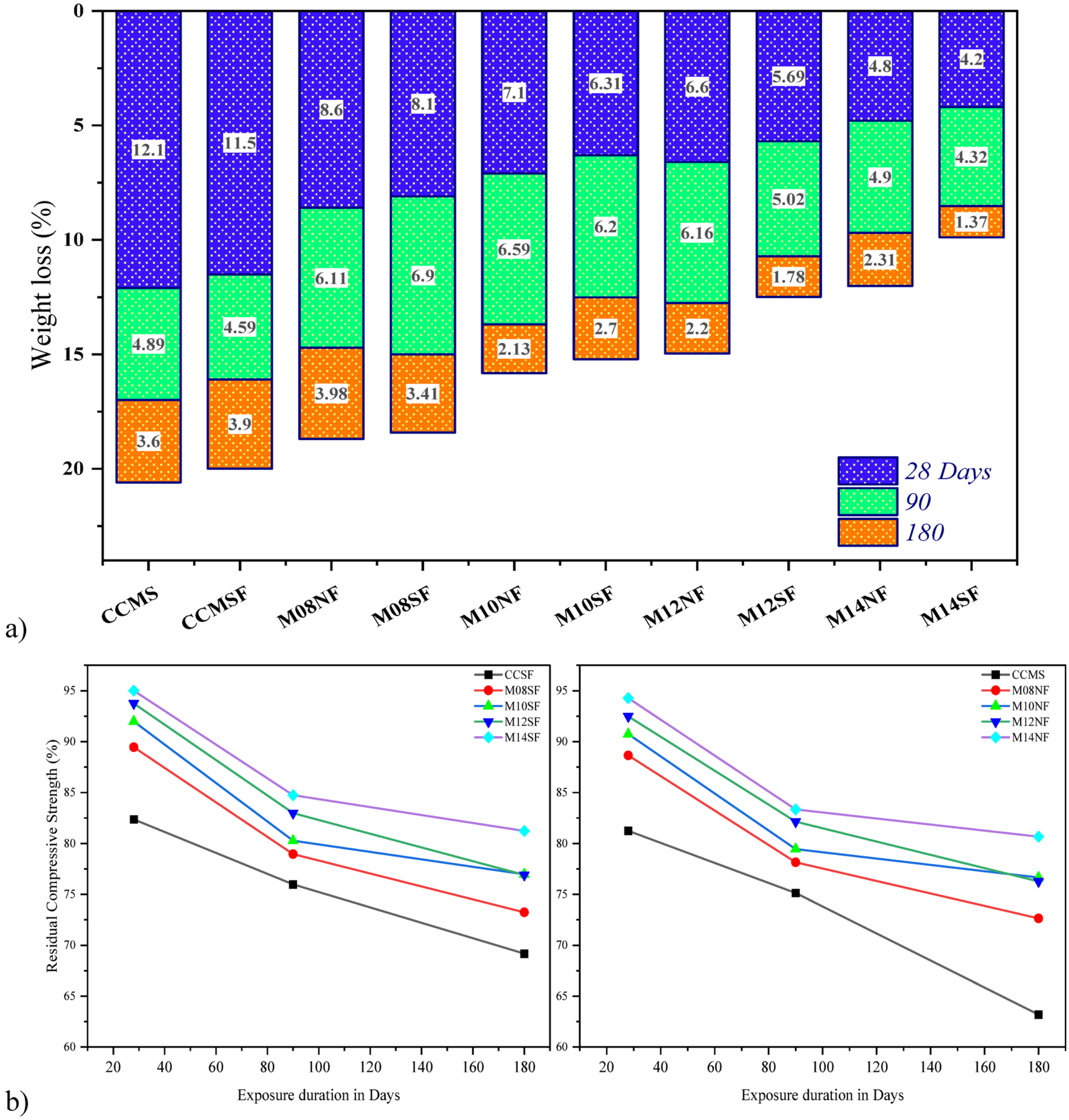
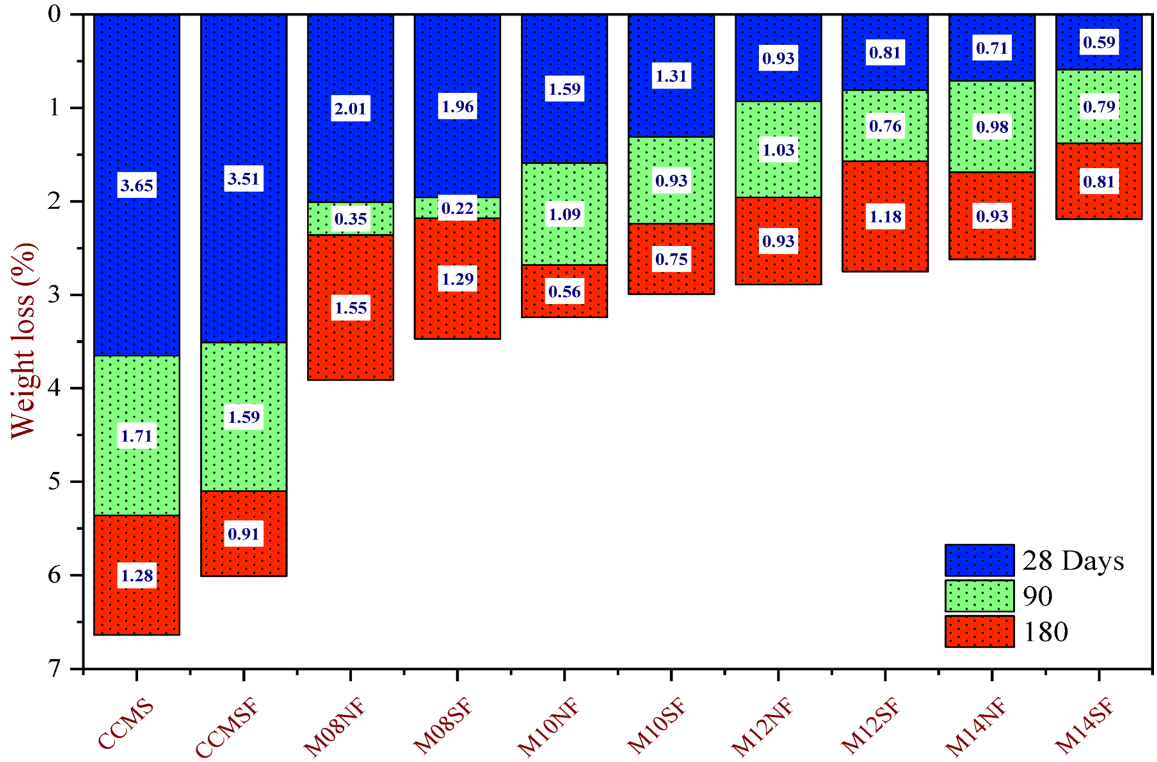


Fig. 5. (**a**) Weight loss and (**b**) residual compressive strength under H_2SO_4 environment.

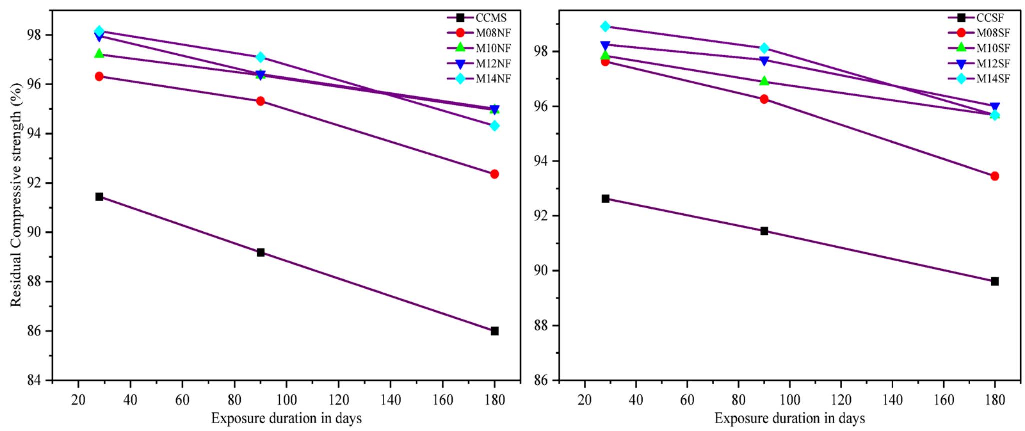
unchanged. Continued immersion disintegrates the surface, allowing sulfate to react with and crack the interior hydration products[55–57]. However, in GPC strength loss is up to 16% which is a similar observation in the literature. The strength loss in geopolymer concrete, because of the crystallisation of sodium sulphate within the pore structure of concrete itself can be particularly damaging to concrete.

Resistance to HCL environment

Figure 7 shows the resistance to HCl, with weight loss for CCMSF and CCMS ranging from 10.88% to 12.73% at 180 days. GPC exhibited better resistance, with weight loss decreasing from 9.72% to 6.98% as SH concentration increased from 8 to 14 M. Additionally, the inclusion of SF further improved resistance, with M141SF experiencing a weight loss of 5.94%, which is 53.34% less than that of cement concrete. These findings align with previous research[30]. In samples exposed to HCl, GPC exhibited a residual compressive strength loss ranging from 4.63% to 8.9%, compared to 26.2% for OPC and 21.23% for CCMSF. GPC samples showed excellent resistance, with no interior deterioration after the exposure period. While substantial surface decay was observed in cement concrete, GPC showed only slight surface erosion. Overall, all samples exposed to H_2SO_4 solutions deteriorated more than those attacked by HCl solutions which is similar to findings from other researchers[58].



a)



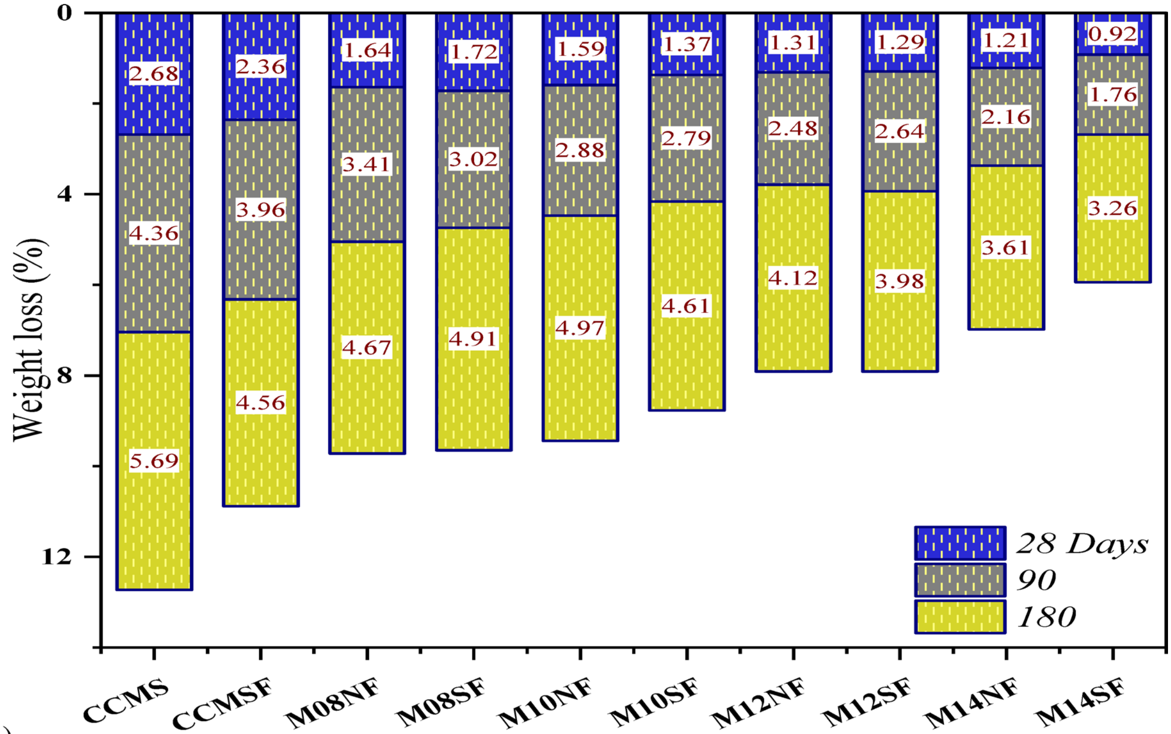
b)

Fig. 6. (**a**) Weight loss and (**b**) residual compressive strength under Na_2SO_4 environment.

Ecological analysis of concretes and Cost analysis

The embodied energy (EE) and embodied carbon emissions (ECO_2e) of concrete in this case study were computed to assess their ecological impacts, in line with previous studies[40] and as stated in various literature sources[41]. As illustrated in Fig. 8, a system boundary for concrete EE estimation used throughout the extraction, transportation, production, assembly, installation the product system during its production. The EE and ECO_2e statistics for the components and the concrete were obtained from the literature[40,41]. The computations are presented in Table 5 for geopolymer concrete mix with 14 M concentration and normal concrete. The numerical figures presented are indicative and are derived from the current case study. The EE of GPC and OPC were 1597 and 3062 MJ/m^3, respectively, indicating that GPC requires 47.84% less energy. Figure 9 clearly shows that the embodied energy of cement concrete is predominantly due to the cement, which accounts for nearly 82% of the total. In contrast, for geopolymer concrete, the alkaline activators account for approximately 47% of the embodied energy.

The ECO_2e of GPC and OPC were 146.37 and 345.3 kgCO_2e/m^3, respectively, showing that GPC had 57.6% lower embodied CO_2 emissions. Therefore, GPCs are more environmentally friendly. Figure 10 shows that embodied CO_2 emissions from cement concrete are predominantly due to cement use, which accounts for nearly



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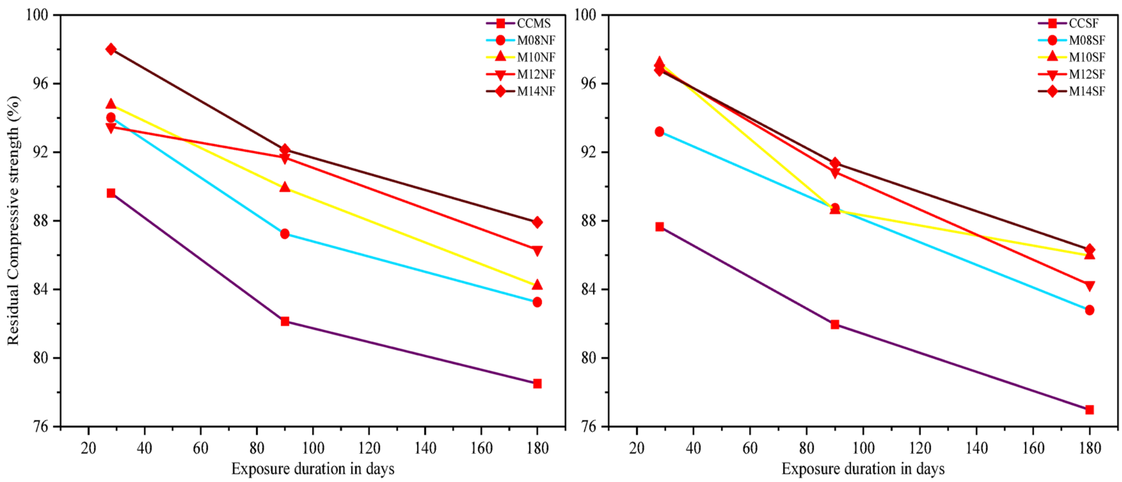

b)

Fig. 7. (**a**) Weight loss and (**b**) residual compressive strength under HCL environment.

95% of the total emissions. In contrast, for geopolymer concrete, alkalis account for approximately 72% of the CO_2 emissions.

From Table 5, the approximate cost of GPC is Rs 7013/m^3, whereas OPC costs Rs 5693/m^3 based on the rates incurred during the laboratory study. According to the literature, the cost of OPC ranges from Rs 5700 to Rs 6300 per m^3[59] and GPC costs around 7600 per m^3[60]. GPC is more expensive than OPC, with costs influenced by the source of materials and transportation[60]. In this research, alkalis were sourced from over 300 km away, increasing the cost per m^3 of GPC. As GPC usage grows in the construction industry, the local availability of all ingredients is expected to improve, potentially reducing the cost per m^3 of GPC. Figure 11 shows the cost distribution by ingredients for producing one m^3 of GPC and OPC based on individual material costs. It is clear from the figure that the cost of cement accounts for around 51% of OPC's total cost, whereas the cost of alkalis accounts for 54% of GPC's total cost, even considering the long-distance procurement of alkalis.

The advantages of GPC over OPC in terms of embodied energy, embodied CO_2 emissions and cost can be observed in Table 6 and expressed in terms of percentage advantage are presented in Fig. 12. Using the 28 day strength as a benchmark, the energy required to produce one MPa of concrete strength is 37.58 MJ/m^3 for GPC, compared to 76.06 MJ/m^3 for OPC. This value is almost 50% higher for OPC than for GPC. Thus, the energy

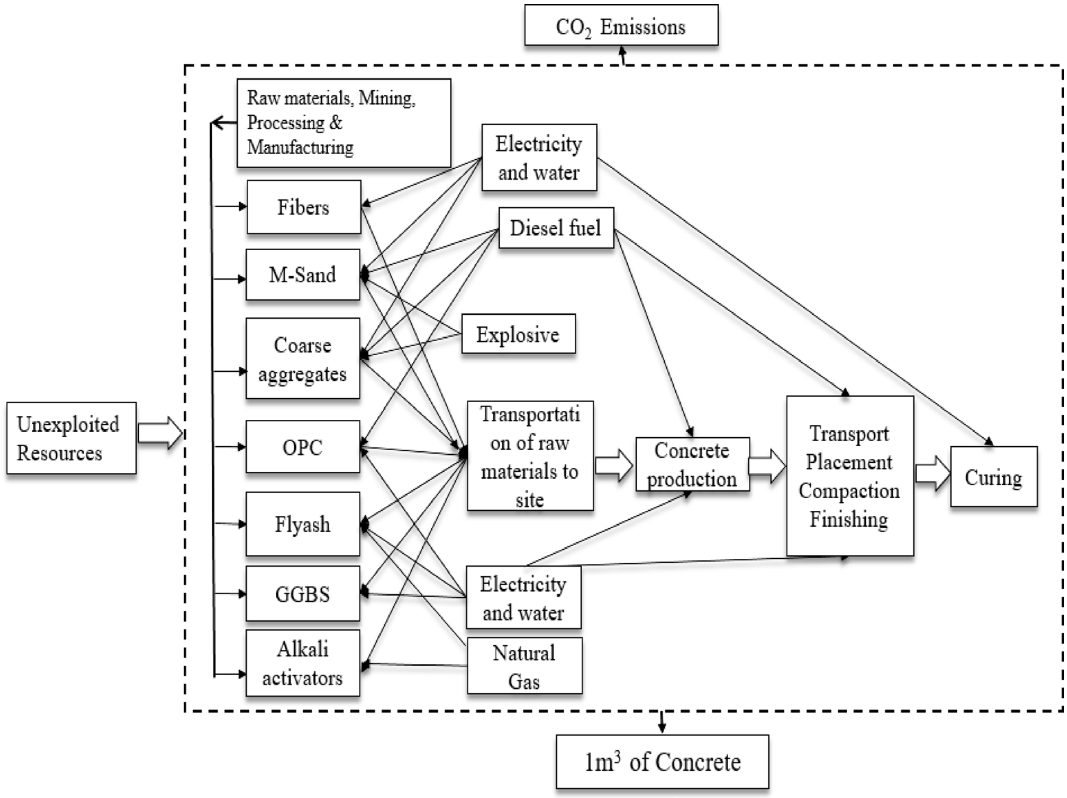

Fig. 8. Flow chart for the system boundaries for the estimation of embodied energy and carbon emission for concrete.

Ingredient of concrete	Cost Rs/kg	GPC					OPC				
		Unit content kg/m^3	EE MJ/ m^3	ECO_2e kgCo_2e/m^3	Cost Rs/m^3	Cost/f_{c28} Rs/MPa	Unit content kg/m^3	EE MJ/ m^3	ECO_2e kgCo_2e/m^3	Cost Rs/m^3	Cost/f_{c28} Rs/MPa
FA	1	260	136	14	260	6.5	–	–	–	–	–
GGBS	2	173.94	136	14	347.88	8.697	–	–	–	–	
SH	29	23.4	475	44	678.6	16.97	–	–	–	–	–
SS	20	161	252	57	3220	80.5	–	–	–	–	–
Cement	7	–	–	–	–	–	416	2499	328	2912	72.8
CA	1.5	1043	424	10	1564.5	39.1125	1235	424	10	1852.5	46.3
M-Sand	1.2	696	120	6	835.2	20.88	648	120	6	777.6	19.44
Steel fiber	36	4.34	9	1.37	156.22	3.91	4.16	9	1.37	149.76	3.744
Water	0.01	–	–	–	–	–	142	10	–	1.42	0.0355
DW	1	41	45	–	41	1.025	–	–	–	–	–
Total	–	–	1597	146.37	7103.42	177.59	–	3062	345.37	5693.28	142.32

Table 5. Embodied energy for GPC and OPC. Rs: Rupees in Indian currency; EE: embodied energy; ECO_2e: embodied carbon dioxide emission.

required to produce one unit of strength in GPC is significantly lower than in OPC. The CO_2e emitted to produce one MPa of strength is 3.44 kg/m^3 for GPC, whereas it is 8.58 kg/m^3 for OPC. Although GPC is approximately 25% more expensive than OPC due to the high cost of alkalis used in its production, it offers significantly greater early strengths and better durability, providing several construction advantages not accounted for in this cost comparison. Similarly, researchers have demonstrated that using geopolymer concrete can reduce global warming potential by over 60% compared to conventional cement concrete[60].

Conclusion

This study presents key insights into the potential of geopolymer concrete for structural applications as a sustainable alternative to ordinary Portland cement concrete. The findings support the following conclusions:

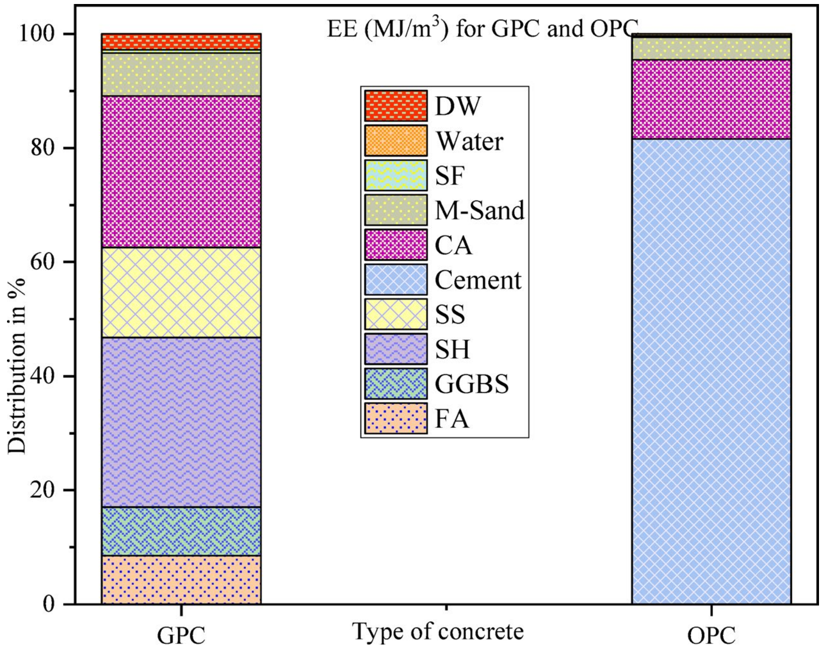

Fig. 9. Embodied energy distribution of concrete ingredients.

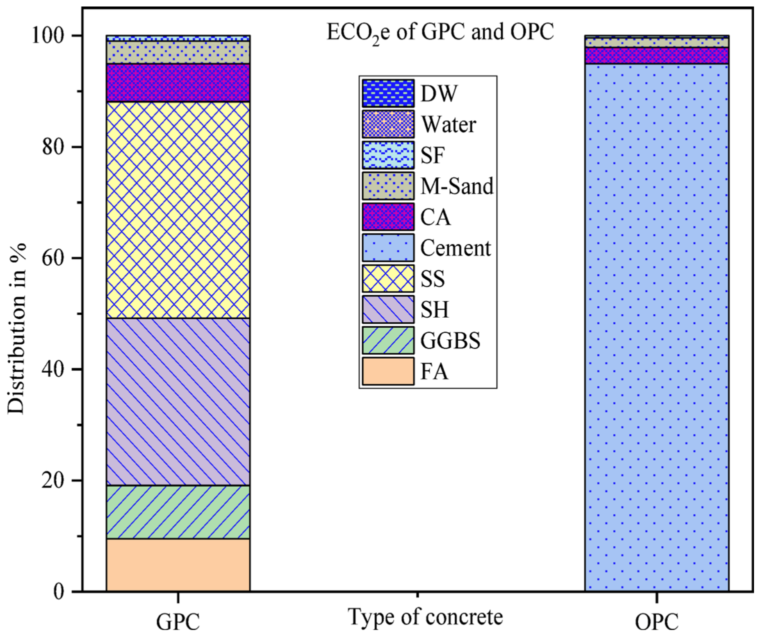

Fig. 10. Embodied carbon dioxide emission of concrete ingredients.

- GPC exhibited enhanced long-term durability, particularly under aggressive exposure conditions such as acid and sulfate environments, where it showed better performance than OPC. GPC demonstrated significantly lower weight loss and strength deterioration across all environments tested, highlighting its superior resistance to harsh conditions and underscoring its potential for structural longevity and performance.
- While an increase in the concentration of sodium hydroxide molarity led to marginal strength improvements, the optimal mix with 14 M provided adequate mechanical properties suitable for structural use.
- The early strength development of GPC can be an advantage in time sensitive structural applications, including precast elements and accelerated construction schedules.
- Despite slightly higher initial costs due to alkali activators, GPC's potential for local material sourcing and reduced lifecycle impacts enhances its feasibility in structural design.

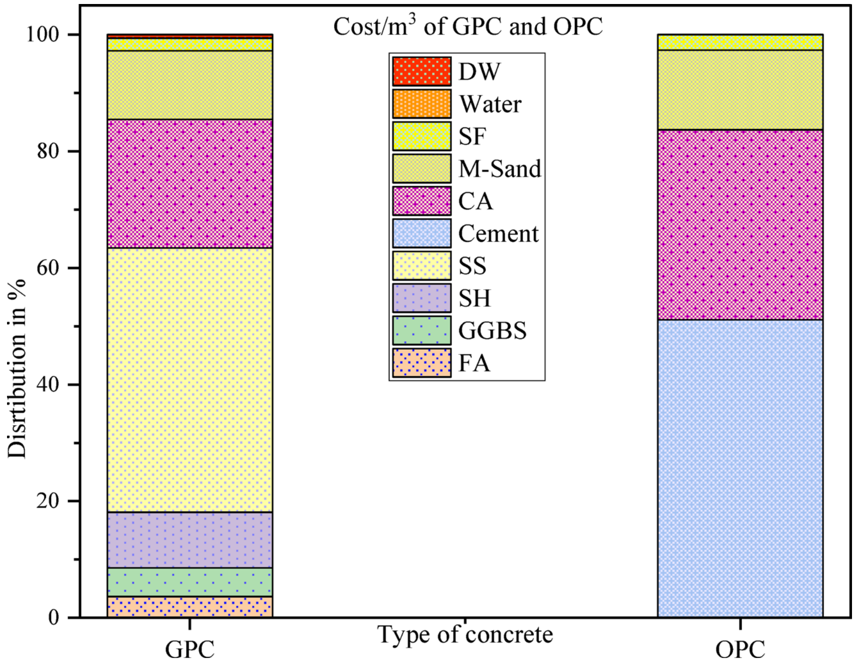

Fig. 11. Distribution of concrete cost per cubic meter by ingredients.

Parameters	Unit	GPC	OPC	Advantage of GPC over OPC (percentage)	Remarks
fc_{28}	MPa	42.50	40.26	5.56	Better strength characteristics
EE	MJ/m^3	1597	3062	47.84	Less in Embodied energy
ECO_2e	$kgCO_2e/m^3$	146.37	345.37	57.62	Emits less carbon emission
Cost	Rs/m^3	7103.4	5693.28	24.77	Cost is more
EE/fc_{28}	MJ/MPa	37.58	76.06	50.59	Requires less energy per unit strength
ECO_2e/fc_{28}	$KgCO_2e/MPa$	3.44	8.58	59.91	Emit less CO_2 for unit Strength
$Cost/fc_{28}$	Rs/MPa	167.14	141.41	18.20	Higher cost for unit strength

Table 6. Comparison of GPC with OPC.

- GPC demonstrated a 47.84% reduction in embodied energy and a 57.62% reduction in CO_2 emissions compared to OPC, aligning with sustainability goals.
- With its lower environmental footprint, improved durability, and structural grade strength, GPC stands out as a viable and eco-efficient material for structural concrete applications.

From the present study, which provides the directions for future research which can explore large scale structural applications of GPC, including beams, columns, and precast components. Further experimental investigations may focus on different types of fiber with optimising them, hybrid fiber systems, chemical admixtures and the use of nano additives to enhance, fresh properties, mechanical properties, crack resistance and overall performance of GPC. Investigating the long term field performance, including leachability and corrosion resistance in real environments, is essential for wider adoption. Additionally, integrating cost analysis with region specific local materials and logistics can improve practical feasibility. Microstructural analysis and life cycle assessment would provide much better understanding into GPC's behaviour, supporting its use in sustainable infrastructure development.

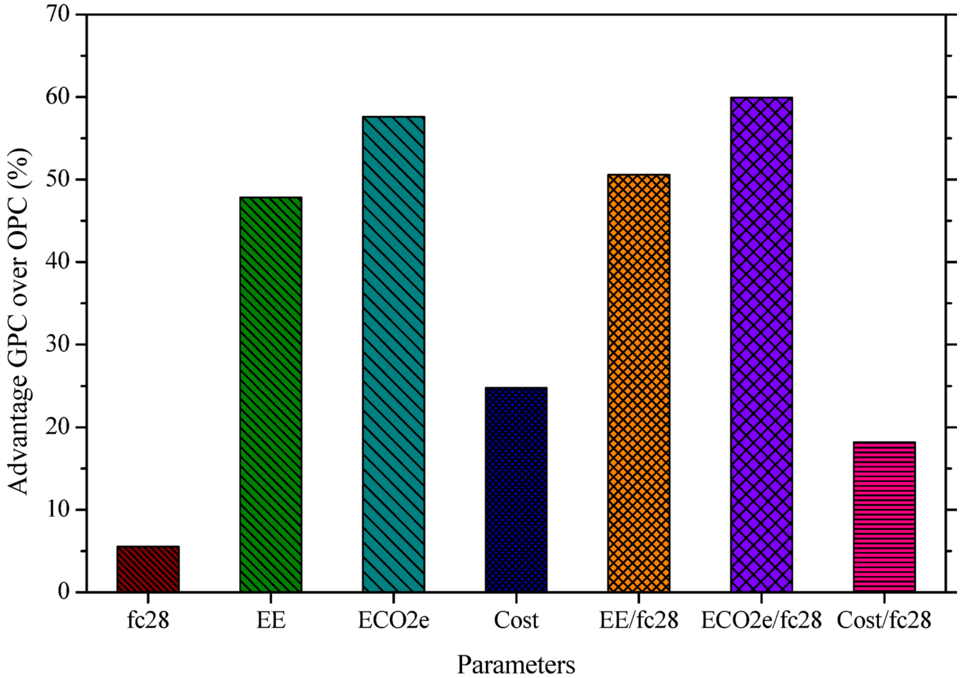

Fig. 12. Compression of advantages of GPC over OPC in percentage.

Data availability

The data used in this study are available upon reasonable request from the author. Author—H M Anil Kumar—anilkumarcv401@gmail.com.

Received: 14 April 2025; Accepted: 4 June 2025
Published online: 01 July 2025

References

1. Friedlingstein et al. Global cement CO_2 emissions 1960–2022 | Statista, 2023 (2023). https://www.statista.com/statistics/1299532/carbon-dioxide-emissions-worldwide-cement-manufacturing/ (accessed March 25, 2024).
2. Shivaprasad, K. N., Yang, H. M. & Singh, J. K. A path to carbon neutrality in construction: An overview of recent progress in recycled cement usage. *J. CO2 Util.* **83**, 102816. https://doi.org/10.1016/j.jcou.2024.102816 (2024).
3. Hassan, A., Arif, M. & Shariq, M. Use of geopolymer concrete for a cleaner and sustainable environment—A review of mechanical properties and microstructure. *J. Clean. Prod.* **223**, 704–728. https://doi.org/10.1016/j.jclepro.2019.03.051 (2019).
4. Biernacki, J. J. et al. Cements in the 21st century: Challenges, perspectives, and opportunities. *J. Am. Ceram. Soc.* **100**, 2746–2773. https://doi.org/10.1111/JACE.14948 (2017).
5. Okoye, F. N., Prakash, S. & Singh, N. B. Durability of fly ash based geopolymer concrete in the presence of silica fume. *J. Clean. Prod.* **149**, 1062–1067. https://doi.org/10.1016/j.jclepro.2017.02.176 (2017).
6. Rozière, E., Loukili, A., El Hachem, R. & Grondin, F. Durability of concrete exposed to leaching and external sulphate attacks. *Cem. Concr. Res.* **39**, 1188–1198. https://doi.org/10.1016/j.cemconres.2009.07.021 (2009).
7. Zhang, J., Shi, C., Zhang, Z. & Ou, Z. Durability of alkali-activated materials in aggressive environments: A review on recent studies. *Constr. Build. Mater.* **152**, 598–613. https://doi.org/10.1016/j.conbuildmat.2017.07.027 (2017).
8. Coppola, L. et al. The improvement of durability of reinforced concretes for sustainable structures: A review on different approaches. *Materials* **15**, 2728. https://doi.org/10.3390/MA15082728 (2022).
9. Aydın, S., Yazıcı, H., Yiğiter, H. & Baradan, B. Sulfuric acid resistance of high-volume fly ash concrete. *Build. Environ.* **42**, 717–721. https://doi.org/10.1016/j.buildenv.2005.10.024 (2007).
10. Zou, D., Qin, S., Liu, T. & Jivkov, A. Experimental and numerical study of the effects of solution concentration and temperature on concrete under external sulfate attack. *Cem. Concr. Res.* **139**, 106284. https://doi.org/10.1016/j.cemconres.2020.106284 (2021).
11. Zhu, P., Hao, Y., Liu, H., Wang, X. & Gu, L. Durability evaluation of recycled aggregate concrete in a complex environment. *J. Clean. Prod.* **273**, 122569. https://doi.org/10.1016/j.jclepro.2020.122569 (2020).
12. Rihan, M. A. M. & Alahmari, T. S. Review of recent development regarding strength, durability, and microstructure properties of geopolymer concrete containing rice husk ash. *Adv. Civ. Eng.* **2025**, 7211661. https://doi.org/10.1155/ADCE/7211661 (2025).
13. Davidovits, J. Properties of geopolymer cements. In *First International Conference on Alkaline Cements and Concretes* 131–149 (1994).
14. Duxson, P. et al. Geopolymer technology: The current state of the art. *J. Mater. Sci.* **42**, 2917–2933. https://doi.org/10.1007/s10853-006-0637-z (2007).
15. Chi, M. & Huang, R. Binding mechanism and properties of alkali-activated fly ash/slag mortars. *Constr. Build. Mater.* **40**, 291–298. https://doi.org/10.1016/j.conbuildmat.2012.11.003 (2013).
16. Al-Otaibi, S. Durability of concrete incorporating GGBS activated by water-glass. *Constr. Build. Mater.* **22**, 2059–2067. https://doi.org/10.1016/j.conbuildmat.2007.07.023 (2008).
17. Rihan, M. A. M., Onchiri, R. O., Gathimba, N. & Sabuni, B. Mix design approaches of eco-friendly geopolymer concrete: A critical review. *Hybrid Adv.* **7**, 100290. https://doi.org/10.1016/J.HYBADV.2024.100290 (2024).
18. Rostami, M. & Behfarnia, K. The effect of silica fume on durability of alkali activated slag concrete. *Constr. Build. Mater.* **134**, 262–268. https://doi.org/10.1016/j.conbuildmat.2016.12.072 (2017).

19. Rihan, M. A. M., Alahmari, T. S., Onchiri, R. O., Gathimba, N. & Sabuni, B. Impact of alkaline concentration on the mechanical properties of geopolymer concrete made up of fly ash and sugarcane bagasse ash. *Sustainability* **16**, 2841. https://doi.org/10.3390/SU16072841 (2024).
20. Gao, X., Yu, Q. L. & Brouwers, H. J. H. Characterization of alkali activated slag–fly ash blends containing nano-silica. *Constr. Build. Mater.* **98**, 397–406. https://doi.org/10.1016/j.conbuildmat.2015.08.086 (2015).
21. Aiken, T. A., Kwasny, J., Sha, W. & Soutsos, M. N. Effect of slag content and activator dosage on the resistance of fly ash geopolymer binders to sulfuric acid attack. *Cem. Concr. Res.* **111**, 23–40. https://doi.org/10.1016/j.cemconres.2018.06.011 (2018).
22. Albitar, M., Mohamed Ali, M. S., Visintin, P. & Drechsler, M. Durability evaluation of geopolymer and conventional concretes. *Constr. Build. Mater.* **136**, 374–385. https://doi.org/10.1016/j.conbuildmat.2017.01.056 (2017).
23. Mehta, A. & Siddique, R. Sulfuric acid resistance of fly ash based geopolymer concrete. *Constr. Build. Mater.* **146**, 136–143. https://doi.org/10.1016/j.conbuildmat.2017.04.077 (2017).
24. Koenig, A., Herrmann, A., Overmann, S. & Dehn, F. Resistance of alkali-activated binders to organic acid attack: Assessment of evaluation criteria and damage mechanisms. *Constr. Build. Mater.* **151**, 405–413. https://doi.org/10.1016/j.conbuildmat.2017.06.117 (2017).
25. Lloyd, R. R., Provis, J. L. & van Deventer, J. S. J. Acid resistance of inorganic polymer binders. 1. Corrosion rate. *Mater. Struct.* **45**, 1–14. https://doi.org/10.1617/s11527-011-9744-7 (2012).
26. Gopalakrishnan, R. & Chinnaraju, K. Durability of ambient cured alumina silicate concrete based on slag/fly ash blends against sulfate environment. *Constr. Build. Mater.* **204**, 70–83. https://doi.org/10.1016/j.conbuildmat.2019.01.153 (2019).
27. Parashar, A. K. et al. An approach for environment protection by regression and cluster analysis of GGBS-based geopolymer composite at different proportion of brick dust. *Mech. Adv. Mater. Struct.* https://doi.org/10.1080/15376494.2023.2269553 (2024).
28. Elyamany, H. E., Abd Elmoaty, A. E. M. & Elshaboury, A. M. Magnesium sulfate resistance of geopolymer mortar. *Constr. Build. Mater.* **184**, 111–127. https://doi.org/10.1016/j.conbuildmat.2018.06.212 (2018).
29. Jena, S., Panigrahi, R. & Sahu, P. Mechanical and durability properties of fly ash geopolymer concrete with silica fume. *J. Inst. Eng. Ser. A* **100**, 697–705. https://doi.org/10.1007/s40030-019-00400-z (2019).
30. Singh, R. P., Vanapalli, K. R., Jadda, K. & Mohanty, B. Durability assessment of fly ash, GGBS, and silica fume based geopolymer concrete with recycled aggregates against acid and sulfate attack. *J. Build. Eng.* **82**, 108354. https://doi.org/10.1016/j.jobe.2023.108354 (2024).
31. Ryu, G. S., Lee, Y. B., Koh, K. T. & Chung, Y. S. The mechanical properties of fly ash-based geopolymer concrete with alkaline activators. *Constr. Build. Mater.* **47**, 409–418. https://doi.org/10.1016/j.conbuildmat.2013.05.069 (2013).
32. Parashar, A. K., Kumar, A., Singh, P. & Gupta, N. Study on the mechanical properties of GGBS-based geopolymer concrete with steel fiber by cluster and regression analysis, Asian. *J. Civ. Eng.* **25**, 2679–2686. https://doi.org/10.1007/S42107-023-00937-2/FIGURES/9 (2024).
33. Chithambar Ganesh, A., Muthukannan, M., Dhivya, M., Sangeetha, C. B. & Daffodile, S. P. Structural performance of hybrid fiber geopolymer concrete beams. *IOP Conf. Ser. Mater. Sci. Eng.* **872**, 012155. https://doi.org/10.1088/1757-899X/872/1/012155 (2020).
34. Zhang, H., Sarker, P. K., Wang, Q., He, B. & Jiang, Z. Strength and toughness of ambient-cured geopolymer concrete containing virgin and recycled fibres in mono and hybrid combinations. *Constr. Build. Mater.* **304**, 124649. https://doi.org/10.1016/J.CONBUILDMAT.2021.124649 (2021).
35. Ahmed, H. Q., Jaf, D. K. & Yaseen, S. A. Flexural capacity and behaviour of geopolymer concrete beams reinforced with glass fibre-reinforced polymer bars. *Int. J. Concr. Struct. Mater.* **14**, 1–16. https://doi.org/10.1186/S40069-019-0389-1/FIGURES/15 (2020).
36. Zhang, H. et al. Comparison of compressive, flexural, and temperature-induced ductility behaviours of steel-PVA hybrid fibre reinforced OPC and geopolymer concretes after high temperatures exposure. *Constr. Build. Mater.* **399**, 132560. https://doi.org/10.1016/J.CONBUILDMAT.2023.132560 (2023).
37. Sharma, R., Jang, J. G. & Bansal, P. P. A comprehensive review on effects of mineral admixtures and fibers on engineering properties of ultra-high-performance concrete. *J. Build. Eng.* **45**, 103314. https://doi.org/10.1016/j.jobe.2021.103314 (2022).
38. Parashar, A. K. & Gupta, A. Investigation of the effect of bagasse ash, hooked steel fibers and glass fibers on the mechanical properties of concrete. *Mater. Today Proc.* **44**, 801–807. https://doi.org/10.1016/J.MATPR.2020.10.711 (2021).
39. Hu, M. A building life-cycle embodied performance index—The relationship between embodied energy, embodied carbon and environmental impact. *Energies* **13**, 1905. https://doi.org/10.3390/EN13081905 (2020).
40. Aneesh, N. R., Shivaprasad, K. N. & Das, B. B. Life cycle energy analysis of a metro station building envelope through computer based simulation. *Sustain. Cities Soc.* **39**, 135–143. https://doi.org/10.1016/j.scs.2018.02.006 (2018).
41. Vázquez-Calle, K., Guillén-Mena, V. & Quesada-Molina, F. Analysis of the embodied energy and CO2 emissions of ready-mixed concrete: A case study in Cuenca, Ecuador. *Materials* **15**, 4896. https://doi.org/10.3390/MA15144896 (2022).
42. Turner, L. K. & Collins, F. G. Carbon dioxide equivalent (CO2-e) emissions: A comparison between geopolymer and OPC cement concrete. *Constr. Build. Mater.* **43**, 125–130. https://doi.org/10.1016/j.conbuildmat.2013.01.023 (2013).
43. IS:269. Ordinary Portland Cement-Specification, Bur. Indian Stand. India 1–10 (2015).
44. IS:2386. Method of test for aggregate for concrete, Indian Stand. (1963) (Reaffirmed 2002).
45. BIS 383. Specification for Coarse and Fine Aggregates From Natural Sources for Concrete, Bur. Indian Stand. Delhi 1–24 (2016).
46. BIS, IS 10262:2019. Indian standard, Concrete mix Proportioning—Guidelines (Second Revision). Bis (2019).
47. IS 1199 (Part 2). Determination of Standard Consistency of Fresh Concrete (2018).
48. IS 516. Method of Tests for Strength of Concrete, Bur. Indian Stand. 1–30 (1959).
49. Manjunath, R., Narasimhan, M. C. & Umesha, K. M. Studies on high performance alkali activated slag concrete mixes subjected to aggressive environments and sustained elevated temperatures. *Constr. Build. Mater.* **229**, 116887. https://doi.org/10.1016/j.conbuildmat.2019.116887 (2019).
50. Ariffin, M. A. M., Bhutta, M. A. R., Hussin, M. W., Mohd Tahir, M. & Aziah, N. Sulfuric acid resistance of blended ash geopolymer concrete. *Constr. Build. Mater.* **43**, 80–86. https://doi.org/10.1016/j.conbuildmat.2013.01.018 (2013).
51. Saravanan, S., Nagajothi, S. & Elavenil, S. Investigation on Compressive Strength Development Of Geopolymer Concrete Using Manufactured Sand (2019).
52. Cheng, H. et al. The effects of SiO2/Na2O molar ratio on the characteristics of alkali-activated waste catalyst-metakaolin based geopolymers. *Constr. Build. Mater.* **95**, 710–720. https://doi.org/10.1016/j.conbuildmat.2015.07.028 (2015).
53. Shivaprasad, K. N. & Das, B. B. Determination of optimized geopolymerization factors on the properties of pelletized fly ash aggregates. *Constr. Build. Mater.* **163**, 428–437. https://doi.org/10.1016/j.conbuildmat.2017.12.038 (2018).
54. Nuaklong, P., Sata, V. & Chindaprasirt, P. Influence of recycled aggregate on fly ash geopolymer concrete properties. *J. Clean. Prod.* **112**, 2300–2307. https://doi.org/10.1016/j.jclepro.2015.10.109 (2016).
55. Neville, A. The confused world of sulfate attack on concrete. *Cem. Concr. Res.* **34**, 1275–1296. https://doi.org/10.1016/j.cemconres.2004.04.004 (2004).
56. Santhanam, M., Cohen, M. D. & Olek, J. Mechanism of sulfate attack: a fresh look. *Cem. Concr. Res.* **33**, 341–346. https://doi.org/10.1016/S0008-8846(02)00958-4 (2003).
57. Kwan, W. H., Ramli, M., Kam, K. J. & Sulieman, M. Z. Influence of the amount of recycled coarse aggregate in concrete design and durability properties. *Constr. Build. Mater.* **26**, 565–573. https://doi.org/10.1016/j.conbuildmat.2011.06.059 (2011).
58. Javed, U., Shaikh, F. U. A. & Sarker, P. K. Corrosive effect of HCl and H2SO4 exposure on the strength and microstructure of lithium slag geopolymer mortars. *Constr. Build. Mater.* **411**, 134588. https://doi.org/10.1016/j.conbuildmat.2023.134588 (2024).

59. Demissew, A. Comparative analysis of selected concrete mix design methods based on cost-effectiveness. *Adv. Civ. Eng.* **2022**, 4240774. https://doi.org/10.1155/2022/4240774 (2022).
60. Abbas, R., Khereby, M. A., Ghorab, H. Y. & Elkhoshkhany, N. Preparation of geopolymer concrete using Egyptian kaolin clay and the study of its environmental effects and economic cost, Clean Technol. Environ. *Policy* **22**, 669–687. https://doi.org/10.1007/S10098-020-01811-4/FIGURES/13 (2020).

Acknowledgements
This work was partly supported by the Technology Development Program of MSS [S3431827] and the ICT development R&D program of MSIT [No. RS-2023-00217322].

Author contributions
H M Anil Kumar worked on the experimental investigation and wrote the main manuscript. K N Shivaprasad reviewed the methodology and formal analysis. M S Sobha and Hyun Min Yang supervised and guided the research. All authors reviewed the manuscript.

Declarations

Competing interests
The authors declare no competing interests.

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