

Performance Optimization of Fiber-Reinforced Geopolymer Concrete Under Coupled Thermal and Mechanical Loading

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ABSTRACT

Fibre-reinforced geopolymer concrete (FRGPC) is a promising low-clinker construction material for infrastructure that must retain load-bearing capacity after thermal exposure. Its performance under combined thermal and mechanical actions, however, depends on the aluminosilicate precursor chemistry, activator composition, aggregate thermal compatibility, fibre geometry and dosage, curing history, heating rate, dwell time, cooling regime, and the applied stress level during heating. This manuscript develops an experimental and statistical framework for optimizing FRGPC under coupled thermal–mechanical loading. The proposed programme combines a fly ash–ground-granulated blast-furnace slag (GGBS) binder, steel and basalt fibres, controlled thermal exposure, residual mechanical testing, microstructural characterization, and response surface methodology. The principal independent variables are total fibre volume fraction, steel-to-basalt fibre ratio, peak temperature, heating rate, and sustained load ratio. Responses include compressive strength, splitting tensile strength, flexural strength, elastic modulus, mass loss, ultrasonic pulse velocity, and a toughness-related index. A central composite design or an appropriate response-surface design is proposed to identify nonlinear effects and interactions while limiting the number of experiments. Analysis of variance, residual diagnostics, lack-of-fit testing, desirability-based multi-response optimization, and confirmation experiments are specified to ensure statistical defensibility. The manuscript synthesizes recent literature indicating that fibres can improve crack bridging and post-cracking integrity, while elevated temperature can induce moisture migration, matrix shrinkage, interfacial debonding, aggregate–matrix incompatibility, and fibre-dependent changes. The optimum composition is expected to represent a compromise between ambient strength, residual strength, toughness, workability, and material efficiency; its location must be established experimentally rather than assumed. The framework is intended to support reproducible development of thermally resilient geopolymer concrete and to provide a transparent basis for subsequent SCI/SCIE publication.

Keywords: fibre-reinforced geopolymer concrete; coupled thermal–mechanical loading; elevated temperature; residual strength; steel fibre; basalt fibre; response surface methodology; ANOVA; multi-response optimization; microstructure

INTRODUCTION

Concrete infrastructure can experience thermal actions during accidental fires, industrial operation, tunnel incidents, geothermal exposure, and post-fire recovery. Temperature gradients generate nonuniform thermal strain, while moisture migration and physicochemical transformations modify stiffness and strength. When thermal exposure occurs simultaneously with sustained or transient mechanical stress, the resulting damage cannot be represented fully by residual-strength tests conducted on unloaded specimens. This distinction is important for structural assessment because load-bearing elements may remain stressed while their material properties are changing. Ordinary Portland cement concrete is widely used because of its availability and established design methods, yet its manufacture has a substantial environmental burden. Alkali-activated and geopolymer binders can use aluminosilicate-rich precursors such as fly ash, GGBS, and metakaolin. Their performance depends strongly on precursor chemistry, activator concentration, silicate modulus, liquid-to-binder ratio, curing regime,

and aggregate selection. Geopolymer concrete is not inherently immune to fire damage: pore pressure, gel dehydration, thermal incompatibility, shrinkage, and microcracking may still produce strength and stiffness losses. A key limitation of geopolymer matrices is their comparatively brittle response. Discrete fibres can bridge cracks, transfer tensile stress across crack planes, delay localization, and increase energy absorption. Steel fibres typically provide mechanical bridging at larger crack openings; basalt fibres can provide distributed reinforcement and are non-combustible, although their high-temperature performance depends on composition and matrix interaction. Hybrid reinforcement may cover multiple crack scales, but fibre addition can reduce workability, increase entrapped air, and create clustering if mixing and dispersion are not controlled. Recent reviews have emphasized the dependence of fibre-reinforced geopolymer behaviour on fibre type, volume fraction, matrix formulation, and thermal protocol. Zhao et al. (2023) reviewed elevated-temperature performance of fibre-reinforced geopolymer composites, while Rihan et al. (2024) and Manzoor et al. (2024) summarized high-temperature behaviour of geopolymer concrete. Recent experimental studies have further investigated steel-fibre and hybrid-fibre systems after heating, reinforcing the need for controlled, composition-specific models rather than universal residual-strength assumptions.

Despite this progress, four gaps remain relevant to design-oriented optimization. First, many studies evaluate temperature exposure without sustained load during heating. Second, fibre dosage and fibre blend are often assessed independently, limiting understanding of interactions. Third, outcomes are frequently reduced to compressive strength even though tensile resistance, stiffness, toughness, damage indicators, and mass loss may respond differently. Fourth, the proposed optimum may not be confirmed using independent specimens or reported with uncertainty. Geopolymerization involves dissolution of reactive aluminosilicate species in an alkaline medium, followed by transport, condensation, and formation of a three-dimensional binding network. Fly ash-rich systems commonly develop sodium aluminosilicate hydrate-type gels, while calcium-rich GGBS additions can promote calcium-containing aluminosilicate hydrate products. These differences influence early strength, pore structure, shrinkage, and high-temperature response. A blend selected for high ambient strength may not automatically provide the best residual performance because dense matrices can be more vulnerable to vapour-pressure accumulation and thermal gradients. Temperature-induced changes include evaporation of free and physically bound water, dehydration or dehydroxylation of reaction products, changes in gel structure, thermal expansion mismatch between paste and aggregate, and crack initiation around inclusions. At still higher temperatures, sintering or ceramic-like transformations may occur in some compositions. The exact sequence is precursor- and protocol-dependent; therefore, the manuscript should avoid generalizing a temperature threshold without specifying the mixture and exposure conditions.

Wu et al. (2020) reviewed temperature-dependent mechanical properties of fibre-reinforced concrete and identified fibre type, dosage, heating and cooling methods, and matrix composition as major sources of variability. Zhao et al. (2023) specifically reviewed fibre-reinforced geopolymer composites, highlighting the role of fibre typology and interface behaviour. Rihan et al. (2024) reported that geopolymer concrete may show different residual-strength trajectories depending on composition and thermal history. Manzoor et al. (2024) likewise emphasized the role of aggregates, fibres, and heating conditions. These reviews collectively caution against direct comparison of numerical results unless specimen geometry, curing, heating rate, holding time, cooling method, and test procedure are aligned. Response surface methodology is suitable when several controllable variables may influence multiple responses and nonlinear behaviour is expected. A central composite design (CCD) can estimate linear, interaction, and quadratic terms; a Box–Behnken design may be more efficient where extreme factor combinations are unsafe or impractical. The chosen design must include replication at the centre point to estimate pure error and should randomize the run order where possible. The model should be selected based on hierarchy, residual behaviour, predictive performance, and lack-of-fit—not merely a high coefficient of determination. For a response Y , a second-order model can be written as $Y = \beta_0 + \sum \beta_i x_i + \sum \beta_{ii} x_i^2 + \sum \beta_{ij} x_i x_j + \varepsilon$. Coded factors x_i facilitate comparison of coefficient magnitudes. ANOVA should report model significance, individual terms, lack of fit, R^2 , adjusted R^2 , predicted R^2 or cross-validated error, and residual diagnostics. Multi-response desirability can maximize strength retention and toughness while minimizing mass loss and workability loss. A confirmation experiment at the predicted optimum is essential.

The key opportunity is not simply to add fibres to geopolymer concrete, but to optimize a fibre blend under a controlled coupled thermal–mechanical protocol and validate the optimum against multiple performance measures. The present framework proposes an explicit sustained-load factor, standardized thermal histories, independent confirmation specimens, and microstructure-linked interpretation. This combination can improve the relevance of laboratory findings to post-fire assessment and heat-exposed infrastructure.

Summary of selected recent literature

Study	Scope / contribution	Relevance to present work
Wu, Lin & Zhou (2020), Cement and Concrete Research, 135, 106117	Review of fibre-reinforced concrete mechanical properties at elevated temperatures	Supports control of fibre type, heating and cooling protocol
Zhao et al. (2023), Cement and Concrete Composites, 137, 104885	Review of elevated-temperature response of fibre-reinforced geopolymer composites	Direct background for FRGPC and fibre-specific thermal response
Rihan et al. (2024), Discover Civil Engineering, 1, 24	Critical review of geopolymer concrete at elevated temperature	Identifies composition-dependent residual-strength behaviour
Manzoor, Bhat & Shah (2024), Construction and Building Materials, 420, 135578	Critical review of geopolymer concrete thermal performance	Supports aggregate and fibre effects
Fire Safety Journal (2024), 146, 104156	Experimental GGBS–FA–silica fume geopolymer concrete, with/without steel fibres	Supports temperature-dependent mechanical and constitutive testing
Construction and Building Materials (2024), 439, 137394	Steel-fibre geopolymer concrete after high-temperature exposure	Supports steel fibre and residual-property modelling
Ceramics International (2024), 50(24), 53851–53866	Hybrid steel–PVA fibre geopolymer concrete under elevated temperature	Supports hybrid fibre and microstructural analysis
Xie et al. (2025), Journal of Building Engineering, 102, 112068	Cellulose nanofibre-modified ultra-high-performance geopolymer concrete	Recent evidence on fibre/nanofibre impacts on mechanical and thermal response
Structures (2025), 77, 109201	Review of natural plant fibre-reinforced geopolymer concrete	Sustainability context and fibre dosage trade-offs
Construction and Building Materials (2025), 474, 141004	Recycled aggregate fibre-reinforced geopolymer concrete: workability, strength, carbon emissions	Links performance optimization and environmental metrics

2. MATERIALS AND METHODS

2.1 Research design overview

The proposed study uses a factorial response-surface design with controlled material batches, replicated specimens, and two thermal-loading pathways: (i) unloaded heating followed by residual testing and (ii) sustained compressive stress during heating followed by residual testing. If in-situ loaded heating equipment is unavailable, the second pathway may be replaced by a carefully justified preloading or post-heating loading protocol, but these pathways must not be treated as equivalent.

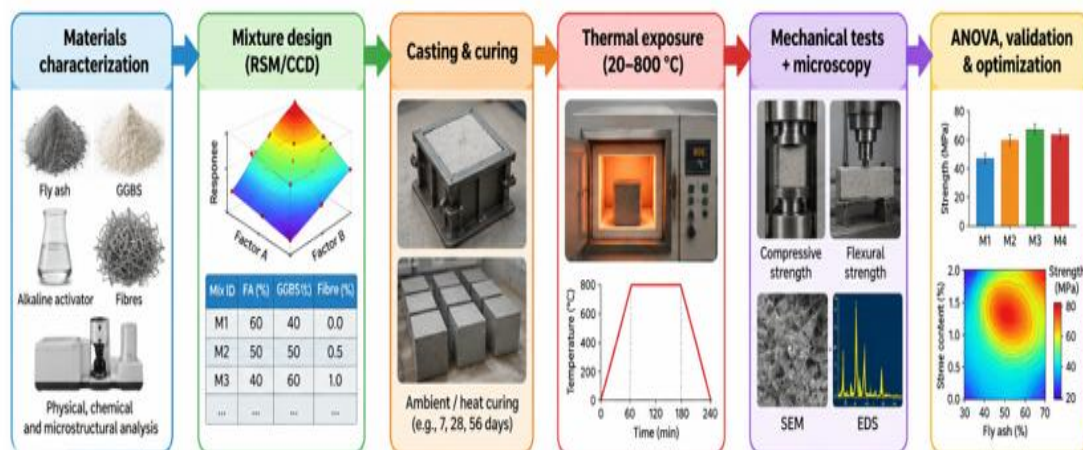


Figure 1. Proposed workflow for experimental optimization.

2.2 Raw materials

Binder precursor: use a characterized blend of low-calcium fly ash and GGBS, with an optional silica-fume fraction only if it is included consistently in the design. Record source, batch, specific gravity, particle-size distribution, loss on ignition, and oxide composition from XRF. Report SiO_2 , Al_2O_3 , CaO , Fe_2O_3 , MgO , Na_2O , K_2O , and SO_3 where available. The precursor blend should be fixed during the fibre/thermal optimization study unless binder ratio is explicitly included as an additional factor. Alkaline activator: sodium hydroxide solution and sodium silicate solution may be used. Report NaOH molarity, sodium silicate composition, silicate-to-hydroxide ratio, activator-to-binder ratio, solution preparation age, and safety precautions. Prepare NaOH solution sufficiently in advance to cool to room temperature before mixing. Use the same activator batch protocol throughout. Aggregates: use oven-dry or moisture-corrected fine and coarse aggregates with recorded grading, specific gravity, absorption, and moisture content. Aggregate type and maximum size should be held constant because aggregate mineralogy and thermal expansion can substantially influence damage. Fibres: use hooked-end or crimped steel fibres and chopped basalt fibres with documented length, diameter, aspect ratio, tensile strength, modulus, density, and supplier specifications. Record actual mass added per batch. The proposed hybrid system uses total fibre volume fraction as a continuous factor and steel:basalt volume ratio as a blend factor. Ensure fibres are added gradually to reduce balling.

2.3 Proposed mixture design

A preliminary binder and activator mixture should be established through trial batches to achieve target workability and adequate 28-day strength. The table below is a starting design window, not a final prescription. Adjust the proportions after precursor characterization and trial mixing; do not compare results from mixes with uncontrolled liquid content.

Parameter	Proposed starting range / control	Rationale
Fly ash:GGBS binder fraction	70:30 by mass (fixed for initial design)	Balances workability and calcium-rich reaction products; verify by trials
Activator/binder ratio	0.40–0.50 by mass	Control workability and pore structure
NaOH concentration	8–12 mol/L	Screen for feasible activation and safe handling
Sodium silicate/NaOH solution ratio	Approximately 1.5–2.5 by mass	Must be fixed or explicitly modelled
Total fibre volume fraction	0–1.0%	Capture unreinforced control through moderate fibre dosage
Steel:basalt fibre ratio	100:0, 75:25, 50:50, 25:75, 0:100	Evaluate single and hybrid systems
Curing	Sealed/covered initial curing; then controlled ambient curing to 28 days	Avoid uncontrolled moisture loss and record exact regime
Peak exposure temperature	20, 200, 400, 600, 800 °C	Covers ambient and progressive thermal damage regimes

2.4 Factor definitions and ranges



Figure 2. Proposed factor ranges; finalize ranges after pilot testing.

For optimization, use coded values for quantitative factors and define the fibre blend as a continuous ratio or categorical factor depending on the design software. Peak temperature may be treated as a quantitative factor only if the selected design can represent its nonlinear response and the thermal protocol is reproducible. If steel:basalt ratio is treated as a mixture variable, a mixture-process design may be more appropriate than a conventional CCD.

2.5 Casting, compaction and curing

Dry-blend precursor powders and aggregates until visually homogeneous. Prepare activator solution under a documented safety procedure and allow it to reach the specified mixing temperature. Add activator to dry constituents and mix using a fixed sequence and duration. Introduce fibres gradually while mixing continues. Record fresh density, flow/slump or an appropriate workability index, temperature, and any visible fibre clustering. Cast specimens in oiled moulds, compact using a consistent vibration protocol, cover to limit moisture loss, demould at the selected time, and cure under a controlled regime. Record any deviations.

Specimen dimensions must match the relevant test standard and machine capacity. Use at least three specimens per condition as a minimum for exploratory screening; increase replication where variability is high or formal confidence intervals are required. Randomize specimen allocation to test conditions and preserve traceability using batch and specimen IDs.

2.6 Thermal exposure and coupled loading

Condition specimens to a consistent moisture state before heating. A laboratory furnace with calibrated thermocouples should be used to achieve target temperatures. Proposed peak temperatures are 200, 400, 600, and 800 °C in addition to an ambient reference. A nominal heating rate of 5 °C/min can serve as a starting protocol, with a dwell time such as 60 minutes after the core or representative specimen temperature reaches the target; the final protocol must be selected based on specimen size and equipment capacity. Furnace set-point alone is insufficient: report specimen surface and, where possible, core temperature. After the dwell period, cool specimens in the furnace to a safe handling temperature unless rapid cooling is the variable under study. Do not mix furnace cooling and water quenching in one dataset without modelling cooling regime as a factor. Record visible spalling, cracking, colour change, mass change, and any specimen fragmentation before testing. For coupled loading, apply a sustained compressive stress ratio during heating using a rated loading frame integrated with the furnace or a validated high-temperature loading fixture. Define the ratio as applied stress divided by the ambient-temperature compressive strength of the corresponding mix. Suggested levels are 0.0, 0.2, and 0.4, subject to equipment and safety constraints. Measure load continuously and document whether load is

3. EXPERIMENTAL SETUP

3.1 Equipment and instrumentation

The experimental system should include a calibrated furnace with adequate uniform-temperature zone, thermocouples and data logger, compression/flexural testing machine, load cell and displacement measurement, mass balance, ultrasonic pulse velocity apparatus, and optional SEM/EDS, XRD, FTIR, and TGA facilities. Provide manufacturer, model, calibration date, measurement range, accuracy, and laboratory location for every major instrument in the final manuscript.

Equipment	Minimum reporting details
High-temperature furnace	Maximum rating, uniformity, ramp control, thermocouple type/location, calibration
Thermocouples/data logger	Type, range, accuracy, sampling frequency, attachment method
Universal testing machine	Capacity, load-cell accuracy, loading rate, platen geometry
Sustained-load fixture	Load control, thermal shielding, frame expansion correction, safety interlocks
Balance	Capacity, readability, calibration
UPV apparatus	Transducer frequency, path length, coupling method
SEM/EDS and XRD	Model, voltage/radiation source, scan range, specimen preparation

3.2 Test matrix and replication

A practical screening stage should first determine workability and safe fibre dosage. A second stage should use a formal response-surface design across the most influential variables. The final confirmation stage should test the predicted optimum, a baseline mixture, and at least one alternative near the Pareto frontier. Each condition should include independent specimens; technical repeats on the same specimen do not replace independent replication.

Stage	Purpose	Suggested outputs
Stage I: pilot mixes	Check activator, fibre dispersion, moulding and curing	Workability, fresh density, 7/28-day strength
Stage II: designed experiment	Estimate main, quadratic and interaction effects	Strength, modulus, toughness, mass loss, UPV
Stage III: microstructure	Explain damage mechanisms	SEM/EDS, XRD, optional FTIR/TGA
Stage IV: confirmation	Validate predicted optimum	Observed vs predicted, uncertainty, prediction error

4. RESULTS AND DISCUSSION

4.1 Fresh-state performance and fibre dispersion

Report flow or slump, fresh density, and visible fibre dispersion for each mixture. Discuss the effect of fibre volume fraction and steel:basalt ratio on workability. Increasing fibre dosage commonly increases internal friction and may reduce flow; this effect depends on fibre length, geometry, surface condition, paste volume, and mixing sequence. A reduction in workability should not automatically be interpreted as a material-strength benefit. If a high-fibre mixture contains voids or fibre balls, lower compressive strength may reflect processing defects rather than an intrinsic disadvantage of the fibre. Insert Table 5 with measured workability, fresh density, and batch observations. Report the number of batches, average $\pm$ standard deviation, and any rejected batch with its documented reason. Representative photographs should show fresh mixtures and fibre distribution.

4.2 Ambient mechanical properties

Compare control, steel-fibre, basalt-fibre, and hybrid-fibre mixtures at ambient temperature. Present compressive, splitting tensile, and flexural results together because fibre benefits may be more pronounced in tensile/flexural response than in compressive strength. A small or statistically insignificant change in compressive strength can coexist with a substantial change in post-cracking toughness. Explain trends using fibre bridging, crack deflection, interfacial bond, fibre pull-out, and possible porosity changes. Report confidence intervals and effect sizes rather than relying exclusively on p-values. If the hybrid mixture exceeds the weighted expectation from the individual fibres, test the interaction statistically before claiming synergy. Use representative stress-strain or load-deflection curves to demonstrate post-peak behaviour.

4.3 Effect of temperature on residual compressive strength

Plot residual compressive strength and residual-strength ratio against peak temperature for each fibre system. The main expected trend from the literature is progressive damage at higher temperatures, but some compositions may show a non-monotonic response at intermediate temperatures due to competing dehydration, continued reaction, shrinkage, and microstructural changes. Avoid assuming that strength must decrease monotonically at every temperature. Report the onset of visible cracking, edge spalling, colour change, and fragmentation. Distinguish the absolute residual strength from the percentage retention: a mixture with high initial strength may retain a lower percentage while still having a higher absolute residual strength. Interpret the observed response alongside mass loss, UPV, and microstructural evidence.

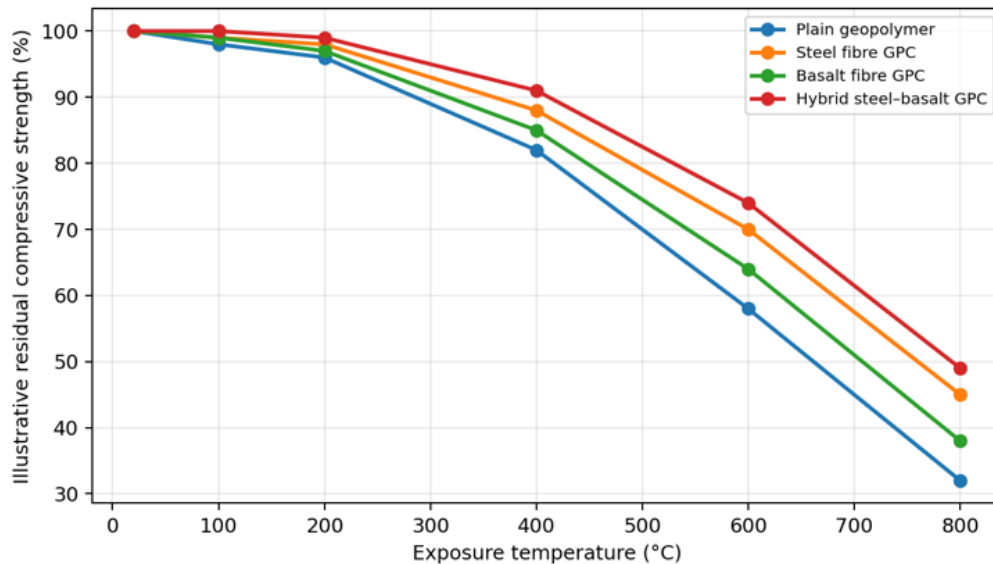


Figure 3. Conceptual illustration of residual-strength trajectories; replace with measured means and error bars.

4.4 Coupled thermal–mechanical interaction

The central analysis compares specimens heated without load against specimens exposed under sustained load. At each temperature, calculate the difference in residual response between load ratios and test the temperature $\times$ load interaction. Sustained compressive stress may close some cracks during heating, but it can also intensify damage through creep, restrained thermal strain, and stress redistribution. The net effect is material- and protocol-dependent; no single direction should be presumed. Use interaction plots for peak temperature and load ratio. If the interaction term is significant, report simple effects at relevant temperature levels. Describe whether specimens failed during exposure, immediately after cooling, or during residual testing. Report the load-control mode and any deviations in applied stress. If the experimental setup cannot maintain stable load at temperature, clearly state the limitation and avoid describing a post-heating loading test as true coupled loading.

4.5 Tensile, flexural and toughness response

Fibre reinforcement is expected to influence crack propagation and residual load-carrying capacity. Present splitting tensile strength and flexural response as complementary measures, not interchangeable quantities. For flexural testing, provide load–deflection curves, first-crack load, peak load, residual load at specified deflections, and energy absorbed up to a defined deflection. State the calculation method for toughness and the standard used. After heating, reductions in fibre tensile capacity, interface bond, matrix stiffness, and matrix continuity may reduce the bridging contribution. Steel fibres may preserve load transfer at temperatures where some organic fibres have degraded, while basalt-fibre performance depends on fibre composition and interface changes. Any claimed superiority must be supported by measured comparisons under the same thermal protocol.

4.6 Elastic modulus and stiffness retention

Elastic modulus is sensitive to microcracking and is often more responsive to distributed damage than compressive strength. Plot modulus retention against temperature and load ratio. Relate reductions to UPV changes, stress–strain slope, and visible cracking. Ensure the modulus method is suitable for the geopolymer mixture and report the stress range used to calculate the slope.

4.7 Mass loss and ultrasonic pulse velocity

Mass loss can indicate moisture release and thermal decomposition, but it does not uniquely quantify damage. Interpret mass loss together with UPV, strength, and microscopy. A decline in UPV may reflect crack formation, increased porosity, or altered elastic properties. Report path length, transducer arrangement, coupling agent, and specimen conditioning. Avoid using UPV as a substitute for direct strength testing unless a calibration relationship is established for the specific material and thermal history.

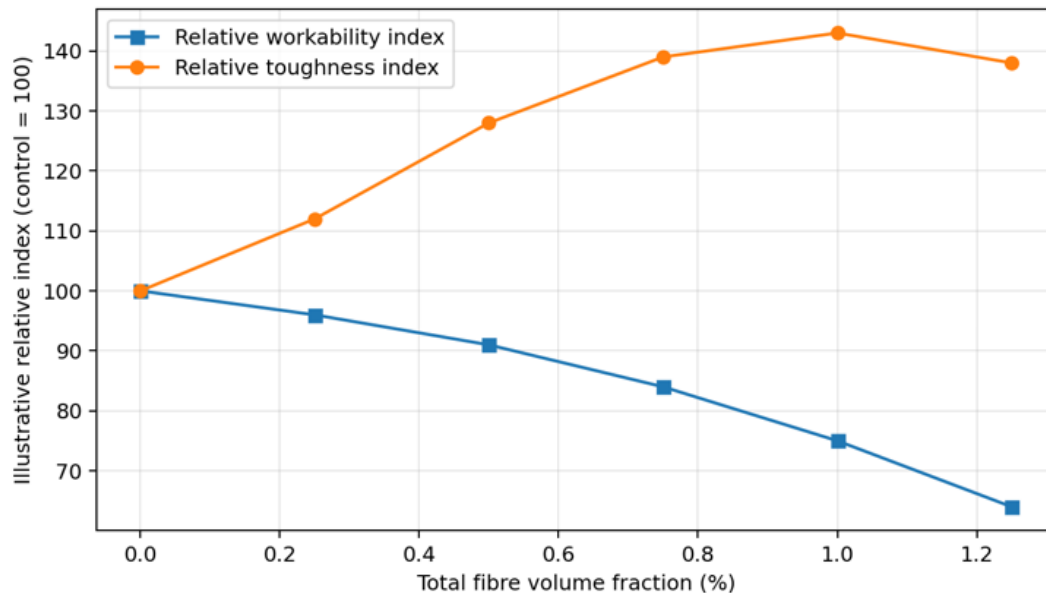


Figure 4. Conceptual fibre dosage trade-off between workability and toughness; illustrative only.

4.8 Response surface and ANOVA

Report the final fitted equation using coded variables, followed by an ANOVA table containing model and residual terms. Identify statistically significant main effects, quadratic terms, and interactions at the chosen significance level. Provide model diagnostics and explain whether transformations were required. Use predicted-versus-observed plots and residual plots. If the response surface has a boundary optimum, investigate whether the optimum is an artefact of the chosen factor range and whether it remains practical under workability and safety constraints.

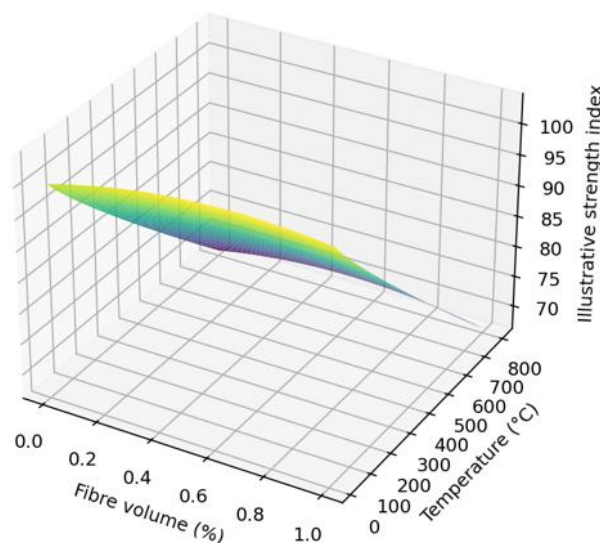


Figure 5. Conceptual response surface. Replace with the fitted model generated from the measured experimental dataset.

The model should not be presented as validated unless an independent confirmation run is performed. Report the predicted value, observed value, prediction interval where available, and relative prediction error for each key response. Where prediction is poor, revise the model, collect more data, or narrow the scope of inference.

4.9 Multi-response optimization

Define optimization goals before solving the desirability function. A defensible formulation could maximize residual compressive-strength ratio, flexural toughness, and modulus retention; minimize mass loss; and constrain workability to a practical threshold. Assign response importance based on intended application, not on which response produces the most attractive optimum. Report the selected optimum and at least two alternative Pareto solutions, including their predicted responses and trade-offs. A recommended final table includes factor settings, predicted response, confirmation mean, standard deviation, confidence interval, and prediction error. The optimum should not be described as universal; it applies only to the materials, curing, thermal profile, load ratio, and factor ranges tested.

4.10 Limitations and reproducibility

The proposed framework is laboratory-scale and cannot directly reproduce the thermal gradients, restraint, reinforcement layout, moisture transport, and fire curves of full-scale structural members. Furnace exposure under a constant ramp is not equivalent to a standard fire curve unless the temperature–time history is designed to match it. Small specimens may also dry more uniformly than thick structural elements. These limitations should be stated and addressed through future coupled heat-transfer and structural modelling. Reproducibility requires full reporting of precursor chemistry, activator composition, mixing sequence, fibre geometry, curing, specimen conditioning, thermal profile, sustained-load control, test standards, instrument calibration, data exclusions, statistical code or settings, and raw data availability. Provide a supplementary file containing specimen-level measurements and the design matrix where journal policy permits.

5. CONCLUSIONS

This manuscript proposes a structured route to optimize fibre-reinforced geopolymer concrete under coupled thermal and mechanical loading. The following conclusions are design conclusions from the proposed methodology and literature synthesis; they are not claims derived from a completed experimental campaign.

Thermal response must be evaluated as a function of precursor chemistry, aggregate selection, fibre type and dosage, heating rate, dwell time, cooling regime, and specimen moisture condition.

Steel and basalt fibres offer complementary crack-bridging potential, but hybrid reinforcement should be justified using measured interactions and post-cracking response rather than assumed synergy.

Unloaded residual-strength tests alone do not establish behaviour under coupled thermal–mechanical loading; sustained-load tests require a controlled and documented high-temperature fixture.

Response surface methodology can identify nonlinear effects and factor interactions, provided that the design includes adequate replication, randomized runs, model diagnostics, and independent confirmation experiments.

Multi-response optimization should balance residual strength, flexural toughness, stiffness retention, mass loss, and practical workability, and should report Pareto alternatives when objectives conflict.

Publication-ready conclusions must be updated after the measured dataset is analysed. Quantitative improvements, optimum factor levels, statistical significance, and prediction accuracy must not be stated until verified by experiments.

6.1 Future work

Future work should extend the optimized material to realistic fire curves, thermal gradients, reinforced structural members, cyclic heating and cooling, and post-fire repair assessment. Coupled heat-transfer and finite-element models can be calibrated against specimen temperature histories, stress–strain curves, and observed damage. Life-cycle assessment may also compare the environmental implications of precursor selection, fibre manufacture, activator use, and service-life benefits.

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