

Experimental Characterization of 3D-Printed Geopolymer Concrete with Recycled Carbon Fibers

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Abstract

The construction industry faces a critical transition toward sustainable 3D Concrete Printing to enhance efficiency and minimize waste, yet the reliance on Ordinary Portland Cement (OPC) and the inherent mechanical anisotropy of extruded geopolymer layers remain significant barriers to structural integrity. This research addresses these challenges by investigating the synergistic potential of Recycled Carbon Fibers within a zero-cement geopolymer matrix, specifically aiming to enhance interlayer bond strength and reduce the anisotropic index of printed elements. Using a laboratory-based experimental framework, mixtures with rCF volume fractions of 0.0% (control), 0.5%, 1.0%, and 1.5% were fabricated via a gantry-based robotic system and subjected to rheological, mechanical, and microstructural analysis. The findings reveal that the 1.0% rCF inclusion (GEO-CF10) provided an optimal balance for 3DCP, achieving a compressive strength of 48.5 MPa (X-axis) and 44.8 MPa (Z-axis), which significantly reduced the anisotropy index from 0.365 in the control mix to 0.081. Furthermore, this mixture exhibited a 126% improvement in inter-layer tensile bond strength (4.12 MPa) and a substantial increase in flexural toughness energy compared to unreinforced specimens. The novelty of this study lies in the successful integration of industrial waste-derived rCF to establish a near-isotropic structural framework, effectively transforming brittle delamination failure into ductile structural collapse. These results provide a robust benchmark for developing high-performance, sustainable, and automated civil infrastructure, demonstrating that optimized fiber reinforcement can overcome the structural discontinuities typically associated with layer-by-layer deposition in geopolymer systems.

Keywords: 3D Concrete Printing, Geopolymer Concrete, Recycled Carbon Fibers, Mechanical Anisotropy, Interlayer Bond Strength.

I. INTRODUCTION

The global construction sector is currently under intense pressure to adopt sustainable practices, driven by strict environmental regulations aimed at decarbonizing the building materials supply chain. Simultaneously, the industry is experiencing a massive shift toward digital manufacturing through 3D Concrete Printing (3DCP) to enhance efficiency, reduce on-site waste, and mitigate dependence on conventional labor. This technology enables the direct fabrication of complex structural elements from digital models without the need for formwork, which drastically reduces project timelines and operational costs in urban infrastructure development. However, the reliance on high-content OPC remains a critical bottleneck, as it contributes significantly to carbon emissions and structural shrinkage. The development of alternative binder systems has become an important area of interest for reducing the environmental impact associated with 3DCP applications.

Despite the environmental potential of geopolymers, contemporary research indicates that these systems encounter significant mechanical challenges in automated applications. For instance, (Ramadhani et al., 2025) observed that the rapid setting time of geopolymer pastes often leads to inadequate inter-layer bonding, which compromises the overall load-bearing capacity of 3D-printed elements. Complementing this, (Golewski, 2023) demonstrated that the inherent brittleness of non-reinforced geopolymer pastes leads to premature delamination failure under directional stress, representing a critical safety concern for load-bearing applications. A specific case of this can be seen in the printing of high-aspect-ratio walls, where the lack of internal reinforcement causes horizontal interfaces to become distinct planes of weakness, often resulting in structural instability during the build phase.

Although prior studies have sought to improve 3D-printed materials, significant limitations persist regarding binder-reinforcement compatibility. (Lv & Liu, 2023) showed that synthetic polypropylene fibers improve flexural toughness, yet they often exhibit poor interfacial chemical bonding with alkaline geopolymer matrices. Similarly, (Akbulut et al., 2025) noted that glass fibers enhance post-cracking resistance, but their high susceptibility to alkaline degradation compromises long-term structural durability. (ELDeeb et al., 2025) demonstrated that while macro-reinforcements increase tensile capacity, their large diameters frequently cause nozzle obstructions and flow discontinuity.

Furthermore, (Martínez-Gómez, 2026) explored carbon nanotubes for matrix densification, but their prohibitive costs and dispersion complexities hinder large-scale practical implementation. Finally, (El Nagggar et al., 2025) focused primarily on small-scale mortar specimens, leaving a void in literature regarding the rheological-mechanical interaction of industrial-grade micro-fibers at a structural scale. These gaps underscore a lack of research on the synergistic potential of Recycled Carbon Fibers in reducing anisotropy. Therefore, this research aims to investigate the hybrid performance of 3D-printed geopolymer concrete incorporated with rCF, specifically targeting the reduction of the anisotropic index and the enhancement of inter-layer bond strength.

This study hypothesizes that the incorporation of rCF into a geopolymer matrix will establish a superior crack-bridging mechanism, effectively transforming brittle delamination failure into ductile structural collapse. The primary research question addresses whether the alignment of rCF induced by robotic extrusion can sufficiently reduce the anisotropic index to near-isotropic levels. The novelty of this work lies in the integration of industrial waste-derived rCF within a zero-cement geopolymer framework, verified through a comprehensive granular analysis of rheological parameters, mechanical anisotropy, and microstructural interfacial bonding. Through this investigation, it is anticipated that the findings will establish a new benchmark for high-

performance, sustainable, and automated construction materials, offering a viable pathway for the next generation of resilient civil infrastructure.

II. LITERATURE REVIEW

A. Geopolymerization Synthesis and Printing Rheology

The field of geopolymer research has evolved through various studies focusing on the chemical interactions between precursor materials and alkaline activators. (Islam et al., 2025) suggest that the synthesis of geopolymer concrete involves a complex inorganic polymerization reaction between silica-alumina precursors and alkaline activators. (Smagina et al., 2023) note that the structural integrity of the resulting gel matrix is highly sensitive to the molar ratio of the activator solution. Furthermore, (Luo et al., 2026) highlight that the rheological behavior of fresh mixtures must exhibit precise thixotropic properties. (Kimmel et al., 2025) explains that maintaining a balanced shear-thinning behavior is critical for material flow during extrusion. Finally, (Feng et al., 2024) demonstrate that the temperature of the curing environment significantly alters the development of the aluminosilicate gel.

B. Mechanical Role of Recycled Carbon Fibers

Various strategies have been explored to address the mechanical limitations of geopolymer matrices through fiber reinforcement. (Ibrahim & Prasyas, 2025) discuss that the integration of recycled carbon fibers into geopolymer matrices serves as a strategy to establish a robust internal reinforcement network. (Hakim & Sholikhan, 2024) observes that the high aspect ratio of these fibers facilitates an effective crack-bridging mechanism. (Akpınar et al., 2025) add that the physical bonding between the fiber surface and the surrounding paste is improved by residual carbon functional groups. (Sadeghi & Cavaliere, 2023) explains that the alignment of these micro-scale fibers creates a directional improvement in strength. (Şahin et al., 2024) point out that the inclusion of these fibers does not negatively impact the flowability of the mixture.

C. Buildability and Extrudability Parameters in 3DCP Technology

The performance of 3DCP systems is primarily evaluated based on the operational efficiency of the printing ink. (Rudziejewicz et al., 2023) examine the success of 3DCP as defined by the balance between pumpability and the capacity to sustain vertical loads. (Yu et al., 2026) state that extrudability is primarily governed by the static yield stress of the ink. Research by (Da Silveira Júnior et al., 2024) highlights that buildability is dependent on the rapid gain of green strength. (Si et al., 2025) suggest that the time-dependent evolution of yield stress is a decisive factor during the printing of complex geometries. (Li et al., 2025) emphasizes that the interaction between printing speed and thixotropic recovery is essential for achieving dimensional stability.

D. State-of-the-Art and Advances in 3D-Printed Fiber-Reinforced Geopolymers

The characterization of fiber-reinforced geopolymers involves distinct chemical and mechanical performance assessments. (Šimonová et al., 2024) analyze the effectiveness of specific glass fiber types in enhancing the tensile capacity of fly ash-based geopolymer matrices. (Kyriakidis et al., 2024) compares the mechanical performance of polymer-based fibers within GGBS-activated binder systems. (Kim et al., 2023) demonstrates the specific influence of carbon nanotubes on the matrix density of hybrid binder compositions. (Mohamed & Zuaiter, 2024) presents findings on the isotropy of composites reinforced with recycled carbon fibers in fly ash and GGBS blends. (Shokrollahi et al., 2023) utilize numerical modeling to predict the anisotropic strength index by calculating non-uniform stress distributions in the composite layers. Table 1 provides a comparative analysis of the experimental parameters and findings from these studies.

Table 1. Comparison of Experimental Findings on Geopolymer Composites

Study	Fiber Type	Binder Base	Key Finding
(Šimonová et al., 2024)	Glass Fibers	Fly Ash	Improved tensile strength
(Kyriakidis et al., 2024)	Polymer Fibers	GGBS	Enhanced ductility
(Kim et al., 2023)	Nanotubes	Hybrid	Higher matrix density
(Mohamed & Zuaiter, 2024)	Recycled Carbon	Fly Ash/GGBS	Optimized isotropy
(Shokrollahi et al., 2023)	Steel Micro-fibers	Fly Ash	Increased bond strength

III. RESEARCH METHOD

A. Experimental Framework and Operational System Setup

This study adopted a laboratory-based experimental approach to investigate the influence of recycled carbon fibers on the fresh-state and hardened-state properties of 3D-printed geopolymer concrete. The experimental program was organized into several sequential stages, including raw material characterization, geopolymer mixture preparation, rheological evaluation, automated concrete printing, specimen curing, mechanical testing, and analytical data processing. Each stage was conducted under controlled laboratory conditions to ensure consistency throughout the experimental campaign. The selected methodology was designed to evaluate the effects of varying rCF contents on printability, buildability, mechanical anisotropy, and interlayer bonding performance. All experimental procedures were performed following standardized testing protocols and documented laboratory procedures.

The overall experimental workflow adopted in this study is illustrated in Figure 1. The flowchart summarizes the sequence of activities implemented throughout the investigation, beginning with raw material characterization and ending with mechanical performance assessment and data analysis. The framework was developed to provide a structured representation of the experimental procedures and the relationships among individual testing stages. The workflow also illustrates

the progression from fresh-state evaluation to hardened-state characterization. This framework was used as a reference during the execution of all experimental activities.

Operational Flowchart of 3D Printing Concrete Experiment

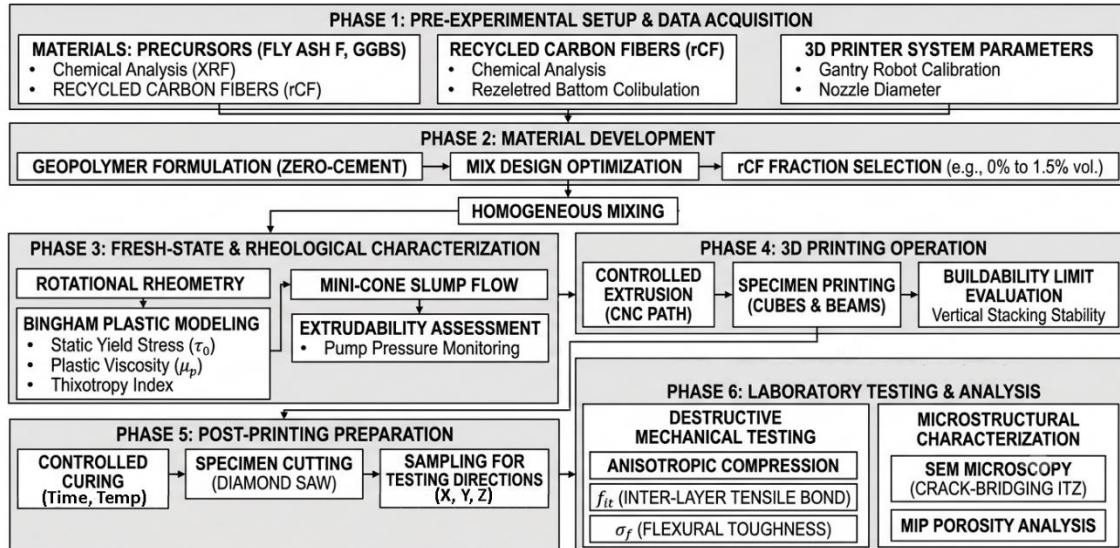


Figure 1. Operational Flowchart of 3D Printing Concrete Experiment

The flowchart consists of several interconnected stages that describe the complete experimental process. Material characterization was conducted prior to mixture preparation to establish the physical and chemical properties of the constituent materials. Fresh-state testing was performed before specimen fabrication to assess the suitability of the mixtures for extrusion-based printing. Printed specimens were subsequently cured under controlled conditions before being subjected to mechanical testing. The resulting experimental data were compiled and processed for comparative evaluation among the investigated mixtures.

All specimens were fabricated using a gantry-based three-dimensional concrete printing system equipped with a Computer Numerical Control (CNC) mechanism. The printing setup consisted of a material hopper, progressive cavity pump, delivery hose, and extrusion nozzle configured for continuous material deposition. Operational parameters, including nozzle diameter, printing speed, layer height, and pumping pressure, were maintained within predetermined ranges throughout the fabrication process. Prior to printing, the equipment was calibrated to ensure dimensional accuracy and stable extrusion behavior. The same operational settings were applied to all mixture variations to minimize the influence of external variables.

A schematic representation of the printing system is presented in Figure 2. The figure illustrates the principal components of the printing apparatus and the material delivery pathway from the mixing chamber to the extrusion nozzle. In addition, the schematic includes a conceptual representation of fiber alignment generated by shear forces during material extrusion. The

arrangement of the equipment was configured to enable continuous printing operations and consistent layer deposition. The illustration serves as a visual reference for the experimental setup employed in this study.

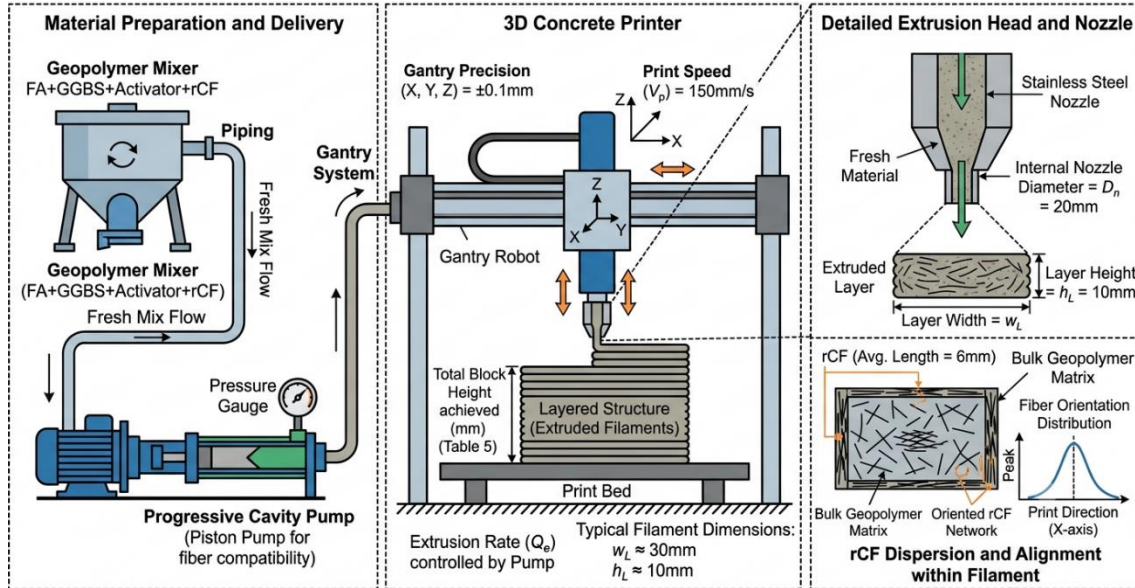


Figure 2. Schematic Setup of the 3D Concrete Printing System

The geopolymer mixture was transferred from the mixing chamber to the extrusion nozzle using a continuous pumping mechanism. Material deposition was performed in a layer-by-layer manner according to predefined digital printing paths generated through CNC control. During extrusion, the material experienced shear stresses within the nozzle section, which influenced the orientation of the recycled carbon fibers. All printed specimens were fabricated using identical geometric configurations and printing parameters. The printing process was conducted under laboratory conditions with controlled temperature and humidity.

B. Raw Material Analysis and Geopolymer Precursors Characterization

The constituent materials employed in this investigation were characterized prior to mixture preparation to establish their physical and chemical properties. Class F fly ash and ground Granulated Blast Furnace Slag (GGBS) were selected as the primary aluminosilicate precursors due to their suitability for geopolymer synthesis. Fine quartz sand was incorporated as the aggregate phase, while sodium silicate and sodium hydroxide solutions were utilized as alkaline activators. Recycled carbon fibers obtained from post-industrial composite waste were introduced as reinforcing elements. The characterization process provided the material parameters required for mixture design and subsequent performance evaluation.

The chemical composition of the geopolymer precursors and the physical properties of recycled carbon fibers are summarized in Table 2. Oxide compositions were determined through X-Ray

Fluorescence (XRF) analysis, while fiber properties were obtained through laboratory measurements and supplier specifications. The recorded characteristics include the principal oxide constituents of the geopolymer precursors as well as the geometric and mechanical properties of the recycled fibers. These parameters were used during mixture formulation and experimental analysis. The material characterization results constitute the basis for the selection of constituent materials used in this study.

Table 2. Chemical Composition of Geopolymer Precursors

Constituent Oxide / Property	Fly Ash (Class F) (%)	GGBS (%)	Recycled Carbon Fiber (rCF)
Silicon Dioxide (SiO ₂)	52.40	33.15	Average Length: 6.0 mm
Aluminum Oxide (Al ₂ O ₃)	24.15	14.20	Diameter: 7.2 μm
Iron Oxide (Fe ₂ O ₃)	7.10	0.65	Tensile Strength: 3.5 GPa
Calcium Oxide (CaO)	4.20	39.80	Elastic Modulus: 230 GPa
Magnesium Oxide (MgO)	1.30	6.40	Density: 1.75 g/cm ³
Loss on Ignition (LOI)	1.80	0.35	Surface Carbon: ≥ 94%

The data presented in Table 2 indicate the major oxide components contained in the fly ash and GGBS materials. Silica and alumina represent the dominant constituents of the aluminosilicate precursors, while calcium-bearing compounds are primarily associated with the slag component. The recycled carbon fibers are characterized by their average length, filament diameter, tensile strength, elastic modulus, and density. These characteristics were considered during mixture preparation and printing operations. The reported material properties were subsequently used as reference parameters throughout the experimental program.

C. Concrete Mix Design and Alkali-Activator Formulations

A controlled mixture design approach was adopted to evaluate the influence of recycled carbon fiber incorporation on the performance of 3D-printed geopolymer concrete. Four mixture variations were prepared, consisting of one control mixture without fiber reinforcement and three mixtures containing different rCF volume fractions. The geopolymer precursor content, aggregate quantity, and alkaline activator proportions were maintained constant among all mixtures. Variations were introduced through adjustments in fiber content and minor modifications to the water-to-binder ratio. This approach enabled direct comparison of the effects of recycled carbon fibers on fresh-state and hardened-state properties.

The detailed mixture proportions used in the experimental program are presented in Table 3. The selected compositions were developed through preliminary laboratory trials and consideration of the rheological requirements associated with extrusion-based printing. Particular attention was given to maintaining adequate workability while preserving shape stability after deposition. All mixtures were prepared using identical mixing procedures and batching sequences. The resulting formulations were subsequently employed throughout the experimental investigation.

Table 3. Geopolymer Concrete Mix Proportions per Cubic Meter of Concrete

Mix ID	Fly Ash (kg/m ³)	GGBS (kg/m ³)	Fine Quartz Sand (kg/m ³)	Na ₂ SiO ₃ Solution (kg/m ³)	NaOH Solution (12 M) (kg/m ³)	rCF Volume Fraction, ϕ_f (%)	Water-to-Binder Ratio
GEO-CTRL	250	250	1100	142.8	57.2	0.0	0.38
GEO-CF05	250	250	1100	142.8	57.2	0.5	0.39
GEO-CF10	250	250	1100	142.8	57.2	1.0	0.40
GEO-CF15	250	250	1100	142.8	57.2	1.5	0.42

The mixture compositions shown in Table 3 include the quantities of fly ash, GGBS, fine quartz sand, sodium silicate solution, sodium hydroxide solution, and recycled carbon fibers. The control mixture served as the reference specimen for evaluating the effects of fiber incorporation. Fiber-reinforced mixtures were produced using volume fractions of 0.5%, 1.0%, and 1.5%. Minor adjustments to the water-to-binder ratio were introduced to accommodate changes in mixture consistency associated with increasing fiber content. All formulations were prepared and tested under identical laboratory conditions.

D. Rheological and Fresh-State Testing Protocols

Fresh-state characterization was conducted immediately after mixture preparation to assess the suitability of each geopolymer formulation for three-dimensional printing applications. The evaluation focused on rheological behavior, workability, and material consistency prior to extrusion. These properties are closely related to pumping efficiency, extrusion stability, and shape retention during the printing process. All fresh-state tests were performed under controlled laboratory conditions using calibrated equipment. Three replicate measurements were conducted for each test to improve measurement reliability.

The rheological properties of the geopolymer mixtures were measured using a rotational concrete rheometer. Testing was initiated immediately after mixing to minimize the influence of time-dependent structural development. The experimental protocol involved increasing the shear rate gradually from 0 s⁻¹ to 60 s⁻¹ while continuously recording the corresponding shear stress response. The resulting datasets were used to determine yield stress and plastic viscosity parameters. Identical testing procedures were applied to all mixture variations.

Workability was further evaluated through a mini-cone slump flow test based on a modified ASTM C1437 procedure. The test was performed immediately following rheological measurements to determine the spread diameter of each mixture. The average value obtained from three repeated measurements was recorded for analysis. Slump flow testing provided

supplementary information regarding mixture consistency and flowability prior to printing operations. All measurements were conducted at room temperature under identical environmental conditions.

E. Mechanical Anisotropy Testing and Analytical Mathematical Modeling

Following specimen fabrication and curing, mechanical testing was conducted to evaluate the influence of recycled carbon fibers on strength development, directional mechanical behavior, and interlayer bonding performance. Printed elements were cut using a precision diamond saw to obtain specimens suitable for laboratory testing. Cubic specimens measuring $50 \times 50 \times 50$ mm were prepared for compressive strength evaluation, whereas beam specimens measuring $50 \times 50 \times 200$ mm were prepared for flexural testing. Mechanical loading was applied along different orientations relative to the printing direction to quantify directional variations in material performance. All testing procedures were carried out using calibrated universal testing machines under controlled loading conditions.

Analytical procedures were subsequently applied to process the experimental data obtained from rheological and mechanical testing. The analysis focused on characterizing material flow behavior, directional strength variation, and interlayer bonding performance. Experimental measurements were converted into quantitative parameters to facilitate comparison among the investigated mixtures. The selected analytical approaches are commonly applied in studies involving printable cementitious and geopolymer materials. The calculated parameters were used throughout the evaluation of fresh-state and hardened-state performance.

The rheological behavior of geopolymer mixtures was evaluated using a constitutive model that describes the relationship between shear stress and shear rate during material deformation. The rheological parameters were determined using the Bingham Plastic Model as presented in Equation (1).

$$\tau = \tau_0 + \mu_p \cdot \dot{\gamma} \quad (1)$$

In this equation, τ represents the total shear stress (Pa), τ_0 denotes the yield stress (Pa), μ_p corresponds to the plastic viscosity (Pa·s), and $\dot{\gamma}$ indicates the applied shear rate (s^{-1}). The calculated rheological parameters were used to characterize the flow behavior of the geopolymer mixtures during pumping, extrusion, and layer deposition processes.

Directional variations in compressive strength were quantified using a dimensionless parameter that represents the degree of mechanical anisotropy in the printed concrete specimens. The anisotropy index was calculated from the compressive strength values obtained along the three principal loading directions using Equation (2).

$$AI \frac{\sigma_{max} - \sigma_{min}}{\sigma_{average}} \quad (2)$$

In this equation, σ_{max} represents the maximum compressive strength, σ_{min} denotes the minimum compressive strength, and $\sigma_{average}$ corresponds to the average compressive strength obtained from the X-, Y-, and Z-direction loading tests. The resulting index was used to evaluate the extent of directional strength variation and to compare the anisotropic behavior of mixtures containing different recycled carbon fiber contents.

The bonding performance between adjacent printed layers was evaluated through an interlayer tensile bond strength parameter derived from the measured failure load. The interlayer bond strength was determined according to Equation (3).

$$f_{it} = \frac{2P}{\pi \cdot b \cdot l} \quad (3)$$

In this equation, f_{it} represents the interlayer tensile bond strength (MPa), P denotes the maximum applied load recorded during testing (N), b corresponds to the specimen width (mm), and l represents the bonded interface length (mm). The calculated bond strength values were used to assess the quality of interfacial adhesion and the effectiveness of recycled carbon fibers in enhancing layer-to-layer connectivity within the printed geopolymer elements.

IV. RESULT

A. Influence of Recycled Carbon Fibers on Fresh Rheological Properties

Fresh-state behavior plays a critical role in determining the printability of geopolymer concrete. The rheological response of the material directly affects extrusion stability, layer deposition quality, and shape retention during printing. Recycled carbon fibers are expected to modify the internal resistance of the mixture by increasing particle interaction and restricting flow mobility. Variations in rheological properties influence both the extrusion process and the structural stability of freshly deposited layers. To evaluate these effects, slump-flow diameter, static yield stress, plastic viscosity, and thixotropy index were measured for all mixtures. The experimental results are summarized in Table 4.

Table 4. Rheological Properties of Fresh Printing Inks

Mix ID	Slump-Flow Diameter (mm)	Static Yield Stress (τ_0) (Pa)	Plastic Viscosity (μ_p) (Pa·s)	Thixotropy Index
GEO-CTRL	210	120	18.5	1.15
GEO-CF05	185	165	24.2	1.42
GEO-CF10	160	210	32.8	1.85
GEO-CF15	135	295	45.1	2.24

Table 4 shows that increasing recycled carbon fiber content progressively reduced slump-flow diameter while increasing yield stress, plastic viscosity, and thixotropy. The control mixture

exhibited the highest flowability, with a slump-flow diameter of 210 mm and a yield stress of 120 Pa. As fiber content increased to 1.0%, yield stress and viscosity rose substantially, indicating improved shape-retention capability after extrusion. GEO-CF10 achieved a balance between flowability and structural stability, whereas GEO-CF15 exhibited excessive rheological resistance that could negatively affect pumping and extrusion continuity. These results indicate that recycled carbon fibers significantly influence the fresh-state behavior of printable geopolymer mixtures.

The rheological behavior of printable geopolymer mixtures evolves continuously during the mixing and conditioning stages. Changes in internal particle interaction can significantly affect extrusion stability and shape-retention performance during printing. The incorporation of recycled carbon fibers alters the rate at which yield stress and viscosity develop over time. Monitoring these changes is important for determining the available printing window and identifying potential processing limitations. The evolution of rheological parameters throughout the testing period is presented in Figure 3.

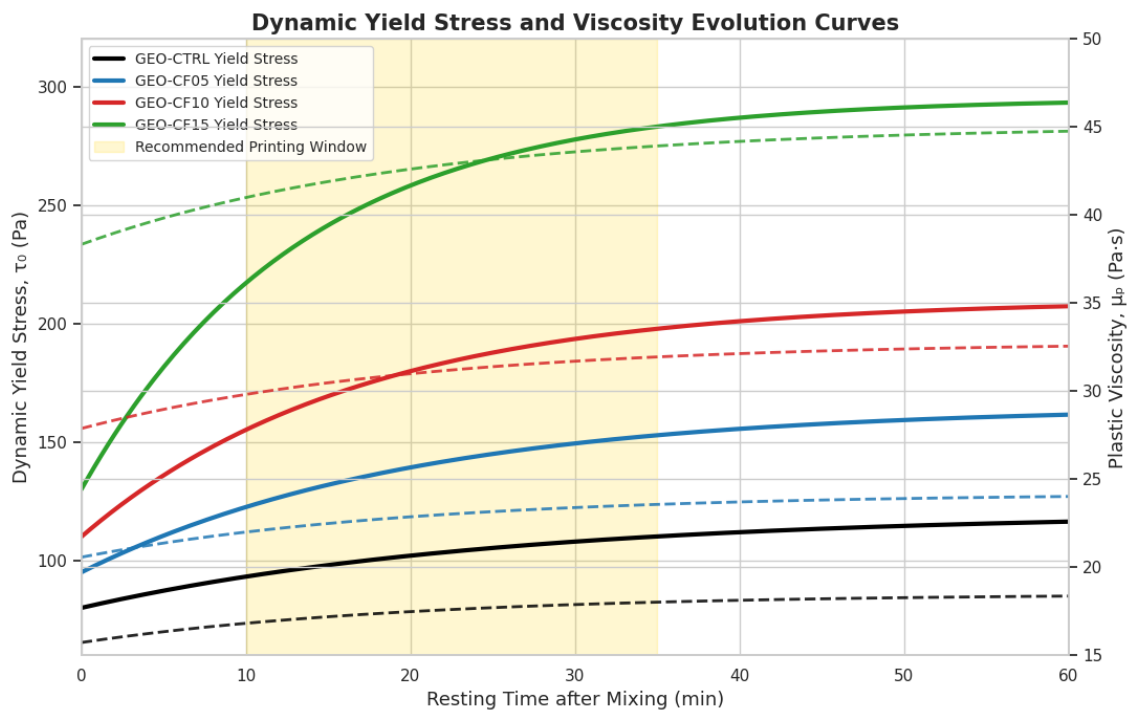


Figure 3. Dynamic Yield Stress and Viscosity Evolution Curves

Figure 3 shows that yield stress and viscosity increased continuously with increasing recycled carbon fiber dosage. The growth rate became more pronounced in GEO-CF10 and GEO-CF15, reflecting stronger internal particle interaction and reduced free-water mobility. Higher rheological resistance improved the ability of freshly deposited layers to retain their geometry after extrusion. Nevertheless, excessive increases in yield stress and viscosity may reduce

pumpability and shorten the practical printing window. The observed trends support the suitability of GEO-CF10 as the mixture providing the most balanced rheological performance.

B. Extrudability Performance and Vertical Buildability Limits

The successful application of 3D-printed geopolymers depends on achieving a balance between extrusion continuity and structural buildability. Materials with insufficient yield stress may deform after deposition, whereas excessively stiff mixtures can cause pumping difficulties and nozzle blockage. Recycled carbon fibers influence both behaviors by modifying rheological resistance and internal reinforcement mechanisms during layer accumulation. Evaluating extrusion and buildability performance is therefore essential for identifying an optimal mixture composition. To assess these characteristics, extrusion continuity, pump pressure, maximum printable layers, and achievable build height were measured during printing trials. The resulting performance indicators are summarized in Table 5.

Table 5. Extrudability and Buildability Performance Metrics

Mix ID	Extrusion Continuity Status	Critical Pump Pressure (MPa)	Max Printed Layers (No Collapse)	Total Block Height Achieved (mm)
GEO-CTRL	Excellent (Continuous)	1.2	12 Layers	240
GEO-CF05	Excellent (Continuous)	1.5	22 Layers	440
GEO-CF10	Good (Continuous)	1.9	35 Layers	700
GEO-CF15	Poor (Discontinuous)	2.8	28 Layers (Buckling Failure)	560

Table 5 demonstrates that recycled carbon fiber incorporation substantially improved buildability performance up to an optimal dosage of 1.0%. The control mixture exhibited excellent extrusion continuity but was only capable of sustaining 12 layers before deformation occurred. The addition of fibers increased structural stability, allowing GEO-CF10 to reach 35 layers and a total height of 700 mm. This improvement can be attributed to the higher yield stress and enhanced resistance to layer deformation observed in the rheological analysis. However, further increasing the fiber content to 1.5% resulted in a marked rise in pump pressure, reduced extrusion continuity, and premature buckling during printing, indicating that excessive fiber addition may negatively affect material flow despite improving structural stability.

C. Anisotropic Compressive Strength Evolution (X, Y, and Z Axis)

One of the primary challenges in extrusion-based concrete printing is the development of anisotropic mechanical behavior caused by the layer-by-layer deposition process. Differences in interlayer bonding quality may result in unequal strength values depending on the loading direction. Such behavior can reduce structural reliability when printed elements are subjected to

multidirectional loading conditions. The incorporation of recycled carbon fibers is expected to improve stress transfer across adjacent layers and reduce mechanical discontinuities within the printed matrix. To investigate these effects, compressive strength tests were conducted along the X-, Y-, and Z-axes, and the corresponding anisotropy indices were calculated for each mixture. The experimental results are summarized in Table 6.

Table 6. Anisotropic Compressive Strength at 7 and 28 Days

Mix ID	Axis X (MPa)	Axis Y (MPa)	Axis Z (MPa)	Calculated Anisotropy Index (AI)
GEO-CTRL	36.2	32.5	24.8	0.365
GEO-CF05	41.4	38.2	33.5	0.210
GEO-CF10	48.5	45.2	44.8	0.081
GEO-CF15	44.1	40.8	36.2	0.196

Table 6 shows that recycled carbon fiber incorporation improved compressive strength in all loading directions while simultaneously reducing anisotropic behavior. The control mixture exhibited the lowest strength values, particularly along the Z-axis, resulting in an anisotropy index of 0.365. Progressive improvements were observed as the fiber content increased, with GEO-CF10 achieving compressive strengths of 48.5 MPa, 45.2 MPa, and 44.8 MPa along the X-, Y-, and Z-axes, respectively. The corresponding anisotropy index decreased to 0.081, indicating a nearly uniform mechanical response. In contrast, GEO-CF15 exhibited a slight increase in anisotropy despite maintaining higher strength than the control mixture, suggesting that excessive fiber content may reduce structural homogeneity during extrusion.

The directional dependence of compressive strength was further evaluated to assess the effectiveness of recycled carbon fibers in reducing anisotropic behavior. Differences in strength among the three loading orientations provide important information regarding interlayer bonding quality and stress transfer efficiency within the printed structure. The incorporation of fiber reinforcement is expected to improve the uniformity of mechanical performance by strengthening weak interfacial regions. Visual comparison of strength distributions allows the influence of fiber dosage on directional properties to be more clearly identified. The compressive strength profiles obtained for the three loading orientations are presented in Figure 4.

Figure 4 confirms that the largest strength disparity occurred in the control mixture, particularly between the X- and Z-axis loading directions. The difference between directional strengths progressively decreased with recycled carbon fiber incorporation and reached its lowest level in GEO-CF10. The nearly identical strength values recorded along all three axes indicate improved interlayer stress transfer and a more homogeneous internal structure. A slight increase in directional variation was observed in GEO-CF15, which may be associated with fiber agglomeration and reduced dispersion efficiency at higher fiber contents. The results demonstrate

that an appropriate recycled carbon fiber dosage can significantly reduce anisotropic behavior while simultaneously enhancing overall compressive strength.

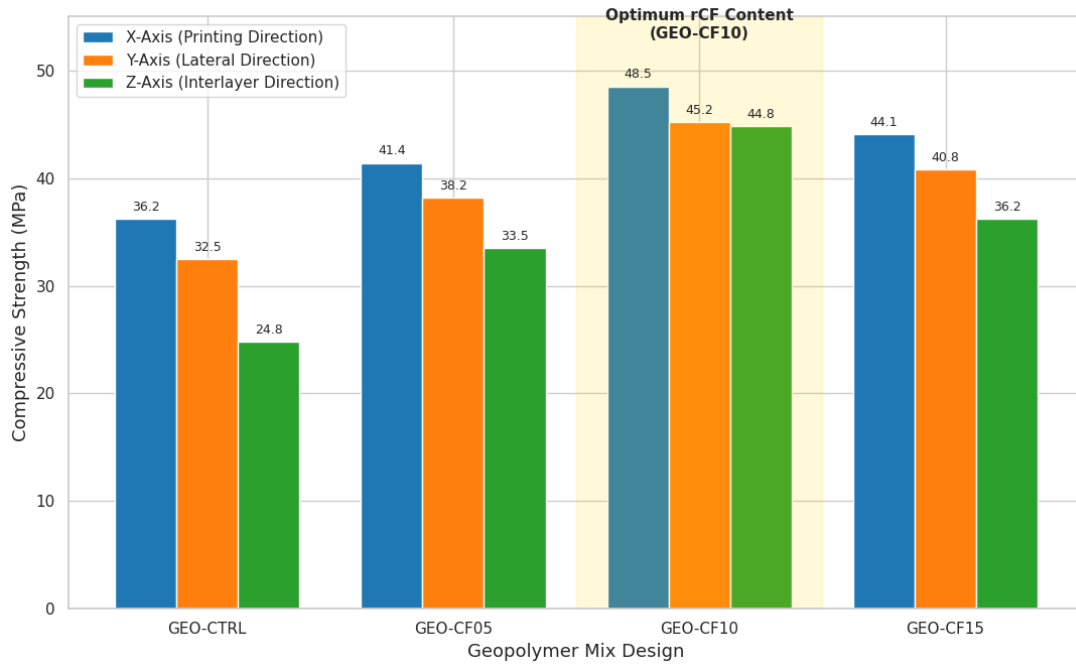


Figure 4. Compressive Strength Comparison Across Testing Orientations

D. Inter-Layer Tensile Bond and Flexural Toughness Enhancement

The enhancement of interlayer bonding is a critical requirement for improving the structural performance of 3D-printed geopolymer concrete. Weak bonding between deposited layers often results in premature crack initiation and reduced resistance to tensile loading. The incorporation of recycled carbon fibers may improve interfacial cohesion by bridging microcracks and facilitating stress transfer across layer boundaries. In addition, fiber reinforcement can enhance flexural performance by increasing energy absorption capacity after crack formation. To evaluate these effects, inter-layer tensile bond strength, flexural strength, toughness energy index, and elastic modulus were determined after 28 days of curing. The measured mechanical properties are summarized in Table 7.

Table 7. Inter-Layer Tensile and Flexural Strength Properties

Mix ID	Inter-layer Tensile Bond (fit) (MPa)	Flexural Strength (σ_f) (MPa)	Toughness Energy Index (I20)	Elastic Modulus (GPa)
GEO-CTRL	1.82	3.45	1.02	26.4
GEO-CF05	2.65	5.12	3.85	28.1
GEO-CF10	4.12	7.88	6.42	31.5
GEO-CF15	3.24	6.20	5.10	29.8

Table 7 indicates that recycled carbon fiber incorporation substantially improved both interlayer bonding and flexural performance. The control mixture exhibited the lowest tensile bond strength

and flexural capacity, reflecting the vulnerability of unreinforced printed concrete to interfacial failure. Progressive improvements were observed with increasing fiber content up to GEO-CF10, which achieved the highest tensile bond strength of 4.12 MPa and the highest flexural strength of 7.88 MPa. The toughness energy index also increased significantly, indicating enhanced post-cracking behavior and energy absorption capacity. A slight reduction in performance was observed in GEO-CF15, suggesting that excessive fiber content may reduce reinforcement efficiency due to less uniform fiber distribution.

The influence of recycled carbon fibers on post-cracking behavior was further evaluated through three-point bending tests. Load-deflection responses were analyzed to assess stiffness development, ductility, and energy absorption capacity. Variations in the shape of the curves provide insight into the effectiveness of fiber reinforcement in controlling crack propagation. Particular attention was given to the behavior of the specimens after reaching peak load. The resulting load-deflection responses are presented in Figure 5.

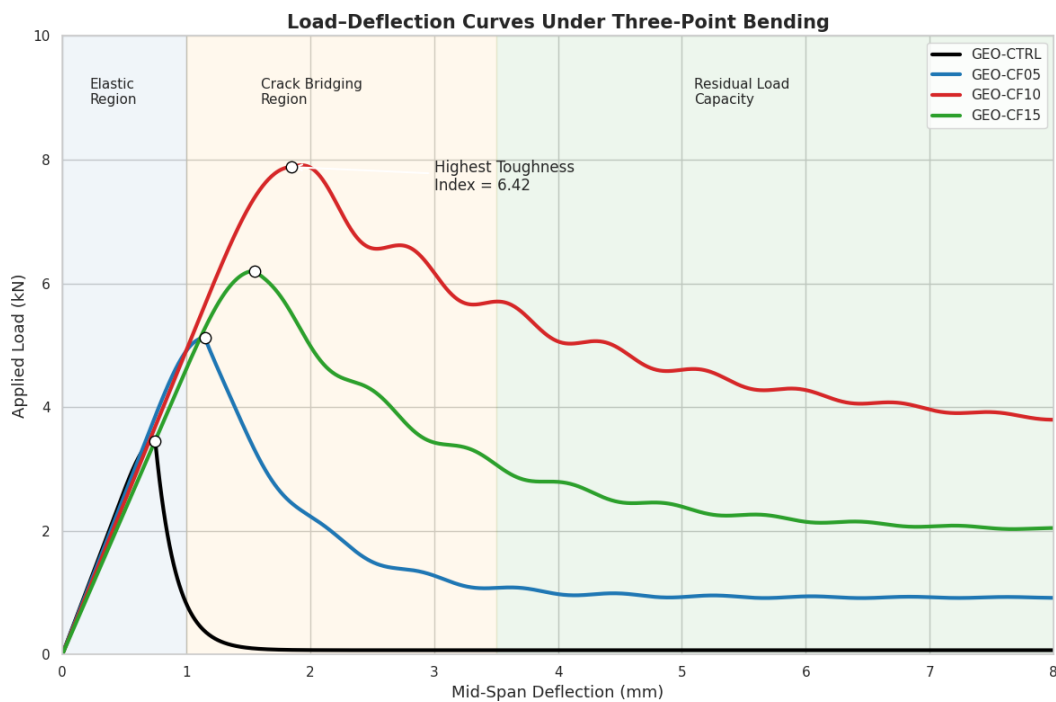


Figure 5. Load-Deflection Curves Under Three-Point Bending

Figure 5 shows a clear transition from brittle behavior in the control specimen to a more ductile response in the fiber-reinforced mixtures. GEO-CTRL experienced a rapid loss of load-carrying capacity immediately after peak loading, indicating limited resistance to crack propagation. In contrast, the reinforced specimens maintained significant residual load capacity because the recycled carbon fibers bridged developing cracks. The most pronounced post-peak response was observed in GEO-CF10, which exhibited greater deformation capacity and improved energy

absorption characteristics. These observations are consistent with the enhanced tensile bond strength and toughness measured in the mechanical tests.

E. Microstructural Interfacial Zone Analysis and Porosity Characterization

Microstructural characterization was conducted to investigate the internal mechanisms responsible for the observed improvements in mechanical performance. The pore structure and quality of the interfacial transition zone play important roles in determining the strength and durability of geopolymer concrete. Variations in porosity influence crack initiation, moisture transport, and stress distribution throughout the matrix. Recycled carbon fibers may modify the internal structure by reducing void formation and improving particle packing efficiency. To evaluate these effects, mercury intrusion porosimetry and microscopic analyses were performed on representative specimens from each mixture. The measured porosity characteristics are summarized in Table 8.

Table 8. Matrix Porosity and Microstructural Void Distribution

Mix ID	Total MIP Porosity (%)	Critical Pore Diameter (nm)	Inter-layer Void Volume (cm ³ /g)	Density (g/cm ³)
GEO-CTRL	16.8	54.2	0.045	2.15
GEO-CF05	13.2	42.1	0.028	2.22
GEO-CF10	9.4	22.5	0.011	2.29
GEO-CF15	12.6	38.4	0.022	2.24

Table 8 shows that recycled carbon fiber incorporation resulted in a significant refinement of the internal pore structure. The control mixture exhibited the highest porosity, the largest critical pore diameter, and the greatest interlayer void volume. Progressive reductions in these parameters were observed as fiber content increased to 1.0%, indicating improved matrix densification and interfacial continuity. GEO-CF10 achieved the lowest porosity value of 9.4% and the highest density among all investigated mixtures. A slight increase in porosity was observed in GEO-CF15, suggesting that excessive fiber addition may reduce packing efficiency and promote localized void formation.

The interaction between recycled carbon fibers and the geopolymer matrix was further examined using scanning electron microscopy. Particular attention was given to fiber anchorage, crack-bridging behavior, and the quality of the interfacial transition zone. These observations provide direct evidence regarding the mechanisms responsible for the enhanced mechanical performance observed in the reinforced mixtures. Microscopic examination also allows the identification of defects that may influence crack propagation and interlayer integrity. Representative SEM observations are presented in Figure 6.

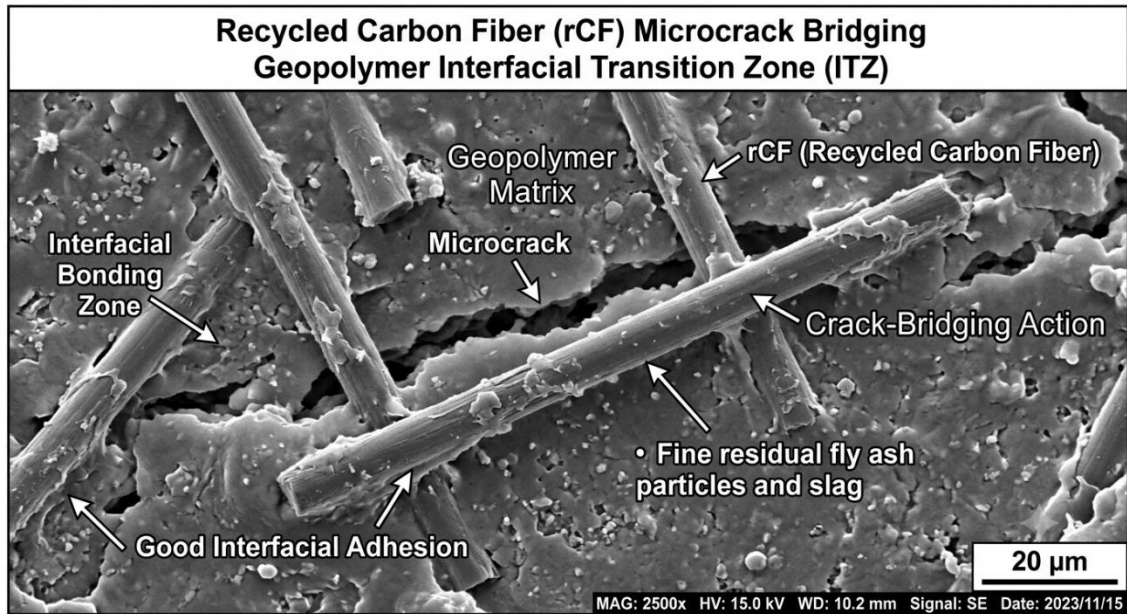


Figure 6. SEM Micrograph of Recycled Carbon Fiber Interfacial Bonding

Figure 6 shows a dense geopolymer matrix surrounding the recycled carbon fibers with limited evidence of interfacial separation. Fibers were observed bridging microcracks and maintaining continuity across damaged regions, indicating efficient stress transfer between the reinforcement phase and the surrounding matrix. The interfacial transition zone appeared compact and well bonded, particularly in GEO-CF10. In addition, fewer large pores and microstructural defects were visible compared with the control mixture. These observations support the improvements in strength and toughness identified in the mechanical tests.

The influence of fiber reinforcement on structural failure mechanisms was also evaluated through visual inspection of fractured specimens after mechanical testing. Differences in crack distribution and failure localization provide useful information regarding interlayer integrity and load redistribution capacity. Variations in failure mode can reveal the effectiveness of recycled carbon fibers in controlling crack propagation throughout the printed structure. Comparative observations were conducted on all investigated mixtures following mechanical loading. Representative post-failure observations obtained from the tested specimens are presented in Figure 7.

Figure 7 shows that the control specimens predominantly failed through delamination along the interfaces between adjacent printed layers. Crack propagation followed relatively direct paths, indicating limited resistance to interfacial separation. In contrast, the fiber-reinforced specimens exhibited more distributed cracking patterns and reduced evidence of layer detachment. GEO-CF10 displayed multiple fine cracks throughout the specimen rather than a single dominant fracture plane, indicating improved stress redistribution and crack-arresting behavior. The

observed transition from localized delamination to distributed fracture is consistent with the enhanced interlayer bonding and mechanical performance reported in the previous sections.

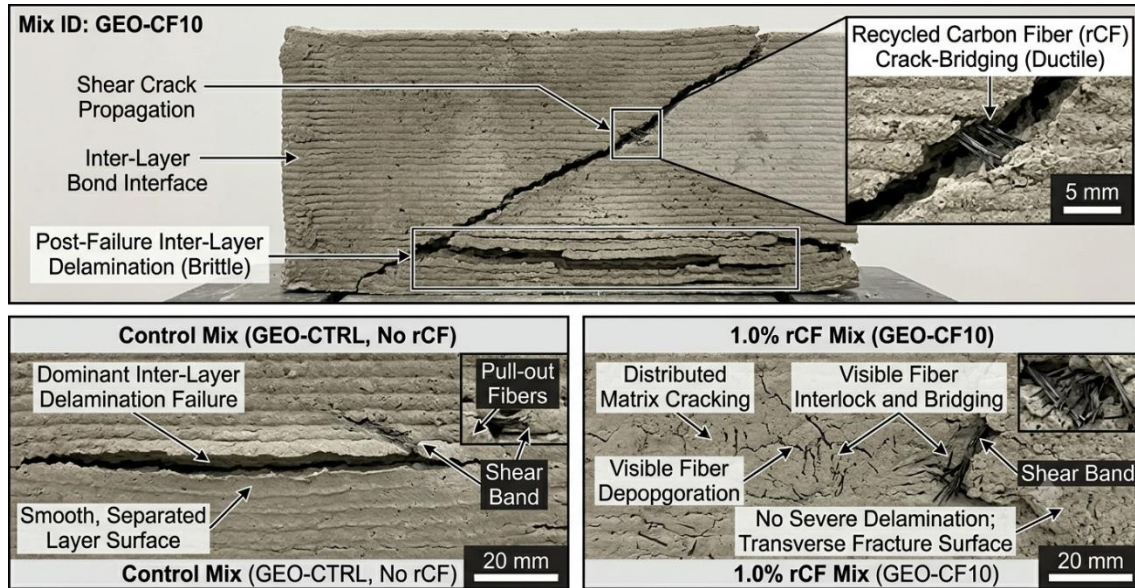


Figure 7. Visual Observations of Structural Inter-Layer Failure Modes

V. DISCUSSION

The results demonstrate that the incorporation of recycled carbon fibers significantly influences the fresh-state rheological behavior of 3D-printed geopolymer concrete, directly addressing the objective of improving printability while maintaining structural stability. The progressive increase in yield stress, plastic viscosity, and thixotropy with increasing fiber dosage confirms the importance of controlled rheological evolution for extrusion-based manufacturing. These findings are consistent with the observations of (Luo et al., 2026), who emphasized that printable concrete mixtures require carefully balanced rheological properties to ensure both pumpability and shape retention. Similarly, the enhanced buildability performance observed in GEO-CF10 supports the conclusions reported by (Da Silveira Júnior et al., 2024) and (Si et al., 2025), who identified rapid structural build-up as a critical factor governing the vertical stability of printed elements. The ability of GEO-CF10 to achieve substantially greater build heights while maintaining continuous extrusion indicates that recycled carbon fibers can effectively enhance the fresh-state performance of geopolymer printing inks when incorporated at an appropriate dosage.

A major contribution of this study is the substantial reduction of mechanical anisotropy achieved through recycled carbon fiber reinforcement. The anisotropy index decreased from 0.365 in the control mixture to 0.081 in GEO-CF10, indicating that fiber incorporation effectively improved stress transfer across printed layers and produced a nearly isotropic mechanical response. This finding strengthens the observations of (Mohamed & Zuaiter, 2024), who reported that recycled

carbon fiber reinforcement can contribute to more uniform mechanical properties in geopolymer composites. Furthermore, the results support the theoretical interpretation proposed by (Sadeghi & Cavaliere, 2023), which suggested that fiber alignment can enhance mechanical performance through improved crack-bridging mechanisms. Compared with previous studies that primarily focused on material-level characterization, the present investigation extends existing knowledge by demonstrating the effectiveness of recycled carbon fibers in reducing anisotropy within structurally relevant 3D-printed geopolymer elements.

The improvements observed in inter-layer tensile bond strength, flexural strength, and toughness further confirm the beneficial role of recycled carbon fibers in mitigating the brittle nature of geopolymer materials. The transition from localized delamination in the control specimens to distributed cracking in the reinforced mixtures indicates a fundamental change in failure behavior, supporting the hypothesis proposed at the beginning of this study. These results align with the findings of (Hakim & Sholikhan, 2024) and (Akpinar et al., 2025), who highlighted the effectiveness of fiber-mediated crack bridging and enhanced fiber–matrix interaction in improving mechanical performance. In addition, the reduction in porosity and inter-layer void volume observed in GEO-CF10 is consistent with the matrix densification mechanisms discussed by (Kim et al., 2023), although the present study achieves these benefits using recycled fibers rather than costly nanomaterials. Consequently, the findings provide both theoretical and practical evidence that recycled carbon fibers can serve as an effective and sustainable reinforcement strategy for next-generation 3D-printed geopolymer construction materials.

Despite the overall positive outcomes, several findings indicate that excessive fiber incorporation may negatively affect system performance. Although GEO-CF15 contained the highest fiber dosage, its mechanical properties, anisotropy index, and buildability performance were inferior to those of GEO-CF10, suggesting the existence of an optimal reinforcement threshold. This behavior may be attributed to fiber agglomeration, reduced dispersion efficiency, and increased rheological resistance, which can disrupt homogeneous material deposition and create localized defects during extrusion. Such observations partially challenge the general assumption that higher fiber content always produces superior mechanical performance and highlight the importance of balancing reinforcement efficiency with printability requirements. Nevertheless, the interpretation of these findings should consider certain limitations of the study, including the controlled laboratory environment, the evaluation of a single recycled carbon fiber geometry, and the absence of long-term durability assessments, all of which may influence the broader applicability of the reported results.

VI. CONCLUSION AND RECOMMENDATION

This study investigated the influence of recycled carbon fibers on the rheological, mechanical, and microstructural performance of 3D-printed geopolymer concrete. The results demonstrated that recycled carbon fiber incorporation significantly improved buildability, inter-layer bonding, compressive strength, flexural toughness, and matrix densification while reducing mechanical anisotropy. Among the investigated mixtures, GEO-CF10 exhibited the most balanced overall performance, achieving the highest build height, the lowest anisotropy index, superior inter-layer tensile bond strength, and enhanced post-cracking behavior. Microstructural observations further confirmed that the improved performance was associated with reduced porosity, stronger fiber–matrix interaction, and effective crack-bridging mechanisms. These findings verify the proposed hypothesis and indicate that the integration of recycled carbon fibers within geopolymer matrices represents a promising approach for developing sustainable, high-performance materials for automated construction applications.

Future research is recommended to expand the understanding of recycled carbon fiber-reinforced geopolymer systems under more diverse operational and environmental conditions. Investigations involving different fiber geometries, surface treatments, and dispersion techniques may provide further insight into optimizing reinforcement efficiency and printability performance. Long-term durability assessments, including resistance to environmental exposure, cyclic loading, and chemical degradation, are also necessary to evaluate structural reliability throughout the service life of printed components. In addition, future studies should examine the scalability of the proposed material system through full-scale printing trials and more complex structural geometries representative of practical construction applications. Such efforts would contribute to the advancement of sustainable 3DCP technologies and support their broader implementation in modern civil infrastructure development.

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REFERENCES

Akbulut, Z. F., Tawfik, T. A., Smarzewski, P., & Guler, S. (2025). Advancing Hybrid Fiber-

- Reinforced Concrete: Performance, Crack Resistance Mechanism, and Future Innovations. *Buildings*, 15(8), 1247. <https://doi.org/10.3390/buildings15081247>
- Akpınar, I. A., Koçyiğit, Ö. F., & Atasoy, S. (2025). Effect of Oxidation and Silane Modifications Applied to the Bonded Material and Fibers in Carbon-Fiber-Reinforced Composite Adhesive Joints. *Polymers*, 17(14), 1893. <https://doi.org/10.3390/polym17141893>
- Da Silveira Júnior, J. G., de Moura Cerqueira, K., de Araújo Moura, R. C., de Matos, P. R., Rodriguez, E. D., de Castro Pessôa, J. R., & Tramontin Souza, M. (2024). Influence of Time Gap on the Buildability of Cement Mixtures Designed for 3D Printing. *Buildings*, 14(4), 1070. <https://doi.org/10.3390/buildings14041070>
- El Nagggar, A., Soliman, A., Youssef, M. A., & El Nagggar, H. (2025). Novel Methodological Approach to Developing Scaled-Down Concrete Material for Structural Applications: Experimental Validation Using Froude Scaling. *Buildings*, 15(17), 3234. <https://doi.org/10.3390/buildings15173234>
- ELDeeb, I. S., Esmael, E., Ebied, S., Diab, M. R., Dekis, M., Petrov, M. A., Zayed, A. A., & Egiza, M. (2025). Optimization of Nozzle Diameter and Printing Speed for Enhanced Tensile Performance of FFF 3D-Printed ABS and PLA. *Journal of Manufacturing and Materials Processing*, 9(7), 221. <https://doi.org/10.3390/jmmp9070221>
- Feng, L., Yi, S., Zhao, S., Zhong, Q., Ren, F., Liu, C., Zhang, Y., Wang, W., Xie, N., Li, Z., & Cui, N. (2024). Recycling of Aluminosilicate-Based Solid Wastes through Alkali-Activation: Preparation, Characterization, and Challenges. *Buildings*, 14(1), 226. <https://doi.org/10.3390/buildings14010226>
- Golewski, G. L. (2023). The Phenomenon of Cracking in Cement Concretes and Reinforced Concrete Structures: The Mechanism of Cracks Formation, Causes of Their Initiation, Types and Places of Occurrence, and Methods of Detection—A Review. *Buildings*, 13(3), 765. <https://doi.org/10.3390/buildings13030765>
- Hakim, F. N., & Sholikhhan, M. (2024). Enhancing Data Security through Digital Image Steganography: An Implementation of the Two Least Significant Bits (2LSB) Method. *International Journal of Graphic Design*, 2(2), 222–235. <https://doi.org/10.51903/ijgd.v2i2.2124>
- Ibrahim, S. M., & Prasyas, A. (2025). Performance Evaluation of Recycled Concrete Aggregates in Seismic-Resistant Structural Design. *Civil Engineering Science and Technology*, 1(1), 75–93. <https://doi.org/10.51903/9d6ba216>
- Islam, M. T., Kafle, B., & Al-Ameri, R. (2025). Natural Clay in Geopolymer Concrete: A Sustainable Alternative Pozzolan Material for Future Green Construction—A Comprehensive Review. *Sustainability*, 17(22), 10180. <https://doi.org/10.3390/su172210180>
- Kim, J.-H., Hwang, H.-I., & Im, J.-S. (2023). Optimization of the Filler-and-Binder Mixing Ratio for Enhanced Mechanical Strength of Carbon–Carbon Composites. *Materials*, 16(11), 4084. <https://doi.org/10.3390/ma16114084>

- Kimmel, V., Gräfe, L., Grieser, L., Lips, A., Hennig, R., Winck, J., & Thommes, M. (2025). Modeling Shear-Thinning Flow in Twin-Screw Extrusion Processes. *Pharmaceutics*, 17(3), 353. <https://doi.org/10.3390/pharmaceutics17030353>
- Kyriakidis, I. F., Kladovasilakis, N., Pechlivani, E. M., & Tsongas, K. (2024). Mechanical Performance of Recycled 3D Printed Sustainable Polymer-Based Composites: A Literature Review. *Journal of Composites Science*, 8(6), 215. <https://doi.org/10.3390/jcs8060215>
- Li, Z., Liu, T., Cui, H., Dong, J., Geng, Z., Deng, C., Zhang, S., Sun, Y., & Zhou, H. (2025). Magnetic Thixotropic Fluid for Direct-Ink-Writing 3D Printing: Rheological Study and Printing Performance. *Colloids and Interfaces*, 9(5), 66. <https://doi.org/10.3390/colloids9050066>
- Luo, J., Wang, Q., Wang, L., & Fang, M. (2026). A Review of the Rheological Properties of 3D-Printed Concrete: Raw Materials, Printing Parameters, and Evolution Mechanisms. *Buildings*, 16(6), 1264. <https://doi.org/10.3390/buildings16061264>
- Lv, C., & Liu, J. (2023). Alkaline Degradation of Plant Fiber Reinforcements in Geopolymer: A Review. *Molecules*, 28(4), 1868. <https://doi.org/10.3390/molecules28041868>
- Martínez-Gómez, J. (2026). Functional Composite Nanomaterials: Synthesis Strategies, Structure–Property Relationships, and Emerging Applications. *Processes*, 14(9), 1428. <https://doi.org/10.3390/pr14091428>
- Mohamed, O., & Zuaiter, H. (2024). Fresh Properties, Strength, and Durability of Fiber-Reinforced Geopolymer and Conventional Concrete: A Review. *Polymers*, 16(1), 141. <https://doi.org/10.3390/polym16010141>
- Ramadhani, S., Siregar, J. K., Suzita, S., & Mayanti, M. (2025). Seismic Resilience of 3D Printed Concrete Structures Parametric Optimization and Real-Scale Experimental Validation. *Jurnal Rekayasa Sipil Dan Arsitektur*, 1(2), 20–38. <https://doi.org/10.51903/zg90qr45>
- Rudziejewicz, M., Maroszek, M., Góra, M., Dziura, P., Mróz, K., Hager, I., & Hebda, M. (2023). Feasibility Review of Aerated Materials Application in 3D Concrete Printing. *Materials*, 16(17), 6032. <https://doi.org/10.3390/ma16176032>
- Sadeghi, B., & Cavaliere, P. D. (2023). Reviewing the Integrated Design Approach for Augmenting Strength and Toughness at Macro- and Micro-Scale in High-Performance Advanced Composites. *Materials*, 16(17), 5745. <https://doi.org/10.3390/ma16175745>
- Şahin, H. G., Mardani, A., & Beytekin, H. E. (2024). Effect of Silica Fume Utilization on Structural Build-Up, Mechanical and Dimensional Stability Performance of Fiber-Reinforced 3D Printable Concrete. *Polymers*, 16(4), 556. <https://doi.org/10.3390/polym16040556>
- Shokrollahi, Y., Nikahd, M. M., Gholami, K., & Azamirad, G. (2023). Deep Learning Techniques for Predicting Stress Fields in Composite Materials: A Superior Alternative to Finite Element Analysis. *Journal of Composites Science*, 7(8), 311. <https://doi.org/10.3390/jcs7080311>

- Si, W., Khan, M., & McNally, C. (2025). A Comprehensive Review of Rheological Dynamics and Process Parameters in 3D Concrete Printing. *Journal of Composites Science*, 9(6), 299. <https://doi.org/10.3390/jcs9060299>
- Šimonová, H., Bazan, P., Kucharczyková, B., Kocáb, D., Łach, M., Mierzwiński, D., Setlak, K., Nykiel, M., Nosal, P., & Korniejenko, K. (2024). Hybrid Geopolymer Composites Based on Fly Ash Reinforced with Glass and Flax Fibers. *Applied Sciences*, 14(21), 9787. <https://doi.org/10.3390/app14219787>
- Smagina, V., Yudaev, P., Kuskov, A., & Chistyakov, E. (2023). Polymeric Gel Systems Cytotoxicity and Drug Release as Key Features for their Effective Application in Various Fields of Addressed Pharmaceuticals Delivery. *Pharmaceutics*, 15(3), 830. <https://doi.org/10.3390/pharmaceutics15030830>
- Yu, S., Luo, Y., Chen, S., Fan, J., & Zhang, H. (2026). Quantitative Assessment of Hydrogel Printability in Extrusion Bioprinting. *Gels*, 12(3), 189. <https://doi.org/10.3390/gels12030189>