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Sustainable High-Strength Geopolymer Composite Reinforced with Nano-Silica and Basalt Fibers: Mechanical and Microstructural Evaluation

Moulya H V[1],*, Ashwini Satyanarayana[2], Shivanand C G[3]

Abstract

Sustainable soil composites (SSC) were formulated by incorporating red earth with varying proportions of bagasse ash (BA) and hydrated lime to enhance geotechnical performance and promote the reuse of agro-industrial waste. Red earth served as the primary structural matrix, BA functioned as a pozzolanic filler, and lime acted as a chemical stabilizer. BA content ranged from 0% to 60%, identifying 10% as the optimum level for significant improvement, and lime content varied from 1% to 5% for performance optimization. Standard geotechnical tests in accordance with IS 2720 determined Atterberg limits, compaction characteristics, and property changes after curing for 0, 7, and 30 days. Microstructural analysis using SEM showed a transformation from a porous particle arrangement to a denser, interlocked matrix, while XRD confirmed the formation of C-S-H and C-A-H phases, indicating pozzolanic reactivity. BA addition initially increased the liquid limit due to higher water affinity, later reducing after curing as cementitious bonds developed. OMC increased and MDD decreased with higher BA content due to lower specific gravity, with lime at 3-4% delivering optimal plasticity reduction and strength gain. The developed composite demonstrated improved stability, durability, and environmental compatibility, making it a viable solution for subgrade stabilization in road construction and other geotechnical works, contributing to circular economy practices and offering a cost-effective alternative to conventional methods.

Keywords: Geopolymer concrete, nano-silica, basalt fibers, recycled coarse aggregate (RCA), composite materials, mechanical properties, microstructure, sustainability, hybrid reinforcement

INTRODUCTION

The transition towards sustainable construction has driven research into alternative binder systems that can mitigate the environmental impact of ordinary Portland cement (OPC), which accounts for nearly 7% of global CO_2 emissions [1]. Geopolymer concrete (GPC) emerging as a viable alternative due to its low carbon footprint, high thermal stability, and superior mechanical performance [2-3]. It utilizes aluminosilicate-rich industrial by-products such as fly ash (FA) and ground granulated blast furnace slag (GGBS), which, when activated by alkaline solutions, form a stable binder matrix composed primarily of sodium aluminosilicate hydrate (N-A-S-H) and calcium aluminosilicate hydrate (C-A-S-H) gels [4-5]. These gels provide a dense, three-dimensional polymeric network with enhanced chemical resistance, making GPC suitable for aggressive environments and high-performance applications [6].

***Author for Correspondence**
Moulya H V

[1]Assistant Professor, Department of Civil Engineering, Nitte Meenakshi Institute of Technology (NMIT), Nitte (Deemed to be University), Bengaluru, Karnataka, India
[2]Assistant Professor, Department of Civil Engineering, Dayananda Sagar College of Engineering, Kumaraswamy layout, Bengaluru, Karnataka, India
[3]Assistant Professor, Department of Civil Engineering, The Oxford College of Engineering, Bengaluru, Karnataka, India

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While GPC offers distinct environmental and durability advantages over OPC, it often exhibits lower tensile strength, reduced flexural capacity, and susceptibility to early-age cracking. To address these limitations, reinforcement strategies incorporating nano-scale additives and fibers have been explored. Nano-silica (NS), with its high surface area and reactive amorphous silica content, accelerates the geopolymerization reaction, refines pore structure, and promotes the formation of dense gels, resulting in improved early-age strength, reduced porosity, and enhanced durability [7-10]. Basalt fibers (BF), derived from naturally occurring volcanic rock, provide high tensile strength, alkali resistance, and thermal stability, enabling effective crack bridging, post-crack ductility, and load redistribution under tensile and flexural stresses [13–14]. Integrating multi-scale reinforcement NS for matrix densification at the nano level and BF for mechanical bridging at the macro level offers synergistic benefits. NS enhances gel continuity and fiber–matrix interfacial bonding, while BF improves deformation control and toughness [15–16]. Although both reinforcements have been studied individually, the combined effect of NS and BF on the long-term mechanical and microstructural performance of GPC, particularly with recycled aggregates, remains underexplored.

Incorporating 100% recycled coarse aggregate (RCA) into GPC aligns with circular economy principles and promotes waste valorization [17-18]. RCA, however, introduces adhered mortar and higher porosity, which can weaken the interfacial transition zone (ITZ). The matrix densification effect of NS and the crack-bridging ability of BF have the potential to mitigate these drawbacks [19]. Therefore, the present study develops and evaluates a novel hybrid-reinforced geopolymer composite using a binary FA–GGBS binder (40:60 ratio), alkali activation, 100% RCA, and M-sand as fine aggregate. The mechanical performance is assessed at 7, 28, and 56 days, and microstructural analysis is conducted using scanning electron microscopy (SEM) to understand the reinforcement mechanisms. This work addresses both environmental and structural performance goals, providing sustainable, high-strength material with potential applications in:

- Structural concrete elements requiring high strength-to-weight ratio
- Precast and modular construction systems where early strength is beneficial
- Pavements and industrial flooring are subject to abrasion and flexural stress
- Infrastructure in aggressive environments (marine, chemical plants) due to enhanced durability
- Fire- and seismic-resilient systems, leveraging GPC’s thermal stability and BF’s ductility contribution

By coupling waste utilization with multi-scale reinforcement, this study offers both a scientific advancement in composite design and a practical pathway toward greener, high-performance construction materials.

COMPOSITE CONSTITUENTS

The geopolymer composite in this study was formulated using a binary binder system (fly ash and ground granulated blast furnace slag), reinforced with nano-silica (NS) and basalt fibers (BF), and combined with sustainable aggregates, including recycled coarse aggregate (RCA) and manufactured sand (M-sand). An alkaline activator solution, comprising sodium hydroxide and sodium silicate, was used to initiate geopolymerization. The physical forms of all composite constituents are presented in Figure 1, while their key physical and chemical properties are summarized in Table 1 and Table 2, respectively. The materials were selected based on their synergistic contributions to strength development, durability, and sustainability within high-performance geopolymer concrete applications.

Table 1 presents the physical properties of all composite constituents used in the geopolymer concrete mix. The binder system consisted of Class F fly ash and ground granulated blast furnace slag (GGBS), both of which were fine powders with appropriate specific gravities and particle sizes conducive to effective particle packing and reactivity. Nano-silica (NS), introduced in powder form with nanometric particle size and high specific surface area, served as a microstructural densifier. Basalt fibers (BF), added in chopped monofilament form, exhibited high tensile strength and were used to improve the post-cracking performance of the composite. The recycled coarse aggregate (RCA) had a size range of 10–20 mm and showed higher water absorption due to residual mortar content, necessitating presaturation prior to mixing. Manufactured sand (M-sand), selected as the fine aggregate, offered consistent grading and angularity beneficial to concrete packing and strength. The alkali activator system, composed of sodium hydroxide (12 M) and sodium silicate in a 2.5:1 ratio, was used at a fixed activator-to-binder ratio to ensure uniform geopolymerization across all mixes.

Figure 1. Composite material constituents used in the study: (a) Fly ash (FA), (b) Ground granulated blast furnace slag (GGBS), (c) Nano-silica (NS), (d) Basalt fibers (BF), (e) Recycled coarse aggregate (RCA), (f) Manufactured sand (M-sand).

Table 1. Properties of composite constituents.

Material	**Property**	**Value / description**
Fly Ash (FA)	Type	Class F
	Specific Gravity	2.19
	Particle Size (D50, μm)	15–25
	Color	Grey
GGBS	Type	Ground Granulated Blast Furnace Slag
	Specific Gravity	2.85
	Particle Size (D50, μm)	10–20
	Glass Content (%)	> 90
Nano-Silica (NS)	Form	Amorphous Powder
	Average Particle Size (nm)	15–30
	Specific Surface Area (m^2/g)	> 200
	Purity (SiO_2 Content, %)	> 98
Basalt Fibers (BF)	Form	Chopped Monofilament
	Length (mm)	12
	Diameter (μm)	13–15
	Tensile Strength (MPa)	> 3000
	Density (g/cm^3)	2.70
Recycled Coarse Aggregates (RCA)	Size Range (mm)	10–20
	Specific Gravity	2.55
	Water Absorption (%)	4.5
	Crushing Value (%)	27.8
	Source	Demolished Concrete Waste
Alkali Activators	NaOH Concentration (M)	12
	Na_2SiO_3 / NaOH Ratio	2.5
	Activator / Binder Ratio	0.50

Table 2. Chemical composition of binder materials

Oxide component	Fly ash (FA) (% by weight)	GGBS (% by weight)	Nano-silica (NS) (% by weight)
SiO_2 (Silicon dioxide)	53.5	34.8	>98
Al_2O_3 (Aluminum oxide)	24.1	13.2	–
Fe_2O_3 (Iron oxide)	8.9	0.8	–
CaO (Calcium oxide)	3.6	37.1	–
LOI (Loss on Ignition)	1.4	0.8	–

Table 2 summarizes the major oxide compositions of the binder materials fly ash (FA), ground granulated blast furnace slag (GGBS), and nano-silica (NS) which are critical to the geopolymerization process. Fly ash was rich in silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3), which are essential for the formation of the N–A–S–H gel structure. GGBS, in contrast, exhibited a higher calcium oxide (CaO) content, contributing to early strength development through the formation of C–A–S–H type gels. The presence of minor iron oxide (Fe_2O_3) and loss on ignition (LOI) was within acceptable limits for geopolymer binder performance. Nano-silica showed ultra-high purity with more than 98% SiO_2 content, acting as a reactive filler to enhance gel formation and improve the composite's microstructure. The chemical compatibility of these materials supported the development of a robust and durable geopolymer matrix.

EXPERIMENTAL PROGRAM

The experimental program was designed to evaluate the influence of nano-silica (NS) and basalt fibers (BF) on the mechanical performance of geopolymer concrete incorporating recycled coarse aggregates (RCA) and manufactured sand (M-sand). A total of ten mixes were prepared: three with varying NS content (1–3%), three with varying BF content (0.5–1.5%), and three hybrid mixes combining both NS and BF. One control mix without any NS or BF was also included. All mixes were designed for a target density of 2400 kg/m³. The binder content was fixed at 400 kg/m³ with a fly ash to GGBS ratio of 40:60. The alkaline activator solution comprised 12 M sodium hydroxide and sodium silicate in a 1:2.5 weight ratio, maintaining an activator-to-binder ratio of 0.5. NS was added as a percentage of binder weight, and BF was added by volume of concrete. Mix proportions are provided in Table 3.

Concrete mixing was carried out using a pan mixer under controlled laboratory conditions. Standard cube specimens (150 × 150 × 150 mm) were cast for compressive strength testing, cylinders (150 × 300 mm) for split tensile strength, and prisms (100 × 100 × 500 mm) for flexural strength. All specimens were demolded after 24 hours and cured under ambient conditions until testing. Tests were conducted on 7, 28, and 56 days in accordance with IS 516:2018 for compressive and flexural strength and IS 5816:1999 for split tensile strength. Selected samples were subjected to scanning electron microscopy (SEM) to evaluate microstructural development and assess the influence of hybrid reinforcement.

Table 3. Mix proportions for geopolymer concrete (per m³)

Mix ID	FA (kg/m³)	GGBS (kg/m³)	NS (%)	NS (kg/m³)	BF (%)	BF (kg/m³)	NaOH (kg/m³)	Na_2SiO_3 (kg/m³)	Aggregates (kg/m³)
NS0	160.0	240.0	0	0.0	0.0	0.0	57.14	142.86	1800.0
NS1	160.0	240.0	1	4.0	0.0	0.0	57.14	142.86	1796.0
NS2	160.0	240.0	2	8.0	0.0	0.0	57.14	142.86	1792.0
NS3	160.0	240.0	3	12.0	0.0	0.0	57.14	142.86	1788.0
BF0.5	160.0	240.0	0	0.0	0.5	13.5	57.14	142.86	1786.5
BF1.0	160.0	240.0	0	0.0	1.0	27.0	57.14	142.86	1773.0
BF1.5	160.0	240.0	0	0.0	1.5	40.5	57.14	142.86	1759.5
NS1_BF0.5	160.0	240.0	1	4.0	0.5	13.5	57.14	142.86	1782.5
NS2_BF1.0	160.0	240.0	2	8.0	1.0	27.0	57.14	142.86	1765.0

RESULTS AND DISCUSSION

Compressive Strength

The compressive strength development of the geopolymer concrete mixes is presented in Table 4 and Figure 2. The control mix without any reinforcement (NS0) exhibited a moderate strength of 24.8 MPa at 28 days. The inclusion of nano-silica (NS) significantly enhanced compressive strength, with the mix containing 3% NS reaching 38.1 MPa at 28 days indicating a 53.6% improvement. This enhancement is attributed to the high surface area and pozzolanic activity of NS, which accelerates geopolymer gel formation and contributes to matrix densification. Similarly, basalt fiber (BF) addition improved compressive performance, particularly in the BF1.0 mix, which achieved 35.5 MPa. This increase is due to fiber-induced crack bridging and energy dissipation underloading. However, further increase to 1.5% BF led to a slight reduction in strength, likely due to fiber agglomeration and reduced compactability. The hybrid mixes combining both NS and BF demonstrated superior performance across all ages. Notably, the NS2_BF1.0 mix recorded the highest compressive strength of 43.9 MPa at 28 days, reflecting a synergistic effect between micro-scale matrix enhancement by NS and macro-scale crack control by BF. Overall, the results indicate that a balanced hybrid reinforcement strategy significantly improves compressive behavior by optimizing microstructural packing, crack resistance, and stress distribution.

These findings are consistent with recent reports on nano-silica modified sustainable concretes, which have shown compressive strength gains of 50-55% due to accelerated gel formation and pore refinement [20]. Similarly, the role of basalt fibers in enhancing compressive strength through crack-bridging and improved stress redistribution has been highlighted in previous studies [21-22]. Notably, the peak strength achieved by the hybrid mix (NS2_BF1.0) in this study surpasses the performance of comparable hybrid geopolymer systems reported in recent literature [23-24], indicating that the synergy between micro-scale matrix densification by NS and macro-scale reinforcement by BF is more pronounced when combined with a binary FA–GGBS binder and 100% recycled coarse aggregates.

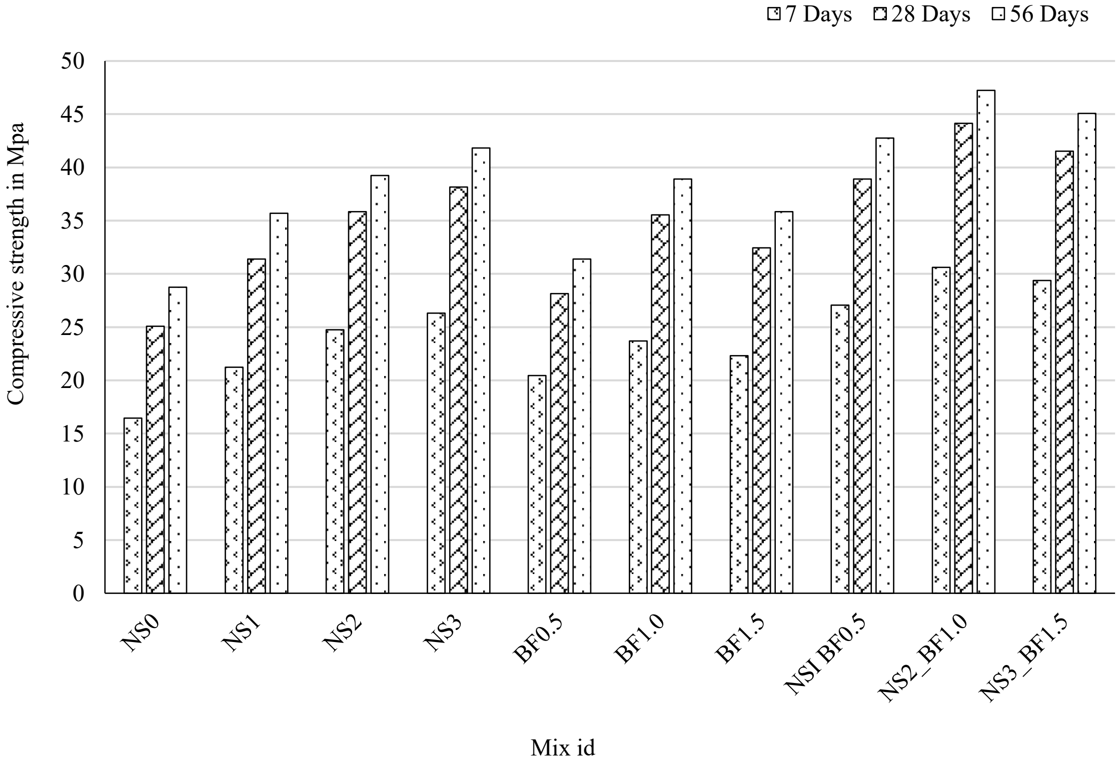

Figure 2. Compressive strength of geopolymer concrete mixes at 7, 28, and 56 days.

Split Tensile Strength

The split tensile strength values of the geopolymer concrete mixes are presented in Table 5 and illustrated in Figure 3. The control mix (NS0) achieved 1.86 MPa at 28 days. With the addition of nano-silica (NS), a steady increase in tensile strength was observed due to enhanced gel formation and improved matrix cohesion. The mix with 3% NS achieved 2.65 MPa at 28 days, reflecting a 42.5% improvement over the control. This enhancement is attributed to the refined microstructure and reduced internal voids provided by the nano-scale particles. Basalt fiber (BF) inclusion significantly contributed to tensile performance, particularly in the BF1.0 mix, which reached 2.58 MPa at 28 days. The improvement results from the fiber's ability to resist crack propagation and transfer tensile loads across the fracture plane. However, a slight reduction in tensile strength at 1.5% BF was noted, likely due to fiber clumping and reduced bonding efficiency. Hybrid mixes combining NS and BF demonstrated the most pronounced improvements. The NS2_BF1.0 mix recorded the highest tensile strength of 3.11 MPa at 28 days, showing a 67.2% increase over the control. This indicates that simultaneous matrix densification by NS and crack-bridging by BF leads to synergistic reinforcement, enhancing tensile load resistance. The results affirm that hybrid reinforcement at optimized dosages significantly boosts tensile performance without compromising workability or material integrity.

This tensile strength improvement aligns with prior research showing that nano-silica effectively enhances gel formation and matrix cohesion, thereby enabling higher tensile load resistance [25-26]. Basalt fiber inclusion has also been shown to contribute significantly to tensile capacity through its ability to transfer stresses across fracture planes and delay crack propagation [27-28]. The superior tensile performance of the NS2_BF1.0 mix in this study exceeds values reported for similar hybrid geopolymer composites [29-30], confirming that simultaneous nano-scale densification and macro-scale bridging produces a synergistic effect not achievable by individual reinforcements alone.

Flexural Strength

The flexural strength results for the geopolymer concrete mixes are summarized in Table 6 and represented graphically in Figure 4. The control mix (NS0) achieved a flexural strength of 3.45 MPa at 28 days. The addition of nano-silica (NS) resulted in progressive improvements in flexural behavior due to enhanced matrix continuity and bonding. The 3% NS mix reached 4.76 MPa, indicating a 38% increase, primarily driven by the densification of the matrix and improved interfacial bonding within the geopolymer gel structure. Basalt fibers (BF), known for their high tensile strength and bridging capacity, contributed more significantly to flexural enhancement than NS alone.

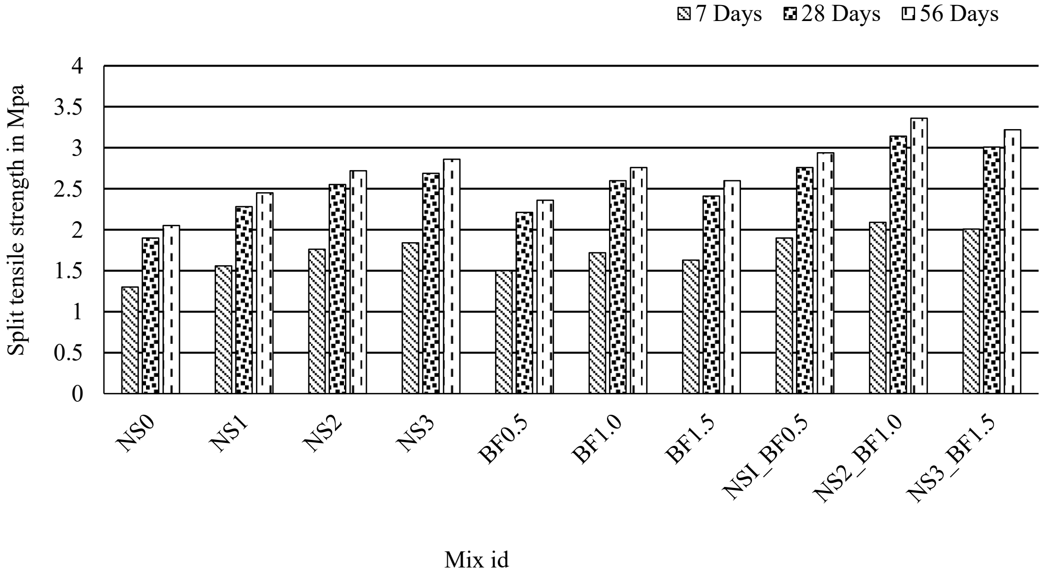

Figure 3. Split tensile strength of geopolymer concrete mixes at 7, 28, and 56 days.

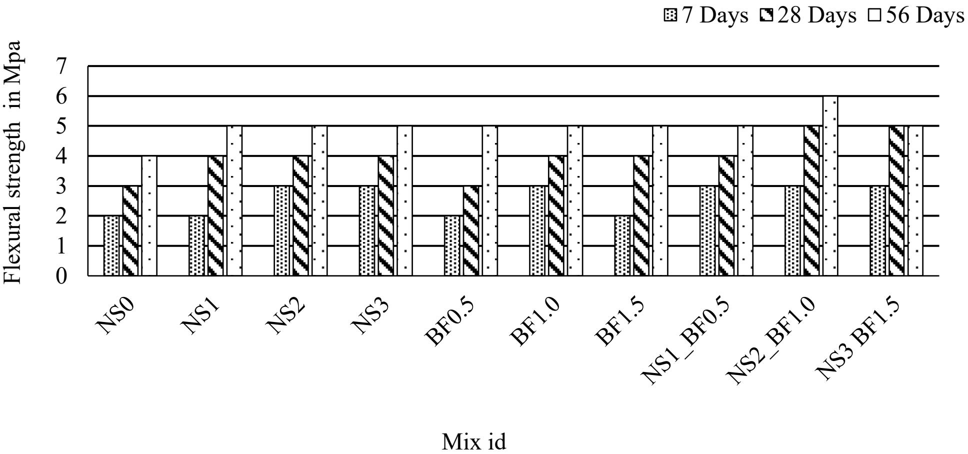

Figure 4. Flexural strength of geopolymer concrete mixes at 7, 28, and 56 days.

The BF1.0 mix exhibited a flexural strength of 4.53 MPa, a 31.3% increase over the control. This improvement is attributed to the fibers' ability to arrest microcracks and carry tensile loads across the matrix under bending stress. The hybrid mixes demonstrated the highest performance, with NS2_BF1.0 achieving the maximum flexural strength of 5.62 MPa at 28 days approximately 63% greater than the control. This confirms the synergistic reinforcement mechanism, where NS refines the matrix and BF provides effective crack bridging and deflection. Additionally, strength gain over time was more pronounced in hybrid mixes, highlighting the beneficial long-term effects of multi-scale reinforcement strategies.

Comparable studies have demonstrated that nano-silica additions refined the geopolymer matrix and enhance interfacial bonding, leading to improved flexural resistance [31-32]. Basalt fibers, due to their high tensile strength and modulus, have been reported to enhance flexural performance through effective crack bridging and deflection under bending loads [33-34]. The flexural strength achieved by the NS2_BF1.0 mix in this work exceeds the highest values reported in recent multi-scale reinforcement studies [35], indicating that the combination of NS-induced matrix densification and BF-based crack control provides a highly effective approach for enhancing bending performance in geopolymer composites.

Microstructural Analysis (SEM)

To elucidate the microstructural evolution resulting from multi-scale reinforcement, Scanning Electron Microscopy (SEM) analysis was performed on four geopolymer composites at 28 days: the unreinforced control matrix (NS0), nano-silica reinforced matrix (NS2), basalt fiber-reinforced composite (BF1.0), and the hybrid composite (NS2_BF1.0), as shown in Figure 5(a–d). The control specimen (Figure 5a) displayed a highly porous and discontinuous matrix with unreacted fly ash particles and loosely packed gel phases, reflecting insufficient geopolymerization and explaining the poor mechanical performance observed. In contrast, the NS2 composite (Figure 5b) exhibited a dense and homogenous matrix with refined pores, attributed to 2 wt.% nano-silica acting as a nucleating agent, which accelerated the formation of N–A–S–H and C–A–S–H gels and enhanced matrix packing. The BF1.0 specimen (Figure 5c) revealed embedded basalt fibers within a coarser matrix, where crack-bridging and partial fiber pull-out zones were evident, validating the improved tensile and flexural responses. However, some interfacial voids persisted, indicating that fiber addition alone does not guarantee matrix densification. The hybrid NS2_BF1.0 composite (Figure 5d) integrated both nano- and macro-scale mechanisms, yielding a compact, multi-phase structure with visible crack deflection, strong fiber–matrix interface (RMI), and well-dispersed reinforcement phases. This hybrid morphology supports synergistic toughening via enhanced load sharing and crack resistance and correlates directly with the superior mechanical performance recorded. Overall, the SEM analysis confirms that the simultaneous incorporation of nano-silica and basalt fibers results in a structurally optimized composite with superior strength, ductility, and damage tolerance.

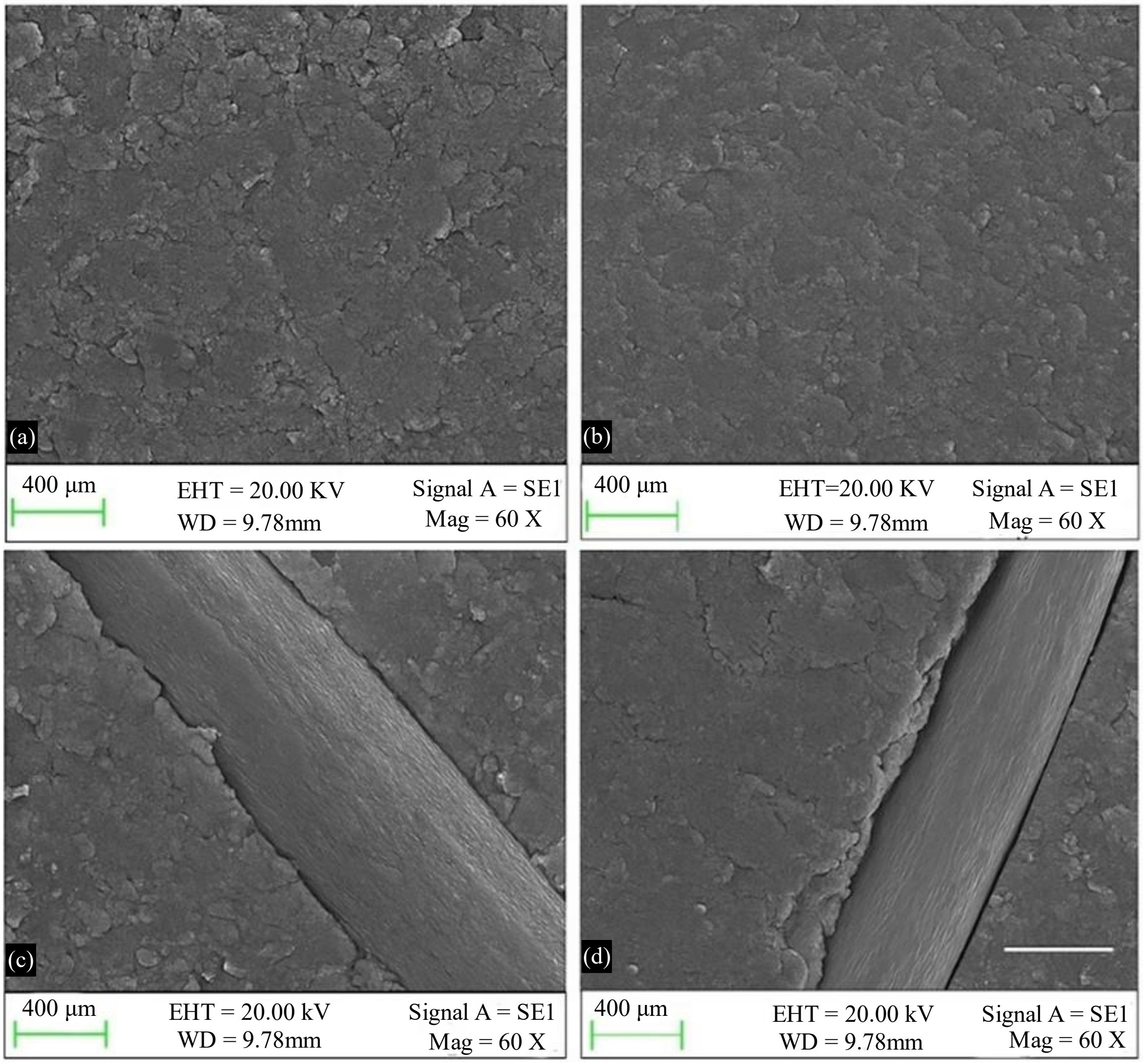

Figure 5. SEM micrographs of geopolymer composites at 28 days: (a) Control mix (NS0) showing porous, unreinforced matrix; (b) NS2 with a densified, compact gel matrix due to nano-silica; (c) BF1.0 exhibiting fiber bridging with matrix discontinuities; and (d) NS2_BF1.0 hybrid composite demonstrating synergistic toughening with crack deflection and strong fiber matrix interface.

CONCLUSION

This study successfully developed and characterized a sustainable geopolymer composite reinforced with nano-silica and basalt fibers, incorporating 100% recycled coarse aggregate and manufactured sand. The experimental results demonstrate that both nano- and macro-scale reinforcements significantly enhance the mechanical performance and microstructural integrity of geopolymer concrete.

Key conclusions drawn from the investigation include:

- Nano-silica (NS) improved compressive strength, matrix densification, and gel formation due to its high surface area and pozzolanic reactivity.
- Basalt fibers (BF) enhanced split tensile and flexural strength through effective crack bridging, load redistribution, and improved ductility.
- Hybrid reinforcement (NS+BF) exhibited synergistic effects, resulting in superior performance across all strength parameters. The mix with 2% NS and 1.0% BF achieved the highest compressive (43.9 MPa), tensile (3.11 MPa), and flexural (5.62 MPa) strengths at 28 days.

- SEM analysis confirmed a denser matrix, better fiber–matrix interface, and effective crack deflection in hybrid composites, validating the mechanical findings.
- The use of recycled aggregates and M-sand aligns the material system with circular economic goals, offering a sustainable alternative to traditional concrete.

Overall, the study establishes that multi-scale reinforcement using nano-silica and basalt fibers can effectively overcome the inherent brittleness and porosity of geopolymer matrices, especially when combined with recycled constituents. The findings support the application of such composites in structural, precast, and resilient infrastructure systems demanding high performance and sustainability.

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