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Research article

Effect of nano-bentonite and *Bacillus subtilis* treatments on the water absorption behavior of RHA-based geopolymer SIFCON through interfacial transition zone modification

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Abstract: In this study, the individual effects of different modification strategies, namely 1% nano-bentonite and *Bacillus subtilis* (*B. subtilis*, 1.0 × 10^8 CFU/mL) combined with 0.3% polyacrylamide (PAM), were investigated to improve the water resistance and mechanical performance of rice husk ash (RHA)-based geopolymer slurry-infiltrated fiber concrete (SIFCON). Our objective of this study was to reduce water absorption through interfacial transition zone (ITZ) refinement and matrix densification without compromising the mechanical properties of the composite material. In addition to microstructural observations using scanning electron microscopy (SEM), an extensive experimental investigation was performed, including compressive strength, splitting tensile strength, flexural strength, and water absorption tests. Our results showed that nano-bentonite boosted matrix compactness and ITZ quality lead to higher compressive strengths, up to 51.7 MPa, and lower water absorption than untreated mixes. In contrast, *B. subtilis* combined with PAM increased the matrix density via bacterial action and internal curing. This combination yielded the best results: a compressive strength of 52.9 MPa, a flexural strength of 22.92 MPa, and least water absorption at 1.46%. The optimum bacteria-treated mixtures exhibited up to 35% lower water absorption than the corresponding untreated mixtures. SEM observations confirmed a denser microstructure, reduced microvoid content, and improved fiber-matrix bonding in the modified composites. The novelty of this study lies in the comparative evaluation of biological and nano-modification approaches as separate

ITZ enhancement strategies for the sustainable RHA-based geopolymer SIFCON. These findings demonstrate the potential of these modification techniques for the development of durable and environmentally friendly geopolymer composites.

Keywords: geopolymer SIFCON; rice husk ash; nano-bentonite; *Bacillus subtilis*; interfacial transition zone; bio-mineralization

1. Introduction

Although concrete is the most widely used construction material globally, concerns over its durability and sustainability have continued to grow over the years. The production of Portland cement alone is responsible for almost 8% of global anthropogenic CO_2 emissions [1,2]. In addition, concrete faces degradation problems owing to harsh environments such as acid and sulfate attacks and chloride ingress, thereby causing structural degradation and cracking [3,4]. Therefore, researchers have focused on sustainable and durable alternatives to concrete.

Slurry-infiltrated fiber concrete (SIFCON) is one such ultra-high-performance concrete that has been designed to solve some of the problems that exist with traditional concrete. SIFCON is fabricated by infiltrating a highly flowable cementitious or geopolymer slurry into dense preplaced networks of steel fibers. This has led to the development of ultra-high-performance concrete with excellent energy absorption capacity and crack resistance [5]. In addition, when this concrete is made using geopolymer binders, such as rice husk ash (RHA), sustainability is also improved.

Studies have shown that *Bacillus subtilis* (*B. subtilis*) has the potential to improve the strength and self-healing properties of geopolymer concretes. Ekinci et al. [6] showed that the addition of *B. subtilis* to ground granulated blast furnace slag (GGBS)-based geopolymers improved their compressive strength, water absorption resistance, and resistance to acid and sulfate attacks. In another study, Mahmood et al. [7] showed that immobilizing *B. subtilis* in zeolite aggregates of fly ash-based geopolymers improved the self-healing of cracks and reduced porosity and water absorption. Tie et al. [8] also showed that *B. subtilis* made self-healing concrete tougher and longer lasting. This occurred because the bacteria helped in mineralizing and densifying the concrete structure, making it stronger overall. These improvements come from the bacteria surviving in alkaline conditions, boosting biomineralization, and microstructurally tightening things up. This helps cracks heal and reduces permeability, so everything remains more intact.

In addition, nano-bentonite has been identified as a powerful nanomodifier in alkali-activated binders. The high pozzolanic activity of nano-bentonite, coupled with its lamellar particle size, has been used to produce geopolymers with refined pore structures and improved mechanical strength in terms of compressive and tensile strength [9]. Frida et al. [10] reported the production of nano-bentonite/oil palm boiler ash composite with an average particle size of 14.46 nm, enhancing the content of silica and the efficiency of fillers. Additionally, Gadkar and Subramaniam et al. [11] reported the addition of up to 5% nano-bentonite to fly ash geopolymers, enhancing the structural integrity and mechanical strength of the geopolymers. According to Ali et al. (2025), bentonite-based composites have lower water absorption and permeability owing to matrix densification and interfacial transition zone (ITZ) refinement, which boosts their mechanical performance [12].

Although the high-performance characteristics of the geopolymer SIFCON have been identified, the high rate of water absorption is one of the major drawbacks of the composite material, particularly when RHA is used as the sole binder. This is mainly attributed to the porosity of the geopolymer matrix and the heterogeneous ITZ between the binder and steel fibers. The ITZ is often more prone to mechanical deterioration and permeability, thus acting as a major entry point for moisture during durability testing [5,13]. Although various methods have been reported in the literature for improving the water absorption resistance of composite materials, such as the use of mineral admixtures, nanotechnology, and microbial treatment [14,15], most of the methods have been individually tested without considering the synergistic effects of the methods or the combined effects of the methods on the refinement of the ITZ.

In this context, we aim to propose the individual effects of different modification strategies based on the use of *B. subtilis* (type 168) combined with polyacrylamide (PAM) and 1% nano-bentonite to improve the mechanical properties and water-resistance characteristics of RHA-based geopolymer SIFCON composites. Nano-bentonite can enhance particle packing, pore refinement, and ITZ quality owing to its ultrafine particle size, high specific surface area, and cation exchange capacity [16]. Additionally, *B. subtilis* can improve matrix densification through bacterial activity, biomineralization, and self-healing mechanisms, thereby reducing pore connectivity and water ingress [14,17]. Nanomaterials and bacterial treatments work well in cement and geopolymer stuff on their own, but limited information is available regarding how they compare when modifying the ITZ in RHA-based geopolymers, especially since RHA is the only binder. This is a big information gap that we want to fill.

In this study, standardized water absorption tests, microstructural observations, and mechanical tests were conducted to evaluate the performance of the RHA-based geopolymer SIFCON composites. This work is novel because we compared biological and nano-modification methods to reduce water absorption and improve ITZ quality in sustainable, high-fiber-volume geopolymer SIFCON. Our primary objective was to develop an environmentally friendly composite with improved resistance to moisture ingress through matrix densification and ITZ refinement. Furthermore, the use of RHA as the sole binder supports global efforts to reduce cement consumption and promote circular economy principles in construction material engineering [18,19].

2. Materials and methods

Our main goals of this study were to examine how the ITZ changes and how those changes affect the mechanical properties and water absorption. First, rice husks from Najaf Mill in Iraq were heated to 600 °C for 2 h, transforming them into RHA. In this study, RHA, which has an average particle size of 45 μm, acted as the only binding agent. The details of its chemical makeup are listed in Table 1.

Table 1. Chemical composition of RHA.

Component	SiO_2	Al_2O_3	MgO	CaO	K_2O	Na_2O	MnO	Fe_2O_3	P_2O_5	S	LOI*
Content (wt%)	93.20	0.12	0.30	0.40	1.20	0.10	0.30	0.15	0.07	0.04	4.12

*Note: loss on ignition.

For the experiment, we chose a 14 M sodium hydroxide (NaOH) solution combined with sodium aluminate ($NaAlO_2$) as the alkaline activator. Both substances were used at their suggested concentrations. NaOH was obtained from a local supplier, whereas $NaAlO_2$ was shipped from MRK Chemical in India. According to ASTM C778 [20], the fine aggregates used satisfied all the necessary requirements for standard sand.

To make the mixture more workable, stronger, and less permeable, a superplasticizer, KUT PLAST SP 400, was added. They obtained this information from the Specialties Construction Chemical Factory in Kuwait. Finally, according to ASTM A820 [21], hooked steel fibers measuring 0.7 mm in diameter and 35 mm in length from Atlas Company in Turkey, and straight steel microfibers, each 0.2 mm and 15 mm long, provided by Jingiang Hangtu in China, completed the setup. *B. subtilis* strain 168 was chosen for bioadditive preparation because of its established capacity for survival in alkaline environments and for inducing microbially induced calcium carbonate precipitation (MICP). Bacterial preparation was performed according to standard microbiological procedures to ensure cell viability. The specific steps involved in the preparation of bacterial cultures are schematically shown in Figure 1.

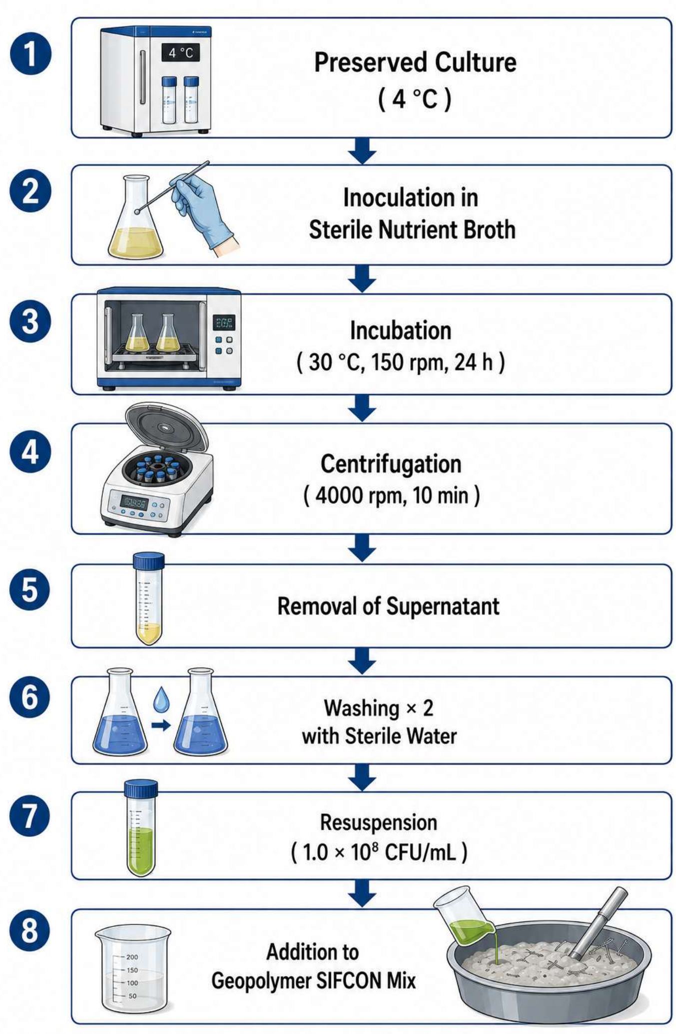

Figure 1. *Bacillus subtilis* strain preparation and addition to the geopolymer SIFCON matrix.

The culture was procured from a recognized culture collection of microbes and stored at a refrigerated temperature of 4 °C until use. A loopful of the stored culture was aseptically transferred to 100 mL of nutrient broth culture medium, which was prepared according to the manufacturer’s specifications. The inoculated nutrient broth culture was then subjected to incubation at a temperature of 30 ± 1°C and a shaking speed of 150 rpm for 24 h in a shaking incubator to enhance aerobic growth and reach the exponential growth phase.

After incubation, bacterial cultures were placed in a series of sterile centrifuge tubes. The bacterial culture was then centrifuged at 4000 rpm for 10 min. Bacterial cells were separated from the culture medium by centrifugation. The culture medium was discarded to ensure that there was no interference with geopolymer reactions. The bacterial culture was washed twice with sterile distilled water. The washing process was aimed at ensuring that no culture medium remained in the bacterial culture. The bacterial culture was resuspended and centrifuged under the same conditions.

After washing, the bacterial culture was resuspended in sterile distilled water. The bacterial culture was then adjusted to a concentration of 1.0×10^8 CFU/mL using an OD600 spectrophotometer. The bacterial culture was then ready for use in the SIFCON geopolymer mix. The bacterial culture was immediately used to ensure optimal bacterial viability and calcite precipitation.

A bacterial culture was prepared to ensure optimal bacterial viability and calcite precipitation. The bacterial culture was then ready for use in the geopolymer SIFCON mix, ensuring optimal bacterial viability and calcite precipitation. The bacterial culture was aimed at promoting bacterial activity, localized biomineralization, and matrix densification, which contributed to pore refinement, improved the ITZ, and enhanced water resistance.

Based on the findings of other investigations, an optimized reference mix was selected with RHA as the sole binder, with the addition of steel fibers and alkaline activators. The reference mixture used in this investigation had 500 kg/m^3 RHA, an activator-to-binder ratio (Al/Bd) of 80 wt%, a sodium aluminate-to-sodium hydroxide ratio (SAL/SHd) of 2, and a 14 M NaOH solution. Additional water (75 kg/m^3) was used to obtain the desired consistency of the mixture. Following the principles of the SIFCON concept, no coarse aggregates were used in the mixture; however, standard sand (328 kg/m^3) was used. A superplasticizer of 6 wt% relative to RHA was used in the mixture to enhance the slurry infiltration process. The reference mixture had a flow value of 19.5 cm, ensuring the desired flowability of the mixture with adequate strength and fluidity for the production of the SIFCON castings.

The baseline mix design used in this study is presented in Table 2, which is based on another study [19]. This study is an extension of another study, with further refinement of the mixture design parameters for better slurry penetration, improved fiber distribution, and enhanced structural and durability characteristics of RHA-based geopolymer SIFCON mixes with varying types and contents of steel fibers.

Table 2. The geopolymer SIFCON concrete mix designs adopted from another study [19].

Mixture	RHA	Sand	Alkaline/RHA ratio 0.8	SPA 6%	Water 12%	Hooked fiber	Micro fiber
RA	500	328	400	30	60	----	----
HR3	500	328	400	30	60	780	----
HR4	500	328	400	30	60	975	----
HR5	500	328	400	30	60	1170	----
MR3	500	328	400	30	60	----	784
MR4	500	328	400	30	60	----	980
MR5	500	328	400	30	60	----	1176
CR3	500	328	400	30	60	390	392
CR4	500	328	400	30	60	487.5	490
CR5	500	328	400	30	60	585	588

Note: MR stands for mixes reinforced with micro-steel fibers, whereas CR stands for mixes reinforced with equal amounts of hooked-end and micro-steel fibers. HR stands for mixes reinforced with hooked-end steel fibers, and RA stands for the control mix using RHA without the addition of steel fibers. SPA stands for the superplasticizer.

The impact of PAM, nano-bentonite (NB), and *B. subtilis 168* on the performance of RHA-based geopolymer SIFCON composites was investigated in this study. To improve the matrix densification and pore refinement within the matrix, nano-bentonite was used at 1% of the weight of RHA. To ensure the availability of moisture within the matrix and to maintain the viability of the bacteria, 0.3% polyacrylamide was used as an internal curing agent. To adjust the rheological changes and ensure the flowability of the slurry, the superplasticizer dosage was adjusted from 6% to 7% of the weight of the rice husk ash. *B. subtilis 168* was used in the mixing water at a concentration of about 1.0×10^8 CFU/mL, replacing the mixing water to ensure uniform distribution of the bacteria within the matrix. The selected dosages were based on the findings reported in other studies. A bacterial concentration of 1×10^8 CFU/mL was adopted, as it fell within the effective range reported for *B. subtilis*-based geopolymer systems [22]. The commercial bentonite sample was dried at 105 °C for moisture removal. Then, in a lab ball mill spinning at 300 rpm, the dried material was ground for 6 h. Stainless steel balls, each 10 mm in diameter, along with a ball-to-powder weight ratio of 10:1, helped in the grinding process. This setup and timing came from past research, highlighting the effectiveness of such mechanical milling in producing tiny particles [23]. The chemical composition of the nano-bentonite consisted mostly of SiO_2 (61.3%), Al_2O_3 (18.5%), Fe_2O_3 (5.4%), CaO (3.2%), and MgO (2.1%), with the remaining constituents present in minor amounts. High silica and alumina contents are beneficial for matrix densification, pore refinement, and enhancement of the geopolymer matrix through filler and aluminosilicate interactions. The nano-bentonite content was fixed at 1% because low nanoclay dosages have been reported to enhance matrix densification and pore refinement while minimizing particle agglomeration [24]. Furthermore, the PAM dosage was fixed at 0.3%, as this level has been identified as approximately corresponding to the adsorption saturation threshold, thereby promoting effective particle bridging and water retention mechanisms without excessive polymer accumulation [25]. After processing, the average particle size of the new nano-bentonite was approximately 80 nm. We then fabricated SIFCON specimens using the preplaced-fiber technique. First, we spread the required steel fibers uniformly inside the molds to form a dense network. We then added the geopolymer slurry and applied gentle vibrations to help it move in and avoid trapping air. We performed this in layers for full coverage. Post-casting, we kept the specimens covered to prevent moisture from escaping. The molds came off after 24 h, and then the specimens were cured in lab conditions until it was time to test them. Figure 2 shows the components used in this experiment. The components included (a) RHA as the main source of aluminosilicate, (b) nano-bentonite, (c) PAM, (d) *B. subtilis*, (e) suspension of bacteria of *B. subtilis*, (f) microscopic photograph of bacteria of *B. subtilis*, (g) hooked-end steel fibers, and (h) straight steel fibers. These were chosen to facilitate geopolymerization, densification of the matrix, and healing of cracks as well as reinforcing fibers.

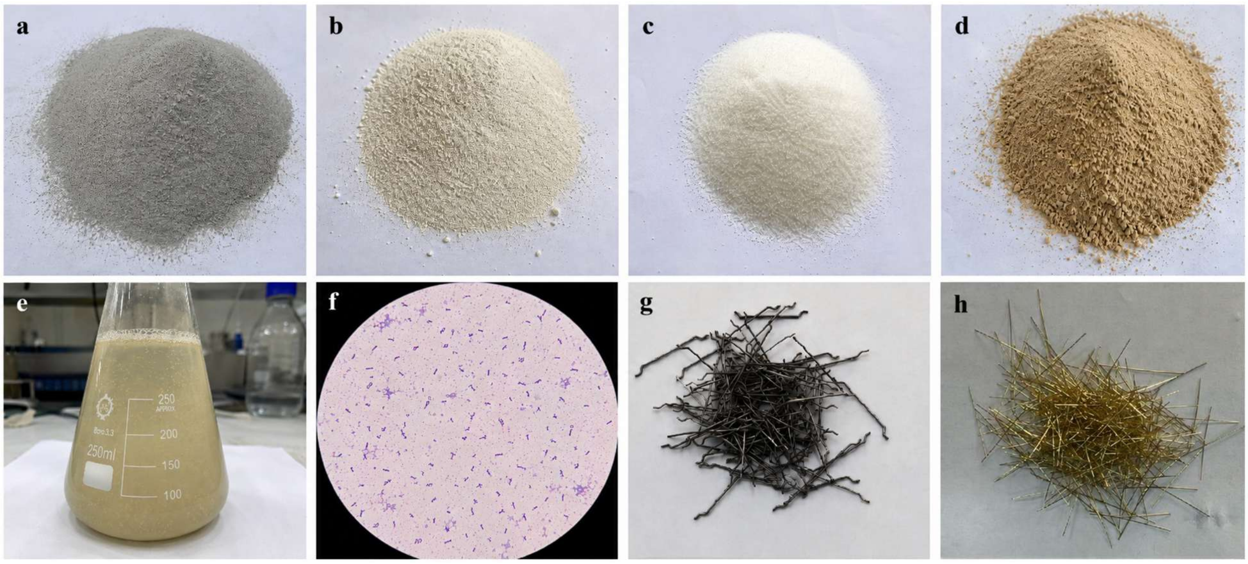

Figure 2. Ingredients involved in the formation of geopolymer SIFCON: (a) RHA, (b) nanobentonite, (c) PAM, (d) *Bacillus subtilis* bacteria, (e) *Bacillus subtilis* bacterial solution, (f) microscopy picture of *Bacillus subtilis* bacteria, (g) hooked-end steel fibers, and (h) straight steel fibers.

The mechanical properties of the developed composites were assessed in accordance with standard test methods. The compressive strength of the developed composites was tested in accordance with BS EN 12390-3 [26], whereby 100 mm cubes were cured under room conditions for 28 days prior to testing under a 0.5 MPa/s loading rate. Splitting tensile strength tests were carried out in accordance with ASTM C496 [27], whereby 150 × 300 mm cylinders were tested under 1.0 MPa/min vertical loads. The flexural strength of the developed composites was tested in accordance with ASTM C78 [28], where 100 × 100 × 400 mm prisms were tested under third-point bending. The water absorption capacity of the developed composites was tested in accordance with ASTM C642 [29]. Three specimens were tested for each mixture, and the reported values represent the averages of the obtained results. Error bars in the figures correspond to the standard deviation of the measured values.

The microstructures of the developed composites were assessed in accordance with standard test methods. The scanning electron microscopy (SEM) technique was employed to examine the microstructure of the developed composites, whereby fractured surfaces of the developed composites were analyzed to determine any changes in their microstructure. This technique was particularly important for determining any significant changes in the ITZ of the developed composites. The backscattered electron mode under high-vacuum conditions was particularly important for determining any densification in the ITZ of the developed composites and any signs of microbially induced calcium carbonate precipitation.

3. Results

In this section, a summary of the experimental results obtained for the geopolymer SIFCON mixtures is presented. We discuss our experimental results and compare them with those reported in our earlier study [19]. The baseline mixtures from that study served as points of comparison. We focused on assessing how *B. subtilis*-PAM and nano-bentonite modification strategies affect the performance of the RHA-based geopolymer SIFCON composites. Tables 3 and 4 illustrate the variations in the results obtained for each category, thereby providing an accurate evaluation of the effects of each treatment.

Table 3. Mixture compositions of geopolymer SIFCON incorporating *Bacillus subtilis 168* and 0.3% PAM.

Mixture	Compressive (MPa)	Splitting (MPa)	Flexural (MPa)	Water absorption (%)
BA	47.6 ± 0.31	3.19 ± 0.11	5.43 ± 0.29	1.46 ± 0.04
HB3	51.5 ± 0.47	6.81 ± 0.24	21.59 ± 0.81	2.17 ± 0.08
HB4	51.3 ± 0.29	7.05 ± 0.18	22.92 ± 0.56	2.35 ± 0.06
HB5	50.7 ± 0.55	6.92 ± 0.27	21.82 ± 0.93	2.72 ± 0.11
MB3	52.9 ± 0.24	6.54 ± 0.16	20.94 ± 0.62	2.6 ± 0.09
MB4	52.7 ± 0.63	6.8 ± 0.22	21.36 ± 0.78	3.03 ± 0.14
MB5	51.1 ± 0.38	6.62 ± 0.19	20.7 ± 0.71	3.34 ± 0.17
CB3	52.3 ± 0.42	6.71 ± 0.25	21.33 ± 0.84	2.33 ± 0.07
CB4	52.2 ± 0.58	6.92 ± 0.17	22.52 ± 0.59	2.71 ± 0.12
CB5	50.8 ± 0.35	6.79 ± 0.29	21.8 ± 0.96	3.04 ± 0.15

Note: MB stands for microfiber + *Bacillus* + PAM; CB for hybrid fiber + *Bacillus* + PAM; HB for hooked-end fiber + *Bacillus* + PAM; and BA for no fiber.

Table 4. Mixture compositions of geopolymer SIFCON incorporating 1% NB.

Mixture	Compressive (MPa)	Splitting (MPa)	Flexural (MPa)	Water absorption (%)
NA	46.2 ± 0.27	2.92 ± 0.08	5.12 ± 0.22	1.54 ± 0.03
HN3	50.1 ± 0.51	6.45 ± 0.21	20.71 ± 0.75	2.25 ± 0.09
HN4	49.2 ± 0.44	5.9 ± 0.26	19.51 ± 0.88	2.5 ± 0.11
HN5	48.3 ± 0.67	5.62 ± 0.32	18.15 ± 1.03	2.91 ± 0.16
MN3	51.7 ± 0.22	6.19 ± 0.15	19.84 ± 0.68	2.71 ± 0.08
MN4	51.2 ± 0.49	5.73 ± 0.24	17.93 ± 0.91	3.22 ± 0.15
MN5	51.0 ± 0.36	5.56 ± 0.28	17.57 ± 1.05	3.6 ± 0.18
CN3	50.9 ± 0.53	6.38 ± 0.20	20.68 ± 0.73	2.51 ± 0.10
CN4	50.5 ± 0.41	5.92 ± 0.31	18.62 ± 0.98	2.94 ± 0.13
CN5	49.5 ± 0.61	5.57 ± 0.27	18.11 ± 0.86	3.23 ± 0.16

Note: CN = hybrid fibers + nano-bentonite; MN = microfibers + nano-bentonite; HN = hooked fibers + nano-bentonite; NA = no fibers.

4. Discussion

In this section, we focus on a comparison of the behavior of geopolymer SIFCON mixes with various modification strategies, aiming to discuss and interpret the results presented in the tables in the previous section. Comparing the results with the reference mixes, emphasis is placed on highlighting the significant trends and interpreting the results in relation to the influence of the addition of *B. subtilis 168*, polyacrylamide, and nano-bentonite, with reference to the literature, where appropriate, to provide a comprehension of the results.

4.1. Discussion of compressive strength results

The values of the compressive strength in Figure 3 and Tables 3 and 4 indicate the influence of the addition of nano-bentonite, fiber content, and bacterial treatment with polyacrylamide on the geopolymer SIFCON mixes. The control mix without fibers (RA) had the lowest compressive strength of 44.1 MPa in the previous study [19]. According to Meskhi et al. [2] and Florean et al. [1], the addition of steel fibers in amounts up to 10% considerably improves the compressive strength of the mixes owing to the bridging action of the fibers and the improvement in the stress transfer from the fibers to the matrix. The mixes with straight micro-steel fibers (MR series) had relatively higher values of compressive strength than those with hooked-end fibers (HR series) for similar amounts of fibers used in the production of the mixes. This is because of the higher aspect ratio of the MR series, which enables more fibers per unit volume of the mixes and facilitates more uniform stress distribution during compressive loading [1,2,30]. A slight reduction in the compressive strength of the mixes was observed when the fiber content exceeded the optimal amount of 10%. This was due to the incomplete infiltration of the slurry in the molds and the formation of air voids in the mixes [5,19].

In comparison to the baseline, mixes with *B. subtilis 168* and 0.3% polyacrylamide (Table 3) showed a steady increase in compressive strength. This is in accordance with the research of Bertolesi et al. [14] and Spencer [17], in which microvoids and microcracks were partially sealed through bacterial activity, localized biomineralization, and matrix densification mechanisms, leading to a more compact microstructure. The addition of polyacrylamide to the mixes, according to Basri et al. [18], led to internal curing, which retained moisture within the mixes and caused geopolymerization to occur. However, because the bacterial treatment mainly sealed the microcracks in the mixes without significantly improving their compressive strength, this improvement remained limited. Table 4 shows that there was an increase in the compressive strength with 1% NB compared to the control mix. Nano-bentonite refines the matrix structure of the mixes by acting as an active nanofiller that improves the packing of particles in the mixes, leading to an increase in compressive strength, as proven in earlier research [2,18] and supported by Samuvel et al. [16]. Although the fiber content and quality of fiber distribution in the mixes, together with the quality of slurry infiltration, remain important factors that determine the compressive strength in SIFCON mixes, this mechanism has led to the densification of mixes that can resist greater compressive loads. It is evident that although steel fibers play an important role in improving the compressive strength in SIFCON mixes, bacterial bio-mineralization has refined the mixes' structures slightly by counteracting the negative effects of excessive fiber content. Strengthening from nano-bentonite results from its double duty as a nano-filler and reactive aluminosilicate. Its ultrafine particles fill the voids between geopolymer gels, making the matrix denser and reducing the porosity. Moreover, bacterial treatment makes the matrix denser via biomineralization and precipitation in microdefects, which boosts resistance to compression by improving stress transfer.

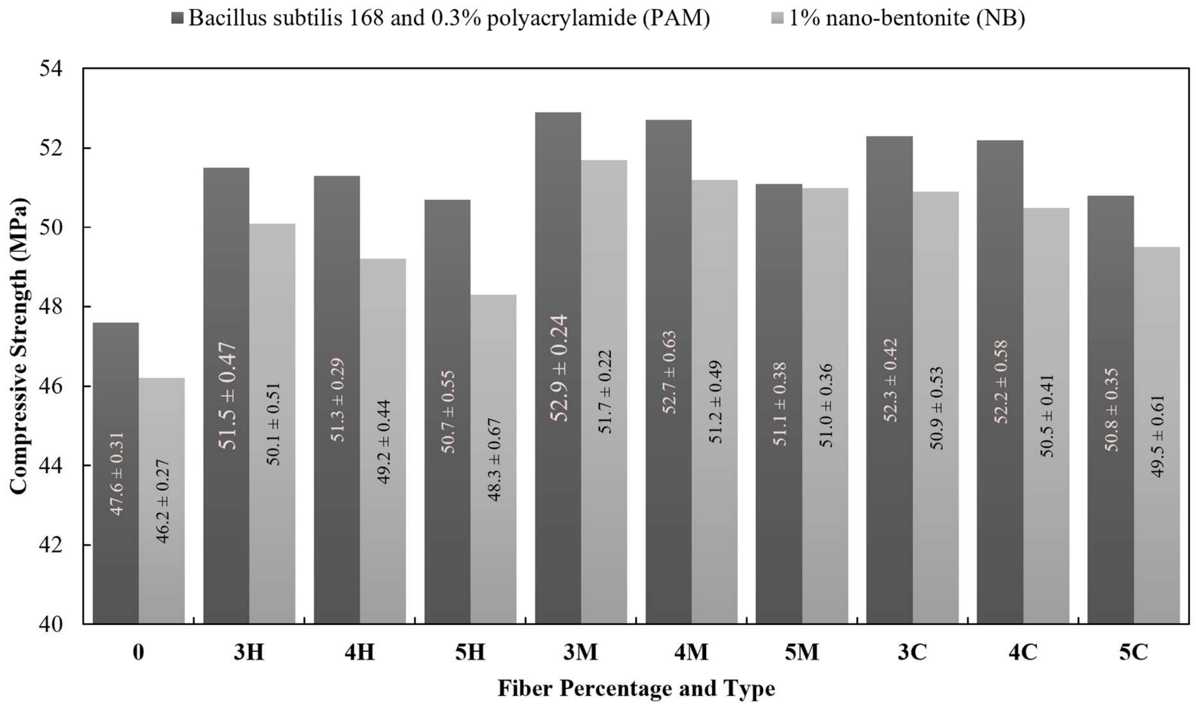

Figure 3. Results of compressive strength for different mixtures.

4.2. Discussion of splitting tensile strength results

The influence of fiber type, bacterial treatment with polyacrylamide, and incorporation of NB particles on the tensile properties of geopolymer SIFCON mixes is evident in the splitting tensile strength values of mixes compiled in Figure 4 and Tables 3 and 4. The plain control RA possessed the lowest splitting tensile strength of 2.8 MPa in plain mixes [19], indicating the inherent brittleness of geopolymer mixes without fibers. As indicated by Florean et al. [1] and Meskhi et al. [2], steel fibers contribute substantially to the improvement in the splitting tensile strength of mixes owing to their bridging action in the cracking of geopolymer mixes and their ability to distribute tensile forces. The hooked-end fibers (HR series) showed substantially higher splitting tensile strength values than straight microfibers (MR series) with equivalent fiber contents owing to their superior pull-out resistance and anchorage in geopolymer matrices [1,2,30]. However, owing to the fiber clustering effects in densely packed mixes, fiber contents above an optimum value of 10% led to slightly reduced splitting tensile strength values [5]. Compared to mixes with untreated fibers, mixes treated with *B. subtilis 168* with 0.3% polyacrylamide (Table 4) showed improvement in splitting tensile strength values. This is in line with the results of Bertolesi et al. [14] and Spencer [17], who reported that microcracks can be partially filled through bacterial activity and localized biomineralization processes induced by microorganisms. Moreover, polyacrylamide improves the bonding between the fibers and matrix and helps in maintaining adequate moisture levels through internal curing [18]. These elements contribute significantly to crack resistance and tensile stress transfer [3,15]. From a comparison of untreated fiber mixes and the 1% NB mix (Table 4), it was shown that the splitting tensile strength was slightly to moderately improved in the latter. Nano-bentonite, which reduces microvoids and improves interfacial transition zones, plays a significant role as an efficient nanofiller for postponing crack development and progression [16,18]. Nano-bentonite improves matrix homogeneity and minimizes weaknesses, thus improving tensile strength, although slightly compared to fibers [2,19]. The combined effect of bacterial self-healing, polyacrylamide, and nano-bentonite further improves the fiber-matrix interfacial interaction and crack control ability. Moreover, this study confirms that the type and distribution of steel fibers are significant parameters affecting the splitting tensile strength in geopolymer SIFCON. Nano-bentonite cuts down interfacial defects by refining pores, whereas bacterial treatment fills microcracks and keeps the matrix continuous. Because of this, cracks take longer to propagate, and tension from the load moves better across the fiber-matrix interface. Therefore, both methods significantly boost the effectiveness of the fiber-matrix ITZ.

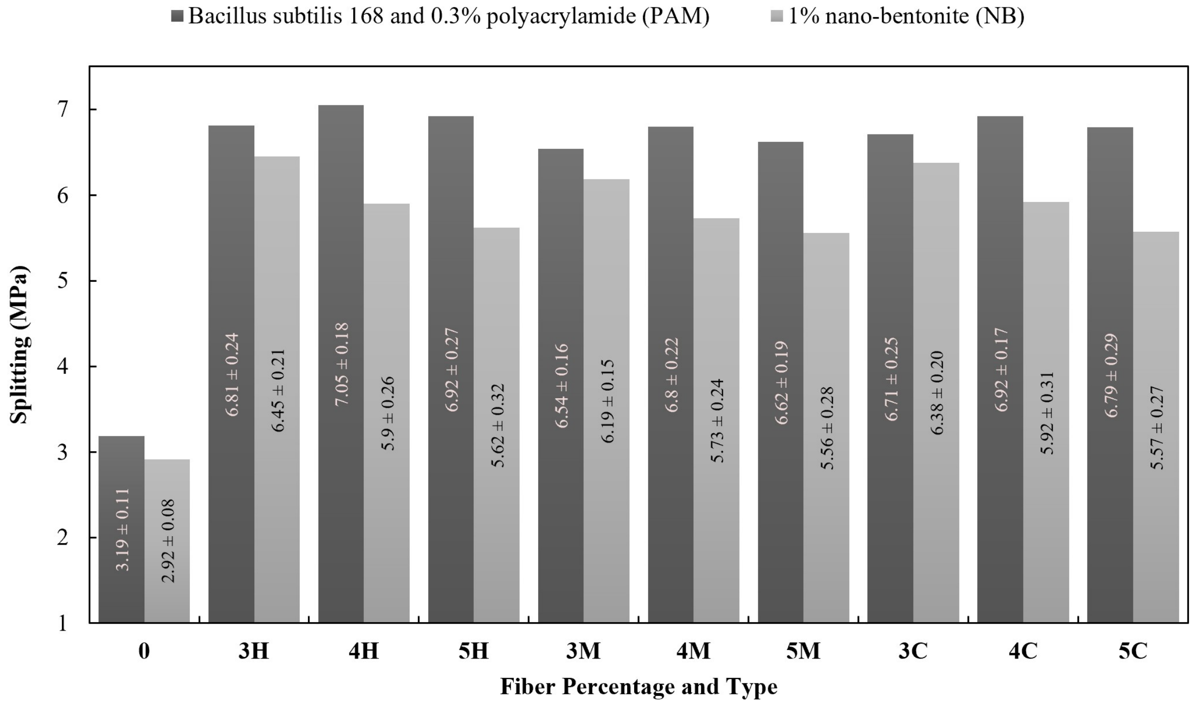

Figure 4. Results of splitting tensile strength for different mixtures.

4.3. Discussion of flexural strength results

The combined effects of the addition of fibers, polyacrylamide-treated bacteria, and NB inclusions on the bending behavior of the developed geopolymer SIFCON mixes are shown in the flexural strength values of the mixes in Figure 5 and Tables 3 and 4. The control mixes without any addition (RA) in the baseline mixes [19] had the lowest flexural strength of 4.9 MPa, which is normal for brittle matrix composites without any reinforcement mechanism to prevent the propagation of cracks during bending. According to Florean et al. [1] and Meskhi et al. [2], the addition of steel fibers in the mixes results in high flexural strength values owing to the ability of the fibers to arrest the formation of cracks in the matrix during bending. The hooked-end steel fibers (HR series) had higher flexural strength values than the straight steel fibers (MR series) in the mixes owing to the better mechanical anchorage of the hooked ends in the matrix, which provided higher pullout resistance and hence enhanced the energy absorption capacity of the composite during bending, thus delaying the formation of cracks in the matrix [1,2,30]. However, as pointed out by Gopalakrishnan and Murthy [5], an increase in the content of steel fibers in the mixes beyond an optimal value of 10% results in difficulties in the infiltration of the slurry into the fibers, which leads to the formation of air bubbles in the matrix, thus marginally reducing the flexural strength values of the mixes with high ratios of steel fibers. The addition of *B. subtilis 168* and 0.3% polyacrylamide to the mixes (Table 3) further enhanced the flexural strength values of the steel fiber-reinforced mixes by improving the matrix integrity through the matrix-fiber interfacial bond strength. The HB4 mix with the addition of polyacrylamide and 12.5% hooked-end steel fibers had the highest flexural strength value of 22.92 MPa in the investigation. As suggested by Bertolesi et al. [14] and Spencer [17], this proves that the bacterial bio-mineralization mechanism was successful in compensating for the deficiencies and discontinuities arising from insufficient slurry infiltration in fiber-rich mixes. The interfacial transition zone was improved, and microcracks were partially sealed through bacterial activity, localized biomineralization, and enhanced matrix densification associated with bacterial metabolism. The role of polyacrylamide, which acts as an internal curing agent and helps retain moisture in the geopolymer matrix, is significant. This ensures a more intense geopolymerization reaction and thus improves the bond strength between the fibers and the matrix [3,15,18]. The flexural ductility and load-carrying capacity of the composite material in the post-cracking region improved significantly. Comparing this with the fiber-rich mixes that were not treated, it was also observed from Table 4 that the mixes containing 1% NB exhibited a moderate increase in the flexural strength. Nano-bentonite, as suggested by Samuvel et al. [16], improves matrix homogeneity and reduces microvoids. Nano-bentonite also improves microstructural properties, which reduces crack propagation and enhances energy absorption during bending. However, its effect on the flexural strength is not as significant as that of the bacterial-polymer composite [2,18,19]. From our research, it was proved that the optimal mix of *B. subtilis 168*, polyacrylamide, and 12.5% hooked-end steel fibers was the mix that produced the maximum value of flexural strength. By filling the microvoids, enhancing the resistance of the fibers to pull-out, and facilitating a dense and well-bonded matrix that can withstand higher levels of bending with improved ductility and cracking resistance, the configuration successfully addressed the infiltration limitation of the fiber volume. The bacteria-treated mixtures exhibited better flexural performance because of their biomineralization products. This boosted the mechanical anchorage of the steel fibers in the geopolymer matrix. This means that fiber pull-out was reduced, and energy absorption improved during crack propagation. As a result, there was higher post-cracking resistance and flexural capacity.

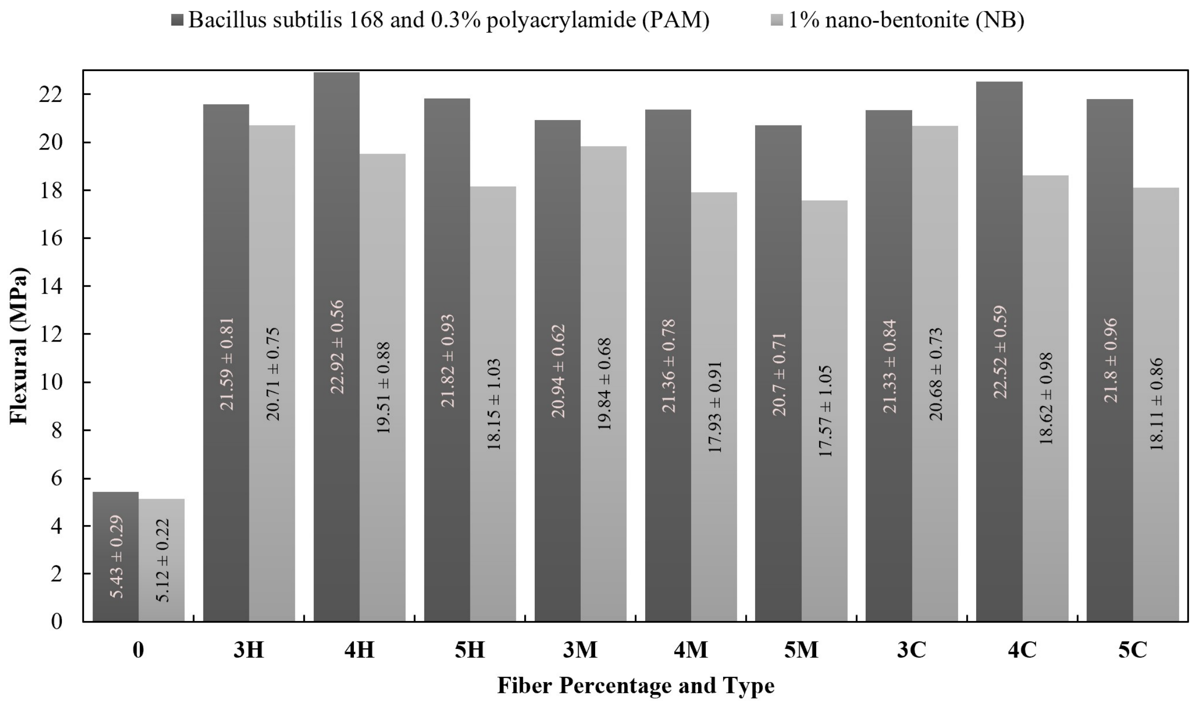

Figure 5. Results of flexural strength for different mixtures.

4.4. Discussion of water absorption results

The effectiveness of fiber type, bacterial treatment in conjunction with polyacrylamide, and NB addition in regulating the permeability of geopolymer-based SIFCON mixes is also evident in the water absorption test results shown in Figure 6 and Tables 3 and 4. Owing to the absence of fiber-induced interfacial voids, the plain RA mix exhibited the lowest water absorption of 2.20%, as shown in Table 2. The water absorption of the mixes increased with an increase in the steel fiber content. The highest water absorption of 5.14% occurred in the mixes with the highest fiber content (HR5, MR5, and CR5). The increase in water absorption with fiber content is consistent with Gopalakrishnan and Murthy [5], who showed that a high fiber content in mixes often results in partial infiltration of the slurry into the mixes, creating microchannels that enable water to penetrate the mixes [2].

The water absorption of the mixes was significantly reduced in all mixes with bacterial treatment in conjunction with 0.3% polyacrylamide (Table 3). The plain bacterial-polymer mix (BA) had the lowest water absorption of 1.46%, indicating the effectiveness of bio-mineralization in conjunction with polyacrylamide in regulating the permeability of the mixes in the absence of fiber reinforcement. Bacterial treatment also compensated for the fiber-induced voids in mixes with a high fiber content. Interestingly, the HB4 mix containing 12.5% hooked-end fibers absorbed only 2.35%, whereas the standard mix containing 12.5% hooked-end fibers absorbed 3.57%. This suggests that water transport pathways are effectively restricted by bacterial activity, localized biomineralization, polymer gel formation, and matrix densification [3,15,18]. In addition to passive nanoparticles, this modification method is more active and dynamic. However, compared with the standard mixes, the addition of 1% NB (Table 4) led to lower water absorption. This is in line with the findings of Meskhi et al. [2] and Samuvel et al. [16], who found that the addition of nano-bentonite mainly acts as a passive nanoparticle that restricts capillary pathways and densifies the microstructure of the mix. However, this modification does not actively seal new microcracks that may form owing to drying shrinkage and structural movement. Despite the improvement in impermeability of the mixes due to these two modification methods, the results showed that the bacterial modification method combined with polyacrylamide gave the lowest water absorption values, and that this method has the potential to improve the water-resistance performance and permeability-related characteristics of high-fiber-volume geopolymer SIFCON mixes. Both modification strategies made the materials last longer, but did so differently. Nano-bentonite focuses on shrinking capillary pores and cutting down pore connections, while the bacterial-PAM method works by making the matrix denser, adding biominerals, and boosting internal curing effects. All these actions help block moisture and make the geopolymer composites tougher in the long term.

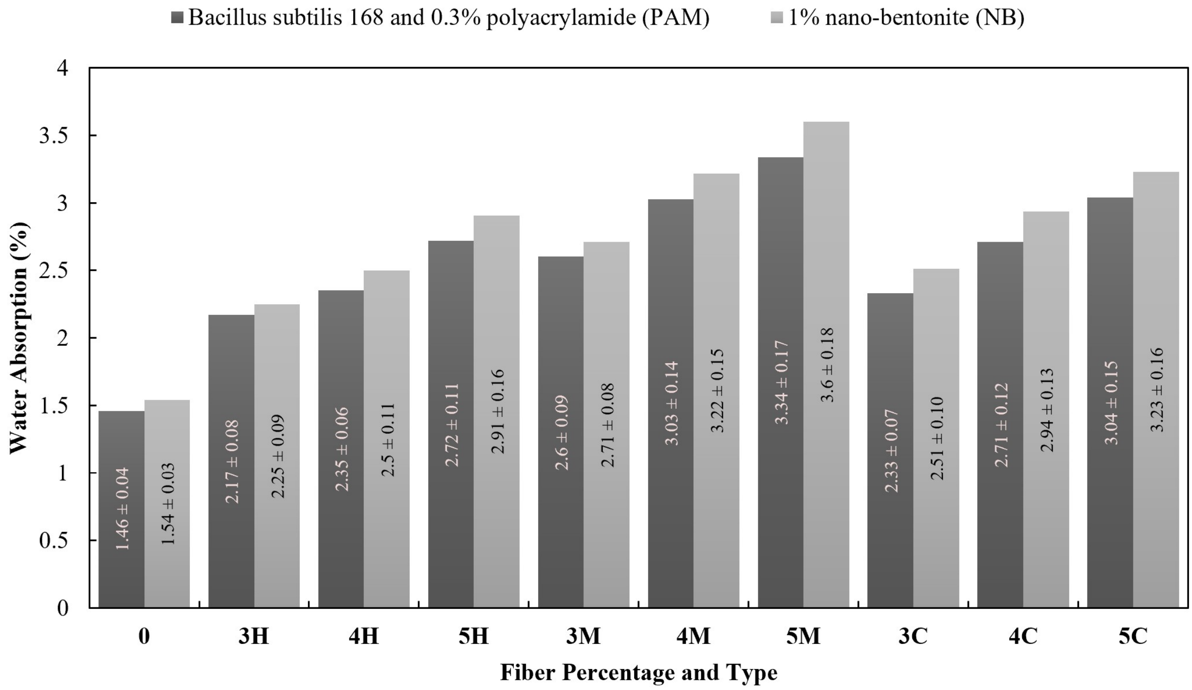

Figure 6. Results of water absorption for different mixtures.

4.5. Cost-performance considerations

From an economic perspective, both modification methods were cost-effective because they required minimal dosage. Only 1% of the binder weight went to nano-bentonite, and *B. subtilis* and PAM were also added in small amounts; no significant changes to the production process were needed. However, these minor additions significantly improved the compressive strength, flexural strength, and resistance to water absorption. The bacterial-PAM combo was superior, slashing water absorption by 35% and boosting compressive strength to 52.9 MPa. Given this, the performance enhancements outperformed the extra costs, showing great cost-to-performance value for making durable geopolymer shrinkage-inhibiting concrete, or SIFCON.

4.6. Discussion of SEM for the microstructure

The microstructural features of three geopolymer SIFCON specimens reinforced solely with straight steel fibers were studied through SEM. Our main goal was to determine the effect of bacterial treatment and the addition of nano-bentonite on the densification of matrices and formation of the fiber-matrix ITZ. The reference sample in Figure 7 is made of 10% straight steel fibers in the absence of any additives. The SEM image shows that the matrix is relatively porous, with visible microcracks, as well as localized weak bonding at the fiber-matrix interface. Unreacted RHA particles were also observed, indicating that geopolymerization was incomplete in some areas. This lack of filler supplements or bio-treatment leads to lower compactness of the matrix and a poorly developed ITZ that can enable moisture entry and low durability performance. Figure 8 shows the specimen with the inclusion of *B. subtilis 168*, PAM, and 12.5% straight steel fibers. A significantly thicker microstructure, pore-filling deposition, and a low void content were observed. The observed deposits are linked to materials created by bacterial activity, such as biomineralization products and densified reaction products. These added to the matrix's compactness and lowered permeability, but we cannot confirm their exact chemical makeup without extra tests. Moreover, the presence of polyacrylamide maintains a continuous supply of internal moisture, which favors the activity of bacteria and enhances calcite growth. The ITZ around the fibers is smoother and more continuous, which means that the interfacial bonding is more effective, and the stress transfer ability of the material is elevated. Figure 9 depicts the specimen that has 10% of straight steel fibers and 1% of nano-bentonite, and no bacteria were added in the specimen. The addition of nano-bentonite leads to significant refinement of the pores and an enhanced filler effect of the particles because the material is ultrafine. The matrix appeared more compact and unified and had a lower capillary porosity than that of the control sample. It is not obvious that steel fibers are present in this particular micrograph; however, when observing the morphology of the surrounding matrix, one can observe the increased densification of the assumed ITZ areas. Overall, the SEM results proved that microbial treatment, as well as nano-bentonite addition, could be used to refine the matrix and enhance the ITZ. This is because the bacterial-polymer system shows a stronger effect on densification through bacterial activity, localized biomineralization, and improved matrix continuity, whereas nano-bentonite mostly promotes microstructure compactness through physical filling and pozzolanic reactions. Based on SEM observations, we can see how NB and *B. subtilis*-PAM work differently. Nano-bentonite boosts the microstructure by filling the pores and tightening the matrix. The *B. subtilis*-PAM method, however, fills tiny voids and creates more continuous matrices owing to its bacterial action and biomineralization. Both treatments lead to a denser interfacial transition zone and stronger fiber-matrix bonding. They also reduce pore connections, resulting in enhanced mechanical properties and durability.

Although SEM observations were helpful for gaining some insight into the densification of the matrix, pore refinement, and formation of interfacial transition zones, SEM-energy dispersive X-ray spectroscopy (EDX) testing was not carried out in this experiment. Thus, confirmation of the elemental distribution and composition of the reaction products is lacking. The use of SEM-EDX testing should be encouraged in future studies to obtain additional information on the mechanisms involved in the process.

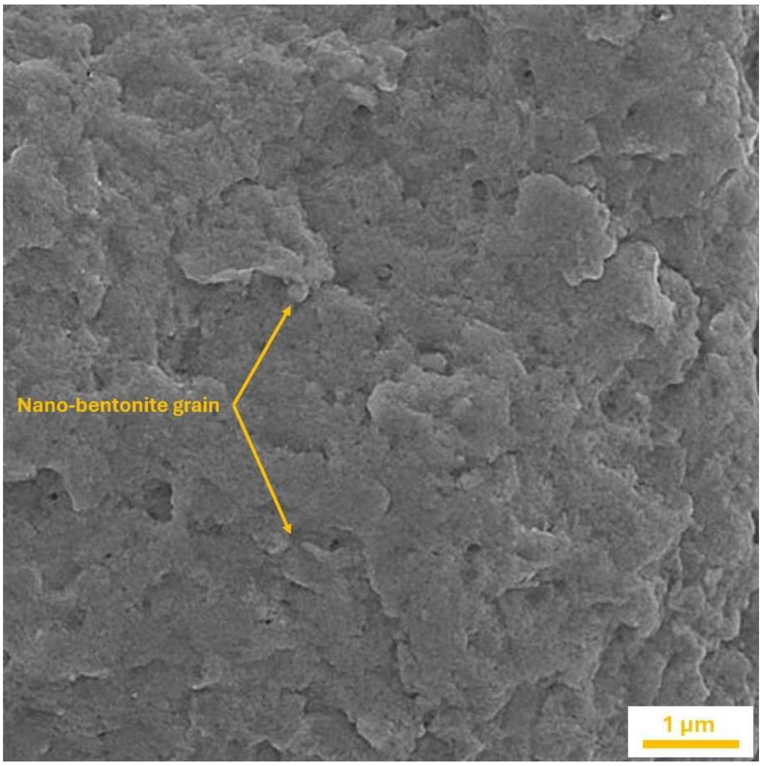

Figure 7. A sample with 10% straight fibers and no additives.

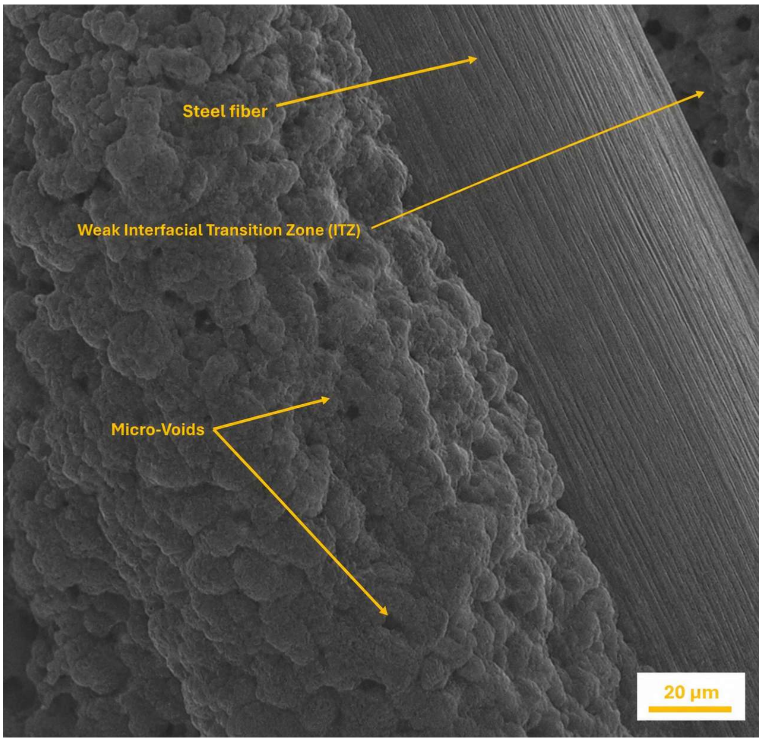

Figure 8. *Bacillus subtilis 168*, polyacrylamide, and 12.5% straight fibers in a sample.

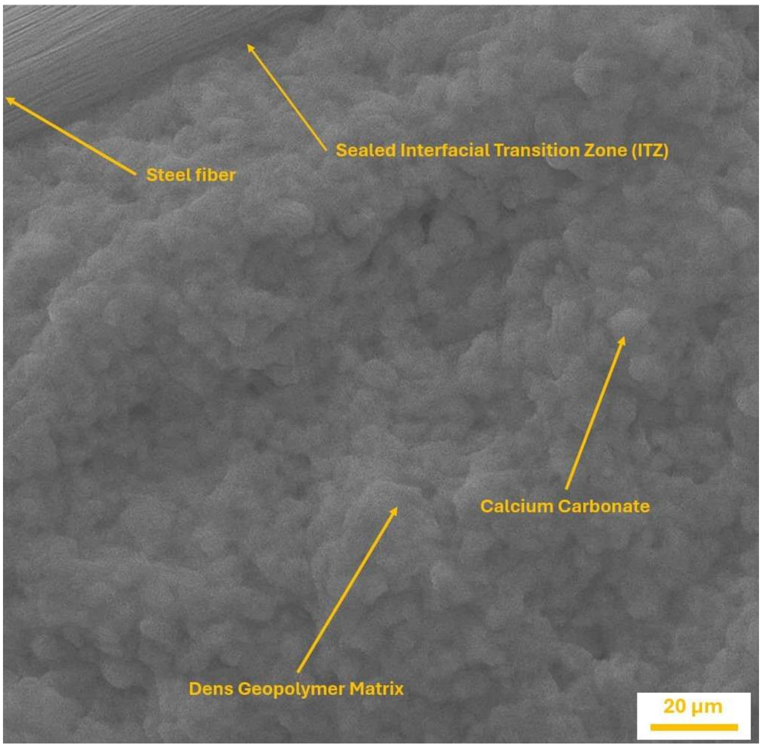

Figure 9. A sample containing 10% straight steel fibers and 1% nano-bentonite.

4.7. Comparison of this study with other studies on RHA-based geopolymer and SIFCON composites

To evaluate the effectiveness of the proposed modification strategies, the results obtained in this study were compared with those reported in previous studies on RHA-based geopolymers and SIFCON composites. Particular attention was given to the compressive strength, flexural strength, and water absorption performance. The comparison results are summarized in Table 5.

According to Table 5, the bacterial-PAM treatment performed better than the older RHA-based geopolymer systems. It obtained a compressive strength of 52.9 MPa and a flexural strength of 22.92 MPa. In addition, it absorbed only 1.46% water, showing major improvements in mechanics and durability.

Table 5. Comparison between this study and other studies on RHA-based geopolymers and SIFCON composites.

Reference	Material system	Modification technique	Compressive strength (MPa)	Flexural strength (MPa)	Water absorption (%)	Main findings
Mohd Basri et al. (2021) [18]	RHA-based geopolymer binder	Optimization of alkaline activator and RHA ratio	47.0	-	-	High-silica RHA improved the geopolymerization and compressive strength.
Abdulrehman et al. (2026) [19]	RHA-based geopolymer SIFCON	Steel fiber reinforcement	49.2	19.8	3.24	Steel fibers improve strength and durability.
Present study	RHA-based geopolymer SIFCON	1% NB	51.7	19.84	2.71	The nano-filler action refined the pore structure and improved the matrix density.
Present study	RHA-based geopolymer SIFCON	*Bacillus subtilis* + 0.3% PAM	52.9	22.92	1.46	Biomineralization reduces porosity and enhances strength and durability.

5. Conclusions

Considering the experimental results obtained from this research, the following conclusions may be drawn:

1. The addition of steel fibers considerably increased the mechanical properties of the RHA geopolymer SIFCON. The hooked-end fibers performed better in the splitting tensile strength and flexural strength tests, whereas the straight microfibers were able to produce a slightly higher compressive strength.

2. The appropriate amounts of steel fiber were 10% and 12.5%.

3. *Bacillus subtilis*-PAM treatment helped improve densification of the matrix and ITZ adhesion between the fiber and matrix, as well as water absorption reduction due to the biomineralization process and internal curing mechanism.

4. The bacteria-treated mixture showed better overall performance, resulting in a compressive strength of 52.9 MPa, flexural strength of 22.92 MPa, and the lowest water absorption percentage of 1.46%.

5. The addition of 1% of NB played an important role in improving pore refinement, densification of the matrix, and water resistance by decreasing connectivity of pores in the geopolymer matrix.

6. As seen from the SEM results, both modification methods were successful in improving the ITZ, decreasing the number of microvoids, and achieving a denser matrix structure than the unmodified samples.

7. Though both modification methods improved the performance of the geopolymer SIFCON composite, the treatment of the *Bacillus subtilis*-PAM method was more efficient than the NB one in terms of mechanical properties and water absorption rate reduction.

8. The novelty of this research consists of evaluating biological and nano modifications separately as ITZ improvement methods of sustainable RHA-based geopolymer SIFCON composites.

Use of AI tools declaration

The authors declare that Figure 1 in this article uses Artificial Intelligence (AI) tools and then checked and edited.

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Author contributions

The study was developed and planned by Mohammed Ali Abdulrehman, who conducted the experiments, analyzed the data, and drafted the original manuscript. The research was supervised by Khairunisak Abdul Razak, who provided assistance in designing the study, verified the findings, and reviewed the manuscript critically. Khalid M. Eweed helped in conducting experiments and interpreting the data as well as reviewing the manuscript. Shah Rizal Kasim was involved in interpreting the findings and reviewing the manuscript.

Conflict of interest

The authors declare no conflict of interest.

References

1. Florean CT, Vermeșan H, Gabor T, et al. (2024) Influence of TiO_2 nanoparticles on the physical, mechanical, and structural characteristics of cementitious composites with recycled aggregates. *Materials* 17: 2014. https://doi.org/10.3390/ma17092014
2. Meskhi B, Beskopylny AN, Stel'makh SA, et al. (2023) Analytical review of geopolymer concrete: Retrospective and current issues. *Materials* 16: 3792. https://doi.org/10.3390/ma16103792
3. Gojević A, Netinger Grubeša I, Marković B, et al. (2023) Autonomous self-healing methods as a potential technique for the improvement of concrete's durability. *Materials* 16: 7391. https://doi.org/10.3390/ma16237391
4. Dinh HL, Liu J, Doh JH, et al. (2024) Influence of Si/Al molar ratio and Ca content on the performance of fly ash-based geopolymer incorporating waste glass and GGBFS. *Constr Build Mater* 411: 134741. https://doi.org/10.1016/j.conbuildmat.2023.134741
5. Li Y, Liu F, Li Q, et al. (2024) Effect of fiber content and end geometry on the pullout behavior of straight and arc-shaped steel fibers embedded in SIFCON. *Constr Build Mater* 451: 138688. https://doi.org/10.1016/j.conbuildmat.2024.138688

6. Ekinci E, Türkmen İ, Birhanli E (2022) Mechanical and durability characteristics of GGBS-based self-healing geopolymer mortar produced using an endospore-forming bacterium. *J Build Eng* 57: 104944. https://doi.org/10.1016/j.jobe.2022.104944
7. Mahmood RA, Delik E, Kockal NU, et al. (2025) Performance of bio-geopolymer mortar incorporating isolates of *Bacillus cereus* and *Bacillus subtilis*: A comprehensive experimental study. *Next Mater* 8: 100845. https://doi.org/10.1016/j.nxmate.2025.100845
8. Tie Y, Ji Y, Zhang H, et al. (2024) Investigation on the mechanical properties of *Bacillus subtilis* self-healing concrete. *Heliyon* 10: e34131. https://doi.org/10.1016/j.heliyon.2024.e34131
9. Ebrahim AAM, Ahmed DA, Abu-Elwafa R (2024) Development of an eco-friendly geopolymer mortar using slag and fly ash with high bentonite content for thermal and environmental applications. *Sci Rep* 14: 26727. https://doi.org/10.1038/s41598-024-76780-5
10. Frida E, Bukit N, Bukit FRA, et al. (2022) Preparation and characterization of bentonite-OPBA nanocomposite as filler. *J Phys Conf Ser* 2165: 012023. https://doi.org/10.1088/1742-6596/2165/1/012023
11. Gadkar A, Subramaniam KVL (2021) Rheology control of alkali-activated fly ash with nano clay for cellular geopolymer application. *Constr Build Mater* 283: 122687. https://doi.org/10.1016/j.conbuildmat.2021.122687
12. Ali SM, Abbas AS, Resan KK, et al. (2025) Enhancing the mechanical and permeability properties of bentonite plastic concrete using pozzolanic additives. *Ann Chim Sci Mater* 49: 307–314. https://doi.org/10.18280/acsm.490310
13. Luo Y, Brouwers HJH, Yu Q (2023) Understanding the gel compatibility and thermal behavior of alkali-activated Class F fly ash/ladle slag: The underlying role of Ca availability. *Cem Concr Res* 170: 107198. https://doi.org/10.1016/j.cemconres.2023.107198
14. Mohamed A, Fan M, Bertolesi E, et al. (2024) Microbial loading and self-healing in cementitious materials: A review of immobilisation techniques and materials. *Mater Des* 245: 113249. https://doi.org/10.1016/j.matdes.2024.113249
15. Van Tittelboom K, De Belie N (2013) Self-healing in cementitious materials: A review. *Materials* 6: 2182–2217. https://doi.org/10.3390/ma6062182
16. Samuvel Raj R, Prince Arulraj G, Anand N, et al. (2024) Nano-bentonite as a sustainable enhancer for alkali activated nano concrete: Assessing mechanical, microstructural, and sustainable properties. *Case Stud Constr Mater* 20: e03213. https://doi.org/10.1016/j.cscm.2024.e03213
17. Spencer C (2021) *Enhancing biocement through incorporation of additives*. PhD thesis. Cardiff University. Available from: https://orca.cardiff.ac.uk/id/eprint/146016.
18. Mohd Basri MS, Mustapha F, Mazlan N, et al. (2021) Rice husk ash-based geopolymer binder: Compressive strength, optimize composition, FTIR spectroscopy, microstructural, and potential as fire-retardant material. *Polymers* 13: 4373. https://doi.org/10.3390/polym13244373
19. Abdulrehman MA, Razak KA, Kasim SR, et al. (2026) Properties of rice husk ash-based geopolymer slurry-infiltrated fiber concrete with various steel fiber types and contents. *J Aust Ceram Soc*. https://doi.org/10.1007/s41779-026-01359-4
20. ASTM International (2021) Standard specification for standard sand. ASTM C778-21. West Conshohocken, PA, USA. https://doi.org/10.1520/C0778-21
21. ASTM International (2022) Standard specification for steel fibers for fiber-reinforced concrete. ASTM A820/A820M-22. West Conshohocken, PA, USA. https://doi.org/10.1520/A0820_A0820M-22

22. Ekinci E, Türkmen İ, Birhanli E (2022) Performance of self-healing geopolymer paste produced using *Bacillus subtilis*. *Constr Build Mater* 325: 126837. https://doi.org/10.1016/j.conbuildmat.2022.126837
23. El-Eskandarany MS, Al-Hazza A, Al-Hajji LA, et al. (2021) Mechanical milling: A superior nanotechnological tool for fabrication of nanocrystalline and nanocomposite materials. *Nanomaterials* 11: 2484. https://doi.org/10.3390/nano11102484
24. Si W, Carr L, Zia A, et al. (2025). Advancing 3D printable concrete with nanoclays: Rheological and mechanical insights for construction applications. *J Compos Sci* 9: 449. https://doi.org/10.3390/jcs9080449
25. Lu H, Dai B, Li C, et al. (2025) Flocculation mechanism and microscopic statics analysis of polyacrylamide gel in underwater cement slurry. *Gels* 11: 99. https://doi.org/10.3390/gels11020099
26. BSI (2019) BS EN 12390-3: Testing hardened concrete—Part 3: Compressive strength of test specimens, London, UK: BSI.
27. ASTM International (2017) Standard test method for splitting tensile strength of cylindrical concrete specimens. ASTM C496/C496M-17. West Conshohocken, PA, USA. https://doi.org/10.1520/C0496_C0496M-17
28. ASTM International (2022) Standard test method for flexural strength of concrete (using simple beam with third-point loading). ASTM C78/C78M-22. West Conshohocken, PA, USA. https://doi.org/10.1520/C0078_C0078M-22
29. ASTM International (2021) Standard test method for density, absorption, and voids in hardened concrete. ASTM C642-21. West Conshohocken, PA, USA. https://doi.org/10.1520/C0642-21
30. Niş A, Eren NA, Çevik A (2021) Effects of nanosilica and steel fibers on the impact resistance of slag-based self-compacting alkali-activated concrete. *Ceram Int* 47: 23905–23918. https://doi.org/10.1016/j.ceramint.2021.05.099