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Research Article

Microfiber Strengthening of Expanded-Perlite-Filled Waste Tile/Glass Geopolymer Composites

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Keywords

Microfiber reinforcement,
Lightweight geopolymers,
Waste tile and glass powder.

Abstract

The present study evaluates the effect of microfiber reinforcement on previously developed expanded-perlite-filled waste tile/glass geopolymer matrices. This study investigated the strengthen ability and mechanical performance enhancement of geopolymers produced from 100% waste materials, lightened with perlite filler, through the addition of microfibers. Tile dust and glass dust were chosen as waste materials in geopolymer production. Sodium hydroxide was added as an activator at different concentrations. Expanded perlite (EP) was added at 2% (semi-lightweight) and 4% (lightweight) dosages to achieve lightweight properties. The main objective of the research was to evaluate the effect of 1.5% microfiber addition on reducing brittle fracture, post-cracking integrity, and overall performance of these porous matrices. Experimental results showed that microfiber addition was effective in reducing the strength loss caused by high bulk porosity. The most notable improvements were observed in increased flexural and splitting tensile strengths at a 6% Na concentration. In addition, the reduction in water absorption and capillarity suggests that microfibers may have partially interrupted water-transport pathways within the porous matrix. The addition of 4% EP successfully reduced the unit weight to 1258 kg/m³, while 1.5% microfiber reinforcement ensured that the compressive strength remained above 8 MPa. The results show that it is possible to develop environmentally friendly lightweight construction materials with microfiber reinforcement, taking into account the activator ratio. Unreinforced reference values were used as baseline data, while the fiber-reinforced mixtures constitute the new experimental contribution of this study.

1.Introduction

The brittle and low tensile strength of geopolymer matrices remains a significant challenge for structural applications [1]. Fiber reinforcement is effective in improving mechanical performance through crack bridging [2]. In fiber-reinforced geopolymers, the homogeneous spreading of fibers in random directions within the binder matrix plays an important role in increasing the toughness of the composite [3]. When a microcrack starts under load, fibers perpendicular to the crack plane can control the crack propagation by providing load transfer. Recent research on geopolymers has focused on the compatibility of fibers with geopolymers and the properties of fibrous geopolymer composites [4, 5].

The use of microfibers in lightweight geopolymer systems creates a complex mechanical equilibrium. Because the presence of porous filler such as expanded perlite (EP) generally leads to a reduction in the binder-aggregate bond area [6]. Lightweight geopolymers are often used for thermal insulation purposes, while also reducing structural loads. However, the decrease in mechanical strength can lead to problems in load-bearing capacity [7]. The inclusion of microfibers in this porous structure supports the lightening of the structure by EP, while playing an important role in reducing strength loss and brittleness [8]. Current studies indicate that the efficiency of these fibers is sensitive to the alkalinity of the binder system. They show that sodium ion concentration directly affects the chemical abrasion of the fiber surfaces and subsequently the interlocking quality within the lightweight geopolymer framework. In these high-alkali systems, attention should be paid to the fiber type, and alkali-resistant fibers should be preferred [9, 10].

This manuscript is a follow-up strengthening study based on a previously developed expanded-perlite-filled waste tile/glass geopolymer matrix. The previous study evaluated the effects of expanded perlite dosage and sodium concentration on unreinforced composites. The present study specifically investigates whether 1.5% microfiber addition can compensate for the mechanical losses and water-transport disadvantages associated with expanded perlite. The novelty of this study lies in quantifying the contribution of microfiber reinforcement to the mechanical and physical performance of lightweight expanded-perlite-filled waste-based geopolymer composites. Despite increasing research on fiber-reinforced cement-based composites, there is a lack of comprehensive data on the behavior of microfiber-reinforced geopolymers synthesized from 100% waste precursors and lightweight expanded perlite. This study aims to address a research gap by investigating the strengthening efficiency of 1.5% microfiber addition in waste-based geopolymer matrices containing 2% and 4% expanded perlite. The research is structured around three different sodium concentrations (3%, 6%, and 9% Na) to evaluate how alkali density affects fiber-matrix synergy. By characterizing the physical and mechanical properties of these hybrid composites, this research offers a unique framework for developing sustainable, high-toughness, and lightweight construction materials that maximize the value of construction and demolition waste.

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2. Testing process

2.1. Test specimens and properties

Waste tile powder (alumina-rich) and waste glass powder (amorphous silica-rich) were used as geopolymer precursors. Both materials were ground and sieved to <45 μm, and their chemical compositions are presented in Table 1. Sodium hydroxide (NaOH) was used as the alkali activator, and sodium concentrations were set at 3%, 6%, and 9% by binder weight to evaluate alkalinity effects.

Table 1. Chemical properties of used waste materials

Component	SiO_2	Al_2O_3	Fe_2O_3	CaO
Tile powder (%)	63.29	18.29	4.32	4.46
Glass powder (%)	71.30	2.18	0.60	9.8
Expanded perlite (%)	74	14	-	-

To make the lightweight geopolymer matrix more usable by eliminating its brittle structure, microfibers were included at a fixed rate of 1.5% by weight. This rate is quite high for the application and is important for determining its effect on mechanical performance. Lower rates are recommended for future studies. The fibers used in this study were monofilament polypropylene microfibers with a length of 6 mm, tensile strength of 625 MPa, elastic modulus of 5 GPa, and density of 910 kg/m³. These fibers were selected due to their high aspect ratios and tensile strengths, and they provide a micro-mechanical bridging mechanism within the NASH gel. The physical and mechanical properties of the microfibers used are summarized in Table 2.

Table 2. Properties of micro fiber

tensile strength	modulus of elasticity	length	density
625 MPa	5 GPa	6 mm	910 kg/m^3

The experimental variable introduced in the present study was the incorporation of 1.5% polypropylene microfiber into the lightweight geopolymer matrices. The corresponding unreinforced mixtures were treated as reference systems for evaluating the strengthening efficiency. This study is based on a previous study investigating the production of lightweight geopolymers with expanded perlite and the properties of the resulting products, and the reference values were taken from this study [11]. This study was designed to evaluate the effects of fiber reinforcement at different alkali levels, which is the main subject of this study. 1.5% fiber reinforcement was added to the reference specimens, to which expanded perlite was added at 2% and 4% dosages to impart lightness properties. Detailed mixing ratios for all series are presented in Table 3. Unreinforced reference values correspond to the baseline expanded-perlite-filled geopolymer mixtures; fiber-reinforced values were generated in the present study.

Table 3. Mixture proportions

Na, %	3	6	9
waste tile powder/binder	0.40	0.40	0.40
waste glass powder/binder	0.60	0.60	0.60
caustic soda/binder	0.04	0.08	0.12
water/binder	0.30	0.30	0.30
perlite/binder	0.02-0.04	0.02-0.04	0.02-0.04
fiber/binder	0-0.015	0-0.015	0-0.015

The production process involved dividing the mixing water into two parts. NaOH was dissolved in the first part. The other part was used to first saturate the perlite. Once the NaOH solution cooled and the perlite released the water it had absorbed, other waste powders were added to ensure proper mixing. Microfibers were then added to the resulting mixture and stirred until a homogeneous distribution was achieved. As shown in Figure 1, the fresh mixtures were poured into 4x4x16 cm prismatic steel molds. Compaction was performed using a high-frequency shaking table. After a setting time of 24 hours under ambient conditions, the specimens were removed from the molds and subjected to thermal curing at 60 °C for 3 hours. Specimens were cast into 4×4×16 cm molds, compacted, demolded after 24 h, and heat-cured at 60 °C for 3 h, followed by storage at 23±2 °C until 28 days.

Figure 1. Preparation mixture and specimens

2.2. Testing system

The physical and mechanical performance of fiber-reinforced lightweight geopolymers was evaluated through physical and mechanical tests conducted after a 28-day curing period. These tests included a unit weight test to determine the effect of 1.5% microfiber reinforcement on the unit weight of the specimens, and an ultrasonic pulse velocity (UPV) test to determine the internal void structure and uniform distribution of fibers. Water absorption tests were conducted to determine the effect of fibers on the water absorption and capillary water absorption of the lightweight geopolymer. A sequential approach was followed to determine the mechanical properties, as shown in Figure 2. Flexural strength was determined using a three-point flexural setup in accordance with the TS EN 196-1 standard. This contributed to determining the post-cracking behavior where microfibers were expected to bridge the tensile zones. Following the flexural tests, the resulting fractured prismatic halves were used for compressive and splitting tensile strength measurements. Fractured specimens from flexural tests were used for compressive and splitting tensile tests. For compressive strength tests, the load was applied at a constant rate using steel plates to ensure uniform load distribution. Splitting tensile strength tests are important in determining the reinforcing effect of microfibers, as this is the condition in which fibers are most active under tensile stresses. All measurements were performed on at least three specimens.

Figure 2. Testing of the specimens

3. Discussion

For each sodium concentration and perlite dosage, the microfiber-reinforced mixture was compared with its corresponding unreinforced reference mixture to quantify the strengthening efficiency. Figure 3 shows the unit weight results of reference geopolymer specimens reinforced and not reinforced with fibers. The influence of expanded perlite (EP), waste tile/glass powders, and NaOH activation on matrix formation has been detailed in the baseline study; therefore, only fiber-related effects are emphasized here [11]. The addition of 1.5% microfibers had a small additional effect on the density of the composites. In the 3% Na semi-light series, the addition of fibers reduced the unit weight from 1470 kg/m³ to 1420 kg/m³, or approximately 3.4%. This decrease is due to the lower density of microfibers compared to glass and tile powder. Here, it was determined that microfibers did not have any negative effect on the lightness of the geopolymer.

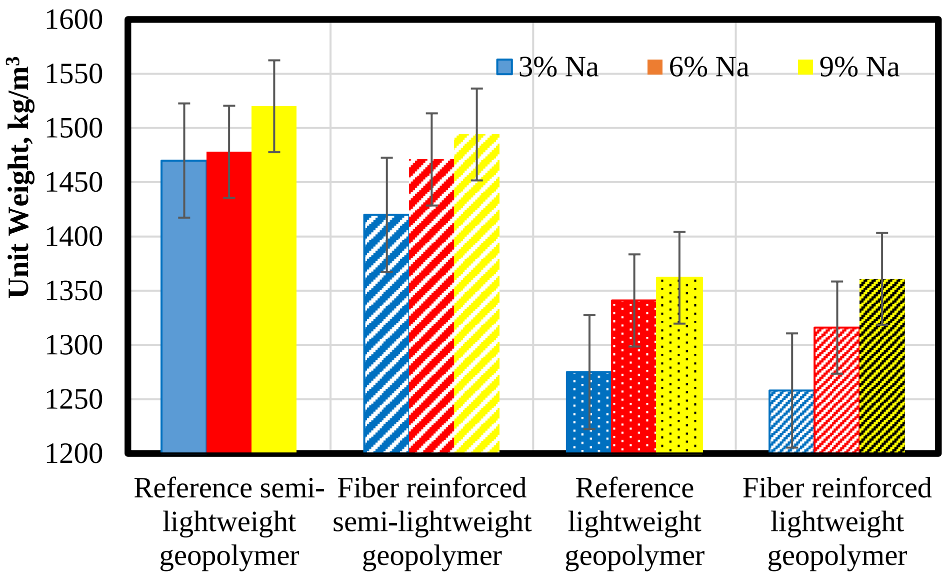

Figure 3. Unit weight values of lightweight geopolymer specimens reinforced with fibers
(Note: Reference mixtures represent unreinforced baseline composites; microfiber-reinforced mixtures represent the new experimental series of this study).

The effect of sodium concentration and fiber reinforcement on the ultrasonic pulse velocity (UPV) of lightweight geopolymers is shown in Figure 4. The data show that the addition of 1.5% microfibers increased the pulse velocity in all specimen groups and effectively counteracted the vibration damping effect of expanded perlite. For the lightweight geopolymer series (4% EP) with 3% Na concentration, the UPV increased by approximately 20% compared to the reference specimen with fiber reinforcement. Similarly, a 9% increase was observed in the semi-light series (2% EP) at the same alkali level. This improvement is associated with the ability of microfibers to enhance internal continuity by bridging discontinuities within the matrix. The fibers have a density that allows for vibration transmission according to the porous structure of expanded perlite. In both fiber-reinforced and unreinforced specimens, increasing alkali concentration reduces UPV values by up to 33%. This can be explained by the fact that while the geopolymer structure densifies in a high-alkali environment, its microporosity increases due to shrinkage.

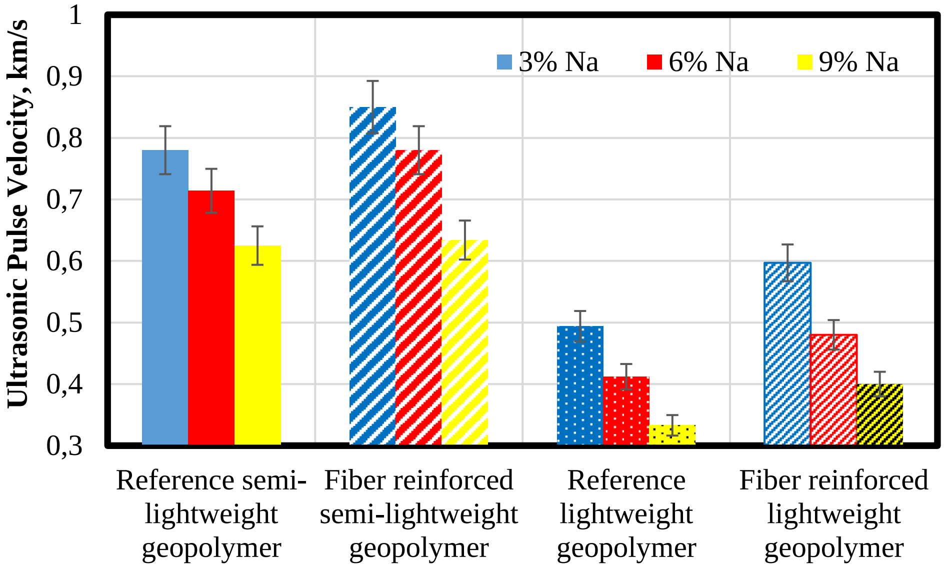

Figure 4. Ultrasonic pulse velocity values of lightweight geopolymer specimens reinforced with fibers
(Note: Reference mixtures represent unreinforced baseline composites; microfiber-reinforced mixtures represent the new experimental series of this study).

The water absorption rates by weight of the specimens are shown in Figure 5. Examining Figure 5, it can be seen that the addition of 1.5% microfibers reduced water absorption by weight in all specimens. For the lightweight geopolymer series (4% EP) with 3% Na concentration, fiber reinforcement reduced water absorption by 13%, while at 6% Na, this reduction reached 19.3%. The decrease in water uptake can be attributed to the microfibers filling the interconnected capillary channels and micro-voids within the NASH matrix, thus disrupting the continuity of the pore network and restricting water ingress. The results also show that increasing the alkali concentration reduces water absorption. In the fiber-reinforced lightweight specimens, when the Na concentration increased from 3% to 9%, water absorption showed a significant decrease of 39.6%. High sodium dosages facilitate the geopolymerization of waste glass and tile dust, resulting in a denser binder that more effectively traps both perlite and fibers. Furthermore, the data show that fibers are particularly effective in "semi-lightweight" systems (2% EP). The fiber-reinforced specimen with 6% Na achieved a water absorption value of 14.05%, which is 7.9% lower than its reference. While the porous structure of EP increases the water absorption capacity of the specimens, the addition of 1.5% microfibers, together with high alkali dosages, increases the impermeability of the lightweight composite.

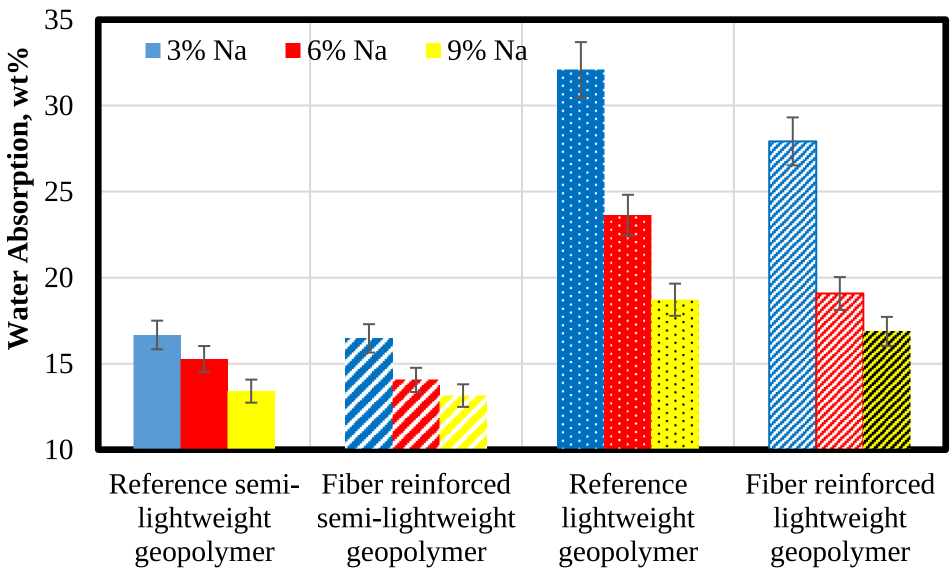

Figure 5. Water absorption values of lightweight geopolymer specimens reinforced with fibers
(Note: Reference mixtures represent unreinforced baseline composites; microfiber-reinforced mixtures represent the new experimental series of this study).

The capillarity coefficient values calculated based on the water absorption rate of the specimens via capillary absorption are presented in Figure 6. Experimental data show that the addition of 1.5% microfibers significantly reduced the capillary absorption rate in all series. For the semi-lightweight geopolymer (2% EP) with a 3% Na concentration, the capillarity coefficient decreased by 28% with the addition of fibers. Similarly, in the 9% Na series, fibers improved capillary resistance by 27.9%. This can be explained by the fact that microfibers do not disrupt the continuity of the capillary pore network in the NASH gel. By cutting and blocking the microchannels formed during the geopolymerization of waste tile and glass dusts, the fibers increase the crimp of the liquid path and thus slow down the water ingress rate. In fiber-reinforced lightweight specimens (4% EP), a 10.5% decrease in the capillarity coefficient was observed when the Na concentration increased from 3% to 9%. High alkalinity promotes the dissolution of aluminosilicate sources, leading to a binding matrix that better traps both perlite and fibers. The 4% EP series exhibits capillarity coefficients approximately 2.5 times higher than the 2% EP series due to the interconnected macroporosity of perlite. The use of fibers in the structure is important for durability, as they not only strengthen the matrix but also increase its resistance to moisture transport.

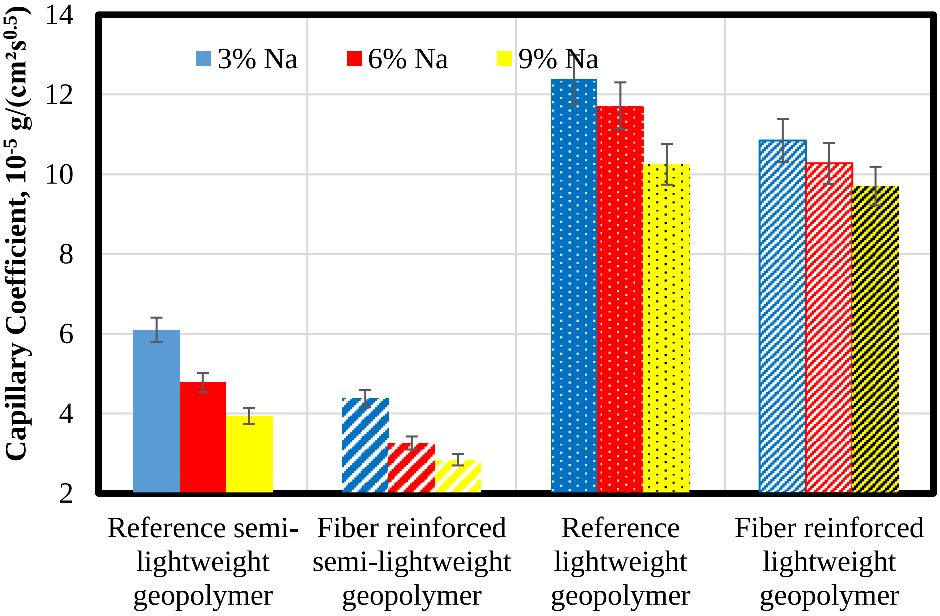

Figure 6. Capillary coefficient values of lightweight geopolymer specimens reinforced with fibers
(Note: Reference mixtures represent unreinforced baseline composites; microfiber-reinforced mixtures represent the new experimental series of this study).

The effect of fibers on the mechanical properties of geopolimers is most clearly seen in the flexural test. Under flexural load, the smallest crack that can occur at the point where the greatest moment occurs leads to fracture of the specimen at that region. Fibers control the growth and branching of these cracks when they are at the micro-crack level, which is invisible to the naked eye. Because they have very high tensile strength, they resist the force that wants to open the crack. Generally, fibers surrounded by the binder paste do not allow the crack to open due to this adhesion effect. As the force increases, slippage, and sometimes rupture, is often observed in the fibers. It is undesirable for structural elements to collapse as soon as cracks form. If a crack occurs, it is desirable to eliminate the factors causing that crack, and to keep the structure standing by repairing and strengthening it. Figure 7 shows the flexural strength results. The addition of 1.5% microfibers increased the flexural strengths. Fiber reinforcement significantly compensated for the strength loss caused by expanded perlite, acting as a strong mechanical bridge. In the semi-light series (2% EP) with a 6% Na concentration, flexural strength showed a remarkable increase of 89.4% with the addition of fiber. In the light series (4% EP) with 6% Na, this increase reached 88.9% with the use of fiber. This increase is due to the fiber bridging effect. In terms of alkali concentration, an increase in concentration resulted in a 78% increase in strength. This indicates that the geopolymer obtained at a 6% Na concentration provides good adhesion to the fibers. However, a concentration reaching 9% led to a decrease in flexural strength due to increased alkalinity.

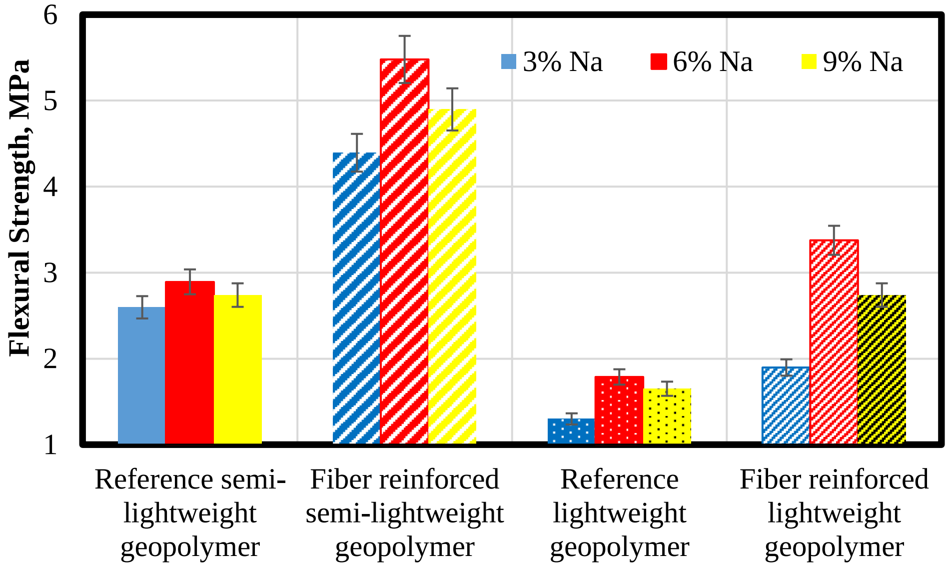

Figure 7. Flexural strength values of lightweight geopolymer specimens reinforced with fibers
(Note: Reference mixtures represent unreinforced baseline composites; microfiber-reinforced mixtures represent the new experimental series of this study).

The changes in compressive strength of lightweight geopolymer specimens with microfiber addition are given in Figure 8. Adding 1.5% microfiber increased the compressive strength of the lightweight geopolymer. For lightweight specimens containing 6% Na, the compressive strength increased by 25% with fiber addition. For semi-lightweight specimens at the same alkali level, the increase in strength with fiber addition was 15%. This increase can be attributed to the fact that the fibers restrict the deformation of the geopolymer and control crack propagation. Considering the alkali concentration, the highest compressive strengths were observed in specimens containing 6% Na. The addition of 1.5% microfiber enabled even the lightest specimens to maintain a compressive strength above 8 MPa, providing an advantage for the application.

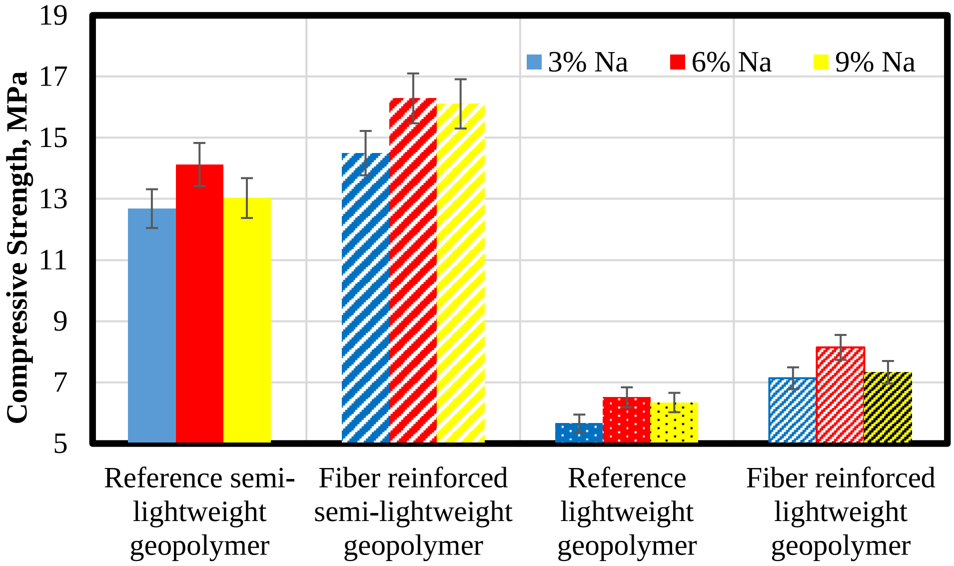

Figure 8. Compressive strength values of lightweight geopolymer specimens reinforced with fibers
(Note: Reference mixtures represent unreinforced baseline composites; microfiber-reinforced mixtures represent the new experimental series of this study).

Figure 9 shows the splitting tensile strength results of the specimens. Examining Figure 9, it can be seen that the addition of 1.5% fiber increased the splitting tensile strength of the lightweight geopolymer specimens (4% EP) at a 6% Na concentration by 1.3 times. Similarly, a 99.3% increase was observed in the semi-lightweight specimens (2% EP) at the same alkali concentration. This increase can be attributed to the fibers strengthening the binder matrix surrounding the porous EP structure. While the reference geopolymer without fiber fractured more easily along the splitting plane due to its brittle structure, it can be said that the fibers perpendicular to the splitting plane made fracture more difficult in the fiber-containing specimens. For fiber-reinforced lightweight specimens, increasing the Na concentration from 3% to 6% led to a 51.7% increase in tensile strength, while 9% Na resulted in a 26.8% decrease. This indicates that a 6% Na concentration provides the optimal alkaline environment for establishing a strong bond between the waste-based binder and the microfiber surfaces. The addition of 1.5% microfiber not only doubles the tensile capacity in many cases but also enables the material to withstand significant tensile strains despite its porosity. The strength increase is consistent with a fiber-bridging contribution; however, direct microstructural or pull-out tests would be required to verify the exact mechanism.

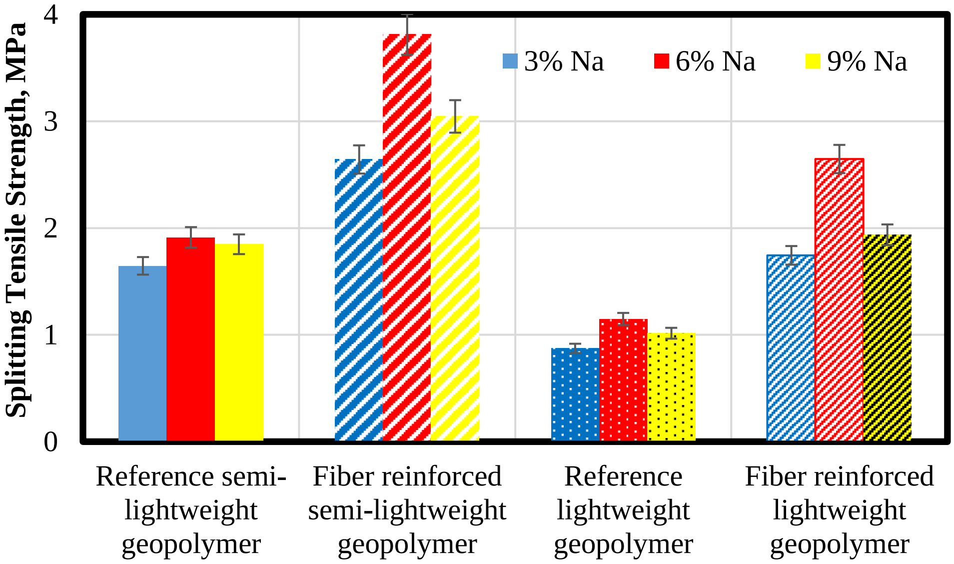

Figure 9. Splitting tensile strength values of lightweight geopolymer specimens reinforced with fibers
(Note: Reference mixtures represent unreinforced baseline composites; microfiber-reinforced mixtures represent the new experimental series of this study).

4. Conclusion

The following results were obtained from this experimental study on microfiber reinforcement of waste-based lightweight geopolymer composites:

- Addition of 4% expanded perlite reduced the unit weight, while fiber addition, due to its low density, reduced the unit weight by up to 3.4%; thus, structural strengthening was achieved while maintaining lightweight properties.
- According to UPV results, microfiber reinforcement improved the internal continuity of the porous matrix. For lightweight series, fiber addition increased the impact velocity by up to 20.8%; this shows that the fibers act as bridges between micro-voids and provide internal reinforcement.
- Microfibers reduced the water absorption properties of the composites. Fiber addition reduced the water absorption rate by up to 19.3% and the capillarity coefficient by approximately 28%. The fibers effectively disrupted the interconnected capillary network in the NASH gel.
- The most striking effect of 1.5% microfiber reinforcement was observed in flexural and splitting tensile strengths. While flexural strength increased by up to 89.4%, splitting tensile strength showed a remarkable increase of 130.5%. This is attributed to the fiber bridging mechanism, which halts crack propagation and transforms brittle damage into reduced brittle fracture tendency.
- Considering mechanical performance, a 6% Na concentration is recommended. 9% Na negatively affected mechanical performance due to excessive brittleness.
- Even lightweight specimens containing 4% perlite achieved compressive strengths above 8 MPa thanks to microfibers. This value is suitable for non-load-bearing structural elements.

The results demonstrate that microfiber addition improved macroscopic performance indicators, especially flexural strength, splitting tensile strength, UPV, water absorption, and capillarity resistance. The proposed fiber-bridging and water-path interruption mechanisms should be considered interpretive explanations rather than directly verified mechanisms. This study has shown that microfiber reinforcement is necessary to eliminate the disadvantages associated with the brittle structure of lightweight geopolymers. As a result of the experiments, a 6% Na concentration along with 1.5% microfibers can be recommended in the production of lightweight geopolymers. In future studies, it is recommended to investigate the impact resistance and fracture toughness of these fiber-reinforced composites. It is also recommended to investigate the fire resistance and thermal insulation properties, which are important for lightweight composites. Future studies should include SEM/EDS, XRD, FTIR, MIP, single-fiber pull-out tests, load–deflection curves, fracture toughness, thermal conductivity, fire resistance, and long-term durability tests.

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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