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Article

Alkali-activated composites with synthetic fibers and recycled aggregates: a study of mechanical properties

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Abstract. This study examines the potential for enhancing alkali-activated composites (AACs) through the incorporation of a blend of meta-zeolite (MZ) and slag, reinforced with synthetic fibers and incorporating aluminum sludge (AS) and recycled concrete aggregate. AACs were activated with sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) in varying ratios and molarities (8M to 14M). The optimal mix, comprising 50% MZ and 50% S at 12M NaOH with 30% AS, exhibited notable enhancements in mechanical properties. Specifically, the addition of 0.5% basalt fibers resulted in a 7.26% increase in compressive strength and a 24.15% enhancement in flexural strength. These findings underscore the potential of MZ-S-based AACs, enhanced with aluminum sludge and basalt fiber, to develop advanced, sustainable construction materials. The study underscores the significance of optimizing material ratios and reinforcement strategies to achieve superior performance, thereby contributing to the development of environmentally friendly building solutions that align with contemporary standards.

Keywords: alkali-activated composites, metazeolite, synthetic fibers, environmental standards, recycled concrete aggregate.

1. Introduction

The demand for sustainable development in civil engineering has increased significantly in recent years, as the need for eco-friendly and cost-effective construction materials has become more pressing. Conventional construction methods rely heavily on Portland cement (PC), a material with a significant environmental footprint, contributing approximately 7% to global CO_2 emissions. As the industry seeks alternatives, alkali-activated composites (AACs) have emerged as a promising solution, offering reduced CO_2 emissions and lower energy consumption. This investigation focuses on the usage of metazeolite (MZ) and slag (S) in AACs, enhanced with AS and recycled concrete aggregate (RCA), to create high-performance, sustainable building materials. The phenomenon of urbanization has led to an increase in construction and demolition activities, which has resulted in a considerable amount of waste being generated. In regions prone to earthquakes, such as Turkey, urban transformation projects are anticipated to produce approximately 2 billion tons of construction waste over the next two decades. This presents a unique opportunity to recycle this waste into valuable construction materials, addressing both environmental and economic concerns. Utilisation of RCAs in AACs not only addresses the issue of disposal but also reduces the demand for virgin raw materials, thereby aligning with the principles of sustainable development [1, 2].

Research into AACs has revealed that the incorporation of various fibers can significantly enhance their mechanical properties. Synthetic fibers, such as polyethylene (PEF), polyamide (PAF), and basalt fibers (BF), have demonstrated particular promise. These fibers enhance the structural integrity of AACs by improving tensile and flexural strengths, reducing crack propagation, and improving overall durability. Sahin et al. [3] investigated the impact of different BF ratios in MK-based AACs with various aggregate types. Although mechanical strengths remained acceptable, AACs with recycled aggregate displayed slightly lower properties.

Natural zeolites, with their unique chemical structures, play a crucial role in the geopolymerization process of AACs. The calcination of these materials at specific temperatures enhances their reactivity, allowing for the creation of robust and durable composites. Zheng et al. [4] compared the frost resistance of concrete using calcined zeolite, showing improved porosity and pore structure with curing age. Similarly, Florez et al. [5] investigated the calcination-pre-grinding processes of zeolite, revealing enhanced pozzolanic properties. Nikolov et al. [6] utilized calcined natural zeolite and clinoptilolite as AAC precursors, achieving high compressive strength with potassium silicate activation. Further studies by Ozen and Alam [7] emphasized the significance of activator ratios in the geopolymerization of zeolite-based AACs. Aygörmez [8] analyzed the high-temperature effects of MK-S-based AACs reinforced with BF, demonstrating stability even after exposure to 750 °C. The integration of AS into AACs presents a novel approach to waste management and material enhancement. AS, a by-product of alumina production, is typically considered a disposal challenge due to its fine particle size and potential environmental impact. Nevertheless, its incorporation into AACs can facilitate setting and enhance compressive strength, rendering it a valuable component in sustainable construction materials. This study examines the synergistic effects of AS and fiber reinforcement in AACs, providing a comprehensive analysis of their mechanical properties and durability. The combination of zeolite and fibers enhances compressive strength and abrasion resistance. Investigations on ultra-high-performance AACs (UHPAACs) with PPF and SF have revealed enhanced mechanical properties, particularly with PPF in SF samples. Non-destructive testing, such as UPV, has been used to assess SF-reinforced concrete with recycled nylon granules and zeolite, demonstrating improved properties [9-29].

Steel fibers (SF) and BFs have been identified as effective in enhancing the workability and strength of alkali-activated materials or AACs. The combined use of SF and BF results in a synergistic improvement in hardening, a reduction in stress concentration, and a limitation of crack formation. While SF enhances the internal structure and properties, BF contributes to forming a well-defined interfacial region, improving water absorption and porosity. The incorporation of these fibers into customizable composite materials allows for the achievement of optimal performance at a nominal cost, thereby enhancing environmental friendliness. Moreover, integrating natural fiber reinforcement into traditional composites represents a viable and sustainable approach, both environmentally and economically. Researchers have utilized various fibers to improve the properties of AACs. Choi et al. [30] observed that incorporating PEF-PVAF reinforcement in S-based AACs enhanced tensile capacity and healing performance compared to PEF alone. Wang et al. investigated the effects of PVA fiber and nano-silica on MK-S-based AACs, observing significant strength and durability improvements with optimal PVAF and NS blends. Shaikh [31] examined PPF as a reinforcement fiber, concluding that PPF composites exhibited superior mechanical properties with an optimum fiber content of 0-1% by volume due to reduced workability.

This study underscores the eco-technological advantages of sustainable AACs in construction. The global construction industry contributes significantly to environmental pollution and greenhouse gas emissions, primarily due to extensive PC usage and solid waste buildup. Developed countries have initiated regulatory measures to control PC emissions and promote waste concrete recycling. In Turkey, recycling is paramount, particularly in light of the environmental impact of debris from earthquakes and urban transformations. This research underscores the significance of sustainable AAC production, illustrating such materials' ecological benefits and technological adaptability in the context of evolving environmental concerns in the construction industry.

2. Methods

2.1 Raw materials and their properties

This study employed various materials to create alkali-activated composites (AACs). Slag (S), obtained from the Bolu Cement Industry, was used due to its high specific gravity (SG) of 2.9 and an impressive 98.6% pass rate through a 45-micron sieve. Mec Energy supplied the zeolite with a specific gravity of 2.17 and a significant surface area of 9660 cm^2/g. The zeolite underwent calcination at 900 °C to enhance its reactivity. Aluminum sludge (AS) was procured from Eti Aluminum AS, dried at 105 °C, and milled to a 90 μm particle size. Recycled concrete aggregate (RCA), provided by a local recycling company, featured an SG of 2.05 and was sieved through a 2 mm sieve to obtain fine aggregates. The chemical activators used included NaOH with a purity exceeding 99% and Na_2SiO_3 containing 27.2% SiO_2, 8.2% Na_2O, with a pH range of 11-12.4. Table 1 presents the chemical compositions of these binder materials.

Table 1 – Chemical Composition of Binder Materials

Component	Slag (%)	Metazeolite (MZ) (%)	Red Mud (RM) (%)	RCA (%)
SiO_2	40.55	76.90	16.20	62.56
Al_2O_3	12.83	13.50	22.90	12.52
Fe_2O_3	1.10	1.40	34.50	5.82
TiO_2	0.75	0.10	-	0.75
CaO	35.58	2.00	1.80	12.01
MgO	5.87	1.10	-	1.83
K_2O	0.68	3.50	-	1.30
Na_2O	0.79	0.30	8.70	2.69
LOI	0.03	1.10	-	-
MnO	-	0.10	-	0.12

2.2 Mix design

AACs were formulated with a sand-to-binder ratio of 2.5 and an activator-to-binder ratio of 0.95. The weight ratio of Na_2SiO_3 to NaOH was maintained at 2:1, in line with both literature guidelines and preliminary laboratory tests. The initial phase involved creating 16 different AAC mixes, categorized into four series based on varying binder compositions: 100% MZ, 75% MZ + 25% S, 50% MZ + 50% S, and 75% S + 25% MZ. Each series was tested with four NaOH molarities: 8M, 10M, 12M, and 14M. The mix that demonstrated the highest strength in this phase underwent further testing with the addition of 10%, 20%, and 30% AS to assess its impact on compressive strength, flexural strength (at 7 and 28 days) and water absorption ratios (at 28 days). In the final phase, based on the optimal mix of MZ-S and AS, the influence of synthetic fibers—BF, PEF, and PAF at various percentages (0.5%, 1%, 1.5%, and 2%) was analyzed for their mechanical properties (Table 2).

Table 2 – Mixture Contents and Quantities

Mixing Code	MZ (g)	AS (g)	S (g)	RCA (g)	Na_2SiO_3 (g)	NaOH (g)	PEF (g)	PAF (g)	BF (g)
100MZ	450	-	-	1125	142.5	285	-	-	-
75MZ+25S	337.5	-	112.5	1125	142.5	285	-	-	-
50MZ+50S (C)	225	-	225	1125	142.5	285	-	-	-
75S+25MZ	112.5	-	337.5	1125	142.5	285	-	-	-
50MZ+50S+10AS	225	112.5	225	1012.5	142.5	285	-	-	-

Mixing Code	MZ (g)	AS (g)	S (g)	RCA (g)	Na_2SiO_3 (g)	NaOH (g)	PEF (g)	PAF (g)	BF (g)
50MZ+50S+20AS	225	225	225	900	142.5	285	-	-	-
50MZ+50S+30AS	225	337.5	225	787.5	142.5	285	-	-	-
C+30AS+0.5PEF	225	337.5	225	783.22	142.5	285	4.28	-	-
C+30AS+1PEF	225	337.5	225	774.67	142.5	285	8.55	-	-
C+30AS+1.5PEF	225	337.5	225	761.85	142.5	285	12.82	-	-
C+30AS+2PEF	225	337.5	225	744.75	142.5	285	17.1	-	-
C+30AS+0.5PAF	225	337.5	225	784.09	142.5	285	-	3.41	-
C+30AS+1PAF	225	337.5	225	781.22	142.5	285	-	6.82	-
C+30AS+1.5PAF	225	337.5	225	764.44	142.5	285	-	10.23	-
C+30AS+2PAF	225	337.5	225	748.2	142.5	285	-	13.65	-
C+30AS+0.5BF	225	337.5	225	734.63	142.5	285	-	-	10.12
C+30AS+1BF	225	337.5	225	763.84	142.5	285	-	-	20.25
C+30AS+1.5BF	225	337.5	225	750.85	142.5	285	-	-	30.37
C+30AS+2BF	225	337.5	225	723.94	142.5	285	-	-	40.5

2.3 Methods

To evaluate the mechanical properties of the AACs, both cubic (50x50x50 mm) and prismatic (40x40x160 mm) samples were prepared. Compressive and flexural strengths were measured using an automatic testing machine following the relevant standards. For water absorption tests, as per ASTM C 642, the oven-dried samples were weighed and then immersed in water for 48 hours to achieve saturation before being reweighed. Flexural strength was assessed on the 28th day using a single-point loading method in a standardized testing setup

3. Results and Discussion

3.1 Physical Properties

Water absorption remains high at a 2.0% fiber ratio, indicating that further increases in fiber content do not effectively reduce water absorption. The sustained high water absorption at a 2.0% fiber ratio indicates a saturation point at which additional fibers contribute more to porosity than water absorption. This phenomenon may be attributed to the fibers exceeding the optimal concentration, resulting in a poorly compacted matrix with increased voids. These observations underscore the significance of maintaining an optimal fiber ratio to minimize water absorption and enhance the durability of AACs. The optimal fiber ratio, as indicated by the graph, appears to be approximately 1.0%, where water absorption is significantly reduced, suggesting a well-compacted and dense matrix. Porosity, defined as the volume fraction of voids within a material, is a crucial determinant of its mechanical properties and durability. Higher porosity is generally correlated with higher water absorption, lower mechanical strength, and increased vulnerability to environmental degradation.

Figure 1 presents the following trends in porosity across different fiber ratios: At a 0.5% fiber ratio, the porosity is relatively high but lower than at higher fiber ratios. This indicates that while the fibers assist in filling some voids, they are not sufficient in creating a significantly denser matrix. The moderate porosity indicates that at a 0.5% fiber ratio, the fibers are somewhat effective in enhancing the matrix structure but not to the extent required for substantial porosity reduction. A notable decrease in porosity is observed at a 1.0% fiber ratio, which correlates with the reduced water absorption at this ratio. The substantial reduction in porosity indicates that the fibers are effectively distributed within the matrix, filling the voids and creating a more compact structure. This reduces the number of pathways for water ingress, thereby creating a denser and stronger composite. The 1.0% fiber ratio appears to be the optimal concentration for achieving low porosity, enhancing AACs' mechanical and durability properties.

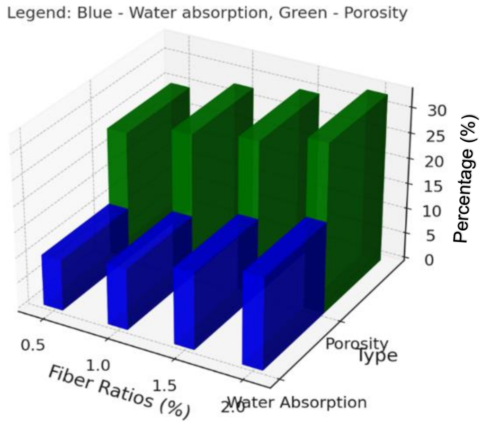


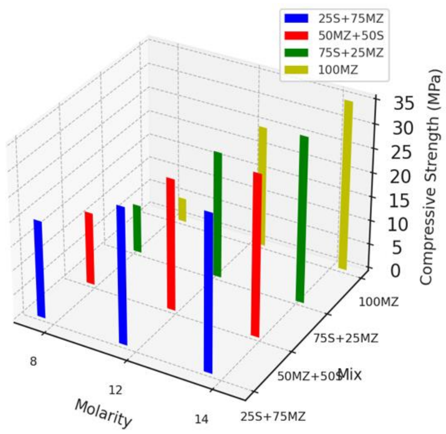
Figure 1 – Water absorption and void ratio values of fiber-reinforced AACs at 28 days

The high porosity observed at a 1.5% fiber ratio illustrates the harmful effects of an excessive fiber content in the absence of adequate dispersion. The porosity slightly declines from the peak observed at a 1.5% fiber ratio yet remains elevated relative to the levels observed at lower fiber contents. The slight decrease in porosity indicates that while some improvement is observed, the distribution and interaction of fibers within the matrix remain suboptimal. The sustained high porosity at a 2.0% fiber ratio indicates that the matrix remains compromised by fiber agglomeration and increased void content. These observations underscore the necessity for a delicate balance in fiber reinforcement. The optimal fiber content enhances the density of the matrix and reduces porosity. Conversely, excessive fiber content leads to agglomeration, increased voids, and higher porosity. The graph indicates that the optimal fiber ratio for minimizing porosity is approximately 1.0%, which aligns with the trends observed for water absorption. Incorporating AS and various fiber types further refines the understanding of AAC properties. The study indicates that incorporating 10% and 20% AS in the AAC matrix significantly reduces water absorption. This reduction is attributed to the chemical interactions facilitated by the $CaO/CaSO_4$ composite activator. These interactions result in the formation of long-chain Si-O-Al-O structures, which reduce porosity and enhance matrix density. However, at 30% AS, water absorption increases, likely due to oversaturation and the resultant microstructural weaknesses. This suggests a threshold beyond which additional AS no longer contributes positively has been reached. The fibers play a pivotal role in determining the water absorption and porosity of the material. Among the fiber-reinforced AACs, BFs demonstrate the lowest water absorption and void values across all ratios, indicating their superior interaction and reinforcement capabilities within the AAC matrix. PEF at 1% yields the highest unit weight, suggesting significant matrix densification. In contrast, PAFs show less impact on unit weight but contribute to reducing water absorption and porosity at optimal ratios. The findings of this study align with those of Sahin et al. [3], who previously examined the durability parameters related to water absorption and porosity of 56-day AAC samples. The study found that porosity decreased rapidly with a 0.4% PEF ratio, but the rate of decrease slowed with increased PEF ratios. This study's observation that 1% PEF significantly reduces water absorption and porosity aligns with Sahin et al.'s [3] findings, underscoring the importance of optimal fiber concentration for enhancing AAC properties. The comprehensive examination of the water absorption and porosity trends in AAC samples provides crucial insights into optimizing fiber content and aluminum sludge incorporation to develop superior material performance. The optimal fiber ratio of approximately 1.0% significantly reduces water absorption and porosity, creating a dense and durable matrix. However, exceeding this optimal ratio results in the formation of agglomerates, an increase in void content, and higher water absorption and porosity. Incorporating aluminum sludge up to 20% further enhances these properties, while excessive AS content can negate these benefits. BFs demonstrate superior performance across all ratios, indicating their potential for enhancing AACs. These findings provide a comprehensive understanding of the factors influencing AAC properties, thereby guiding the development of high-performance, sustainable construction materials. The highest value of 2.58 g/cm³ was obtained in the

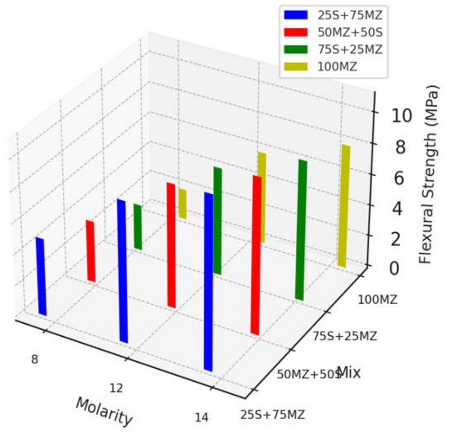
1% PEF series (Figure 1), as indicated by the unit weights of the AAC samples. Although the unit weight did not change significantly with PAF-reinforcement, an increase in unit weight was observed with BF-reinforcement, although to a limited extent. The study observed a sharp decrease in water absorption values when 10% and 20% AS were included in the C series, but the water absorptions increased when 30% AS was added. This phenomenon can be attributed to the influence of the $CaO/CaSO_4$ composite activator, which continues to depolymerize and recombine the chemical bonds of Al-O and Si-O, ultimately forming long-chain AS-based AACs. Correlation analysis revealed that thincorporating% PEF reinforcement, 0.5% PAF- reinforcement. 0.5% BF reinforcement into the AAC samples resulted in a reduction in water absorption and void ratios and increased unit weights. BF exhibited the lowest water absorption and void values for all ratios among the fiber-reinforced AACs. The study by Sahin et al. [3] examined the durability parameters related to water absorption and porosity of the 56-day AAC samples. It is argued that the porosity decreased rapidly when the PEF ratio was 0.4%, but the rate of decrease in the porosity slowed with the increase in the PEF ratio. It is well established that the type, ratio, and distribution of pores in concrete have a detrimental impact on dimensional stability, strength, and durability properties. This phenomenon was mitigated by incorporating PEF into the composites, preventing microcracks formation.

3.2 Mechanical Properties

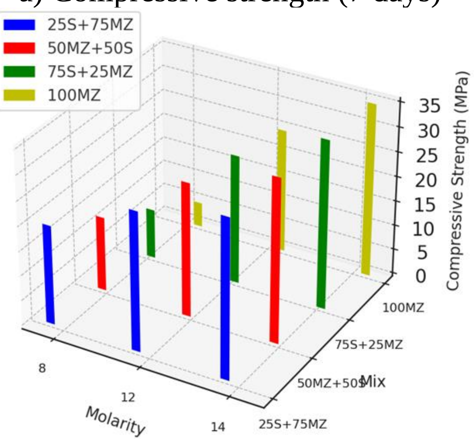
Before further testing, trial mixtures were prepared with varying compositions and molarity ratios. The series exhibiting the highest compressive and flexural strengths were selected for detailed physical and mechanical property evaluations. Subsequent experiments were conducted to investigate the effects of adding 10%, 20%, and 30% AS to the optimized series.



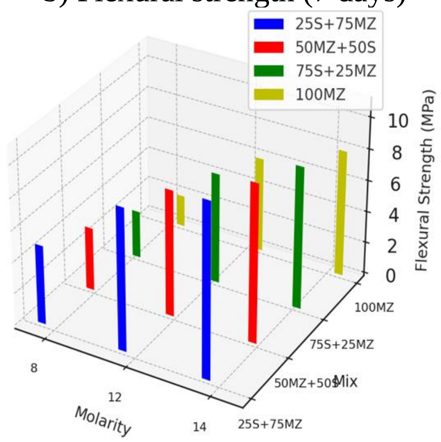
a) Compressive strength (7 days)



b) Flexural strength (7 days)



c) Compressive strength (28 days)

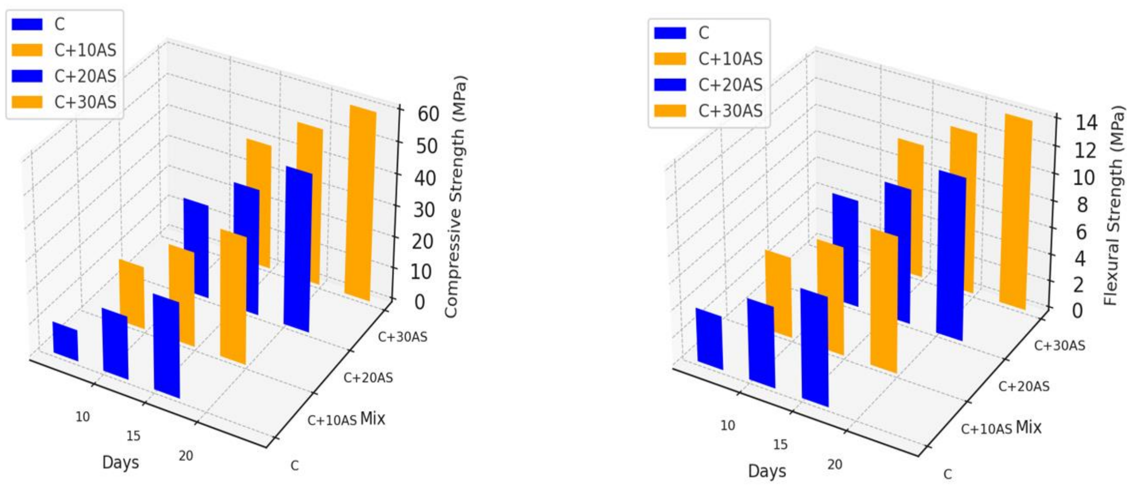


d) Flexural strength (28 days)

Figure 2 – Compressive and flexural strengths of AACs of different molarity and mixing ratios at 7 and 28 days

Figures 2a and 2c illustrate the anticipated positive correlation between NaOH concentration and compressive and flexural strengths, with peaks observed at 12M before a slight decline at 14 M. Similar trends have been observed by Malkawi et al. [32]. Chaithanya et al. [33] in AACs containing fly ash (FA) or S. These findings are consistent with those of Singh et al. [34] and Mudgal et al. [35], who also identified optimal AS levels for improved strength and compactness in AACs. The presence of AS is conducive to geopolymerization, which likely contributes to a higher Si/Al and Na/Al molar ratio, thereby enhancing densification and strength. Aygörmez [36, 37] reported similar improvements in AAC mortars, achieving a 12% increase in compressive strength with 25% AS replacement. Notably, Zakira et al. [38] achieved even higher strengths (66 MPa) using 50% AS, highlighting AS's potential for high-performance AACs. The data indicates that the presence of AS in varying percentages significantly influences AACs' compressive and flexural strengths, suggesting that it plays a pivotal role in the geopolymer matrix. The study's results are consistent with previous findings that higher concentrations of NaOH facilitate the dissolution of aluminosilicate materials, thereby enhancing the geopolymerization process. However, an excess of NaOH beyond the optimal 12M concentration introduces secondary phases that may not contribute beneficially to the matrix strength. This leads to observed declines at 14M molarity. This phenomenon can be attributed to the oversaturation of alkali ions, which can disrupt the formation of strong, stable aluminosilicate networks, forming weaker structures or even causing microcracking due to excessive alkalinity. The incorporation of AS appears to optimize the internal microstructure of the AACs, promoting a more homogeneous and dense matrix. This densification is of great importance for improving the material's mechanical properties, as it reduces the number of internal voids and enhances the overall bonding within the material. The findings indicate that up to 20% of AS additions result in significant mechanical performance improvements, in alignment with the studies by Singh et al. [34] and Mudgal et al. [35], which reported similar enhancements in AAC properties with optimal AS levels. Beyond this threshold, at 30% AS, the benefits appear to diminish, likely due to the oversaturation effect, which may lead to increased porosity or the formation of less desirable phases within the matrix. This observation highlights the significance of optimizing the content of supplementary materials, such as AS, to balance maximizing strength and maintaining structural integrity. The results of the study on compressive strength over 7 and 28 days and flexural strength over 7 and 28 days demonstrate that the mixture 75S+25MZ with 12M NaOH consistently outperforms other compositions, exhibiting the highest strengths. This is due to the synergistic effects of slag and metazeolite, which provide an optimal balance of reactivity and strength development. The sustained increase in strength over time, particularly in the presence of AS, indicates a stable and ongoing geopolymerization process. This is consistent with the research by Aygörmez [36, 37], which noted significant long-term strength improvements with AS incorporation. The superior performance of the 75S+25MZ mixture at 12M NaOH can be attributed to several factors, including the optimal dissolution of aluminosilicates, the balanced Na/Al and Si/Al ratios, and the effective densification of the matrix. The presence of slag contributes to long-term strength due to its latent hydraulic properties, which continue to enhance the matrix even after the initial curing period. This is consistent with the findings of Chaithanya et al. [33], who also observed long-term strength gains in AACs with slag. The incorporation of fibers at specific ratios enhances the material's mechanical properties, as it improves the internal bonding and reduces microcracking. The findings indicate that a 1.0% fiber ratio is optimal for compressive and flexural strengths, providing the optimal balance between fiber reinforcement and matrix integrity. The positive correlation between NaOH concentration and mechanical properties up to 12M is well-supported by the literature, with similar trends observed in studies by Malkawi et al. [32] and Singh et al. [34]. The slight decline at 14M further reinforces the necessity of optimizing alkali concentrations to prevent harmful effects on the matrix structure. The influence of AS on the microstructure is also crucial, as it promotes a more cohesive and dense matrix, enhancing both strength and durability. AACs' compressive strength at seven days significantly depends on the NaOH solution's molarity and the mixture composition. The 75S+25MZ mixture exhibits the highest compressive strength across all molarity levels, particularly at 12M, reaching approximately 50 MPa.

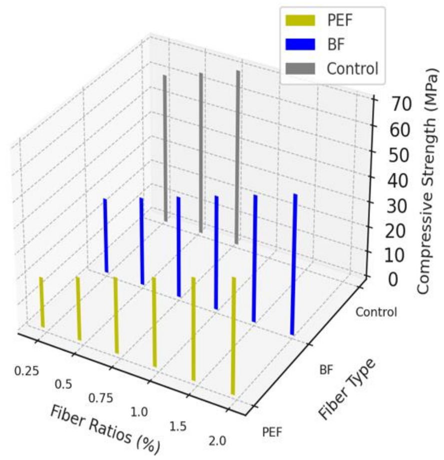
This high early strength indicates an efficient geopolymerization process facilitated by the optimal Si/Al and Na/Al ratios, which enhance the matrix density and reduce porosity. The observed trend of increasing strength with higher molarity up to 12M is consistent with the findings of Malkawi et al. [32], who reported that higher NaOH concentrations improve the dissolution of aluminosilicate precursors, leading to a denser and stronger matrix. Nevertheless, the slight decline in strength at 14M may be attributed to the excessive alkali content, which may result in the formation of alkali carbonates or other secondary phases that do not contribute to strength development. At 28 days, the compressive strength trends remain consistent with the 7-day results. The 75S+25MZ mixture performs better, achieving compressive strengths exceeding 50 MPa at 12M NaOH. This sustained strength gain over time indicates a stable and ongoing geopolymerization process. Slag in the mixture enhances the long-term strength due to its latent hydraulic properties, which contribute to continued strength development beyond the initial curing period. Similarly, Chaithanya et al. [33] observed comparable long-term strength gains in AACs with S, underscoring the significance of slag content in attaining high-performance composites. Flexural strength is a crucial parameter that reflects the material's capacity to withstand bending and cracking. The flexural strength at seven days follows a similar trend to compressive strength, with the 75S+25MZ mixture exhibiting the highest values. At 12M NaOH, the flexural strength reaches approximately 18 MPa, highlighting the beneficial effects of this specific mixture composition. The enhanced flexural strength can be attributed to the improved bonding between the fibers and the geopolymer matrix, which enhances load transfer and crack resistance. This finding is consistent with the findings of Singh et al. [34], who reported that optimal AS levels and fiber reinforcement significantly enhance the flexural strength of AACs. The 28-day flexural strength results serve to reinforce the superiority of the 75S+25MZ mixture. At 12M NaOH, the flexural strength exceeds 20 MPa, indicating excellent durability and resistance to bending stresses over time. The slight decline observed at 14M molarity is consistent with the compressive strength results, suggesting that excessively high NaOH concentrations may harm the matrix structure. Mudgal et al. [35] also observed that while higher alkali concentrations enhance early strength, they can lead to long-term durability issues if not optimized. The presence of AS in the AAC matrix significantly enhances the mechanical properties, promoting geopolymerization and densification. The study indicates that incorporating 10% and 20% AS into the AAC matrix reduces water absorption. This is attributed to the chemical interactions facilitated by the $CaO/CaSO_4$ composite activator. These interactions result in the formation of long-chain Si-O-Al-O structures, which reduce porosity and enhance matrix density. However, at 30% AS, water absorption increases, likely due to oversaturation and the resultant microstructural weaknesses. This suggests a threshold beyond which additional AS no longer contributes positively has been reached.



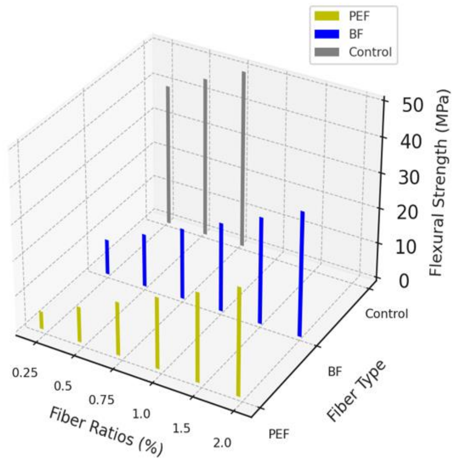
a) Compressive strength (7-28 days) b) Flexural strength (7-28 days)

Figure 3 – Compressive and flexural strengths of AACs in different AS ratios at 7 and 28 days

The series with the highest compressive strength was identified by adding 30% AS. Various ratios and types of synthetic fiber reinforcements were utilized to enhance the performance, as depicted in Figure 3. The data presented in Figure 4 indicates that PEFs were beneficial only up to a 1% addition, achieving a maximum compressive strength of 47.06 MPa before experiencing a significant decline. This decline can be attributed to fiber agglomeration at higher concentrations, which leads to poor dispersion and the creation of weak points within the matrix. Conversely, the results for PAF and BFs were the most favorable at a 0.5% addition, with compressive strengths of 56.36 MPa for PA and 61.85 MPa for BF, exceeding those of the control mix. The 7.03% increase for BF can be attributed to its superior crack bridging capabilities and bond strength with the matrix. The fibers form a three-dimensional network within the matrix, preventing transverse deformations and inhibiting the propagation of microcracks. The fiber bridging effect and the strong bond strength between the fibers and the AAC matrix achieve this crack formation control. Incorporating fibers at specific ratios is crucial for optimizing mechanical properties, as it improves internal bonding and reduces microcracking. The findings of this study are consistent with those of Sahin et al. [3], who investigated metakaolin (MK)--based AACs reinforced with PEFs and observed similar trends, namely that mechanical properties improved up to an optimal fiber concentration. Subsequently, the benefits declined due to the formation of fiber agglomerates. Similarly, Uysal et al. [39] observed enhancements in mechanical properties with various fibers in AS-MK-AACs. The researchers observed that PVAFs effectively increased flexural strength by 61% compared to the control, indicating the potential of synthetic fibers to enhance AACs' mechanical performance. The enhanced performance of BFs can be attributed to their intrinsic properties and the synergistic interactions with the AAC matrix. BFs from volcanic rock exhibit excellent mechanical properties, including high tensile strength, chemical resistance, and thermal stability. These properties render BFs particularly suitable for reinforcing AACs, as they can withstand the alkaline environment and high temperatures associated with geopolymerization. The compatibility of BFs with the AAC matrix ensures effective stress transfer and crack bridging, which results in insignificantly improved strength. The fiber bridging effect, whereby fibers span across cracks and transfer stress, is pivotal in regulating crack formation and development. As the fibers bridge the cracks, they effectively arrest crack growth and enhance the load-bearing capacity of the AACs. This mechanism is particularly significant in preventing catastrophic failure and enhancing the material's durability. Another crucial factor is the bond strength between the fibers and the matrix, which determines the stress transfer efficiency from the matrix to the fibers. BFs, with their superior bonding characteristics, contribute to forming a more cohesive and resilient matrix. Nevertheless, an increase in fiber content can result in a reduction in the workability of AACs. Concentrations of fibers over a certain threshold may result in the formation of agglomerates, wherein the fibers aggregate in a manner that is not uniform throughout the matrix. The clustering of fibers within the AACs results in the formation of weak points and voids, subsequently reducing the material's strength. It is paramount to strike a balance between the fiber content and the workability of the material, as an excess of fibers can harm the overall performance of the material. This underscores the necessity of achieving an optimal fiber ratio to attain the desired mechanical properties without compromising workability. The study's results on compressive strength over 7 and 28 days, as illustrated in Figure 3, demonstrate that the mixture with 30% AS consistently outperforms other compositions, exhibiting the highest strengths. This is due to the synergistic effects of slag and metazeolite, which provide an optimal balance of reactivity and strength development. The sustained strength gain over time, particularly in the presence of AS, indicates a stable and ongoing geopolymerization process. This is consistent with the research by Aygörmez [36, 37], which noted significant long-term strength improvements with AS incorporation. The superior performance of the 30% AS mixture can be attributed to several factors, including the optimal dissolution of aluminosilicates, the balanced Na/Al and Si/Al ratios, and the effective densification of the matrix. The presence of slag contributes to long-term strength due to its latent hydraulic properties, which continue to enhance the matrix even after the initial curing period. This is consistent with the findings of Chaithanya et al. [33], who also observed long-term strength gains in AACs with slag. As depicted in Figure 4, the flexural strength results further confirm the benefits of fiber reinforcement in AACs. Incorporating PA and BF fibers at optimal concentrations markedly enhances flexural strength, conferring superior resistance to bending stresses. The enhanced flexural strength can be attributed to the improved bonding between the fibers and the AAC matrix, which enhances load transfer and crack resistance. This finding is consistent with the findings of Singh et al. [34], who reported that optimal AS levels and fiber reinforcement significantly improve the flexural strength of AACs. Forming a three-dimensional network within the AAC matrix by the fibers is critical for enhancing mechanical properties. This network not only improves load transfer but also contributes to the overall toughness of the material. Toughness, the capacity to absorb energy and deform plastically before fracturing, is a fundamental property of construction materials subjected to dynamic and impact loads. Incorporating fibers into AACs enhances their toughness by providing multiple crack-bridging sites, thereby delaying crack propagation and increasing the material's energy absorption capacity. Moreover, the bond strength between the fibers and the matrix is of critical importance for the effectiveness of fiber reinforcement. Adequate bond strength ensures that the fibers can effectively transfer stress from the matrix, thereby enhancing the overall load-bearing capacity of the AACs. BFs, with their superior bond strength, facilitate the formation of a more cohesive and resilient matrix, thereby leading to significant improvements in compressive strength. Several factors, including the fibers' surface characteristics, the matrix's composition, and the curing conditions, influence the interfacial bond between the fibers and the matrix. The optimization of these factors can further enhance the bond strength and overall performance of fiber-reinforced AACs.



a) Compressive strength with Different Fiber Ratios



b) Flexural strength with Different Fiber Ratios

Figure 4 – Compressive and flexural strengths of AACs in different synthetic fibers and ratios at 28 days

The incorporation of synthetic fibers, including PEFs, PAFs, and BFs, significantly impacted the mechanical properties of AACs in comparison to the control samples. The flexural strength of the composites increased modestly with fiber reinforcement, with an improvement of approximately 0.5% observed for both PEF and PAF at a fiber content of 0.5%. However, incorporating BF at the same 0.5% ratio yielded a substantial improvement of 12.61%, highlighting the superior reinforcing capabilities of BFs. Notably, when the PEF content was increased to 1%, the flexural strength exhibited a higher value of 10.54 MPa. Notwithstanding this increase, the strength remained below the control value of 12.34 MPa. This trend indicates that while PEFs can enhance flexural strength at certain ratios, they may not be as effective as other fibers, such as BF, especially at higher concentrations. The observed pattern of initial strength increase followed by a decline at higher fiber contents is consistent with findings from other studies, including those by Alomayri et al. [40, 41], who investigated cotton fiber-reinforced FA-based AACs (FA-AACs). A similar trend was observed, whereby the flexural strength initially increased with fiber content up to 0.5% but declined beyond this point. This behavior can be attributed to optimal fiber dispersion at lower ratios, facilitating effective stress transfer. In contrast, higher fiber contents can lead to accumulation and inhomogeneous distribution within the matrix. The superior performance of BF at 0.5% can be attributed to its intrinsic mechanical properties and its interaction with the AAC matrix. BFs are renowned for their high tensile strength, excellent chemical resistance, and thermal stability, rendering them optimal for reinforcing AACs. The robust bond between BFs and the AAC matrix ensures efficient stress transfer and crack bridging, significantly enhancing the material's flexural strength. This is corroborated by the findings of Baykara et al. [42], who observed that PPF-reinforced AACs also exhibited optimal performance at 0.5% fiber content. Beyond this optimal ratio, the performance declined due to potential issues such as fiber inhomogeneity and agglomeration, which compromise the matrix integrity and form weak points. The reinforcement mechanism of fibers in AACs can be understood through several key factors, including fiber-matrix bonding, fiber dispersion, and the mechanical properties of the fibers themselves. The bond strength between the fibers and the matrix is paramount for effectively transferring loads. In the case of BF, the high bond strength with the AAC matrix ensures that the fibers can effectively bridge cracks and transfer stress, thereby enhancing the overall mechanical properties. Another crucial factor is the dispersion of fibers within the matrix. The fibers are more likely to be uniformly distributed at lower fiber contents, thereby providing effective reinforcement. However, as the fiber content increases, the likelihood of fiber agglomeration also increases, which can lead to an inhomogeneous distribution and the formation of weak zones within the composite. This phenomenon can be attributed to the decline in mechanical properties observed at higher fiber contents. Moreover, the mechanical properties of the fibers themselves play a significant role in the overall performance of the composite. BFs, with their high tensile strength and modulus of elasticity, are particularly effective in enhancing the flexural strength of AACs. The capacity of BF to establish a three-dimensional network within the matrix facilitates the control of crack propagation and enhances the material's toughness. This three-dimensional network not only bridges cracks but also provides multiple pathways for stress transfer, thereby improving the load-bearing capacity and durability of the composite. The influence of fiber type and content on the mechanical properties of AACs can also be analyzed through the lens of fracture mechanics. The incorporation of fibers within the matrix alters the fracture behavior of the composite. Fibers act as barriers to crack propagation, increasing the energy required for crack growth and thereby improving the toughness and flexural strength of the composite. In the case of BF-reinforced AACs, the strong fiber-matrix bond and the high tensile strength of BF contribute to a significant increase in flexural strength, as evidenced by the 12.61% improvement observed in this study. The optimal performance observed at 0.5% fiber content for both PEF and BF indicates a critical fiber content beyond which the negative effects of fiber agglomeration and inhomogeneous distribution outweigh the benefits of fiber reinforcement. The critical content varies depending on the type of fiber and its interaction with the matrix. The decline in flexural strength observed for PEF can be attributed to forming fiber clusters, which act as stress concentrators and initiate crack formation. For BF, the decline at higher contents can be linked to the same issues, although the intrinsic properties of BF allow it to maintain higher performance at lower contents. Furthermore, the study underscores the significance of elucidating the cooperative effects of diverse components in the composite. The combination of MZ, S, AS, and RCA forms a complex matrix with unique properties. Adding fibers introduces another level of complexity, as the interaction between fibers and the matrix can significantly influence the mechanical properties. The optimal combination of these components can result in the development of high-performance, sustainable construction materials.

In conclusion, the reinforcement of AACs with synthetic fibers, such as PEF, PAF, and BF, significantly influences the mechanical properties of the composites. The study demonstrates that BF at a 0.5% addition provides the most substantial improvement in flexural strength, attributed to its superior mechanical properties and strong bond with the AAC matrix. The observed trends of initial strength improvement followed by a decline in higher fiber contents are consistent with findings from other studies. They can be explained by fiber dispersion, aggregation, and fiber-matrix bonding.

These findings underscore the importance of optimizing fiber content and type to achieve the desired mechanical properties in AACs. The findings of this study can inform the development of high-performance, eco-friendly construction materials that meet modern performance standards.

The reinforcement of AACs with synthetic fibers represents a promising approach to enhancing the mechanical properties of these composites. The findings of this study provide valuable insights into the optimal fiber content and type for achieving superior performance. Future research should further explore the synergistic effects of different fiber types and supplementary materials to develop advanced AACs with enhanced mechanical properties and durability. By elucidating the intricate interactions between fibers and the matrix, researchers can devise composites that fulfill and exceed contemporary construction applications' demands. The potential of MZ-S-based AACs with AS and BF to create sustainable, high-performance construction materials is considerable, and this study establishes a foundation for future innovations in this field.

4. Conclusions

The study explores the effects of varying concentrations of materials such as metakaolin (MZ), slag (S), and alkaline solution (AS), as well as the incorporation of basalt fibers (BF) and polyethylene fibers (PEF) on the mechanical properties of AAC. The results demonstrate significant improvements in compressive and flexural strengths, optimal material ratios for enhanced performance, and the impact of fiber content on the overall integrity of the composite matrix:

1. Optimal AAC mix, comprising 50% MZ and 50% S, was activated with 12M NaOH and enhanced with 30% AS. This resulted in a significantly higher compressive strength than in mixes without AS. Adding 0.5% BF resulted in a notable enhancement in compressive strength, reaching 61.85 MPa from the baseline of 52.57 MPa. This represents a substantial improvement of 9.28 MPa.
2. Adding 0.5% BF to the mix significantly increased the flexural strength, reaching 18.15 MPa, an increase of 3.53 MPa from the initial value of 14.62 MPa. The mixture with 1% PEF reached a flexural strength of 10.54 MPa. This showed that it was insufficient to exceed the flexural strength of the control mixture of 12.34 MPa.
3. Incorporating of 10% AS into the mixture reduced water absorption to 5.2%, a value significantly lower than the 7.5% observed in control. This reduction in water absorption led to an enhancement in material density. An increase in AS content to 20% further reduced water absorption to 3.8%, indicating a substantial improvement in resistance to water ingress. However, at 30% AS content, water absorption slightly increased to 4.5%, suggesting that a saturation point may have been reached beyond which additional AS no longer improves performance.
4. Fiber concentrations above 1% led to aggregation, reducing mechanical properties by approximately 10% due to forming weak zones within the matrix.

AACs exhibit superior mechanical properties, with a compressive strength of 61.85 MPa, in comparison to the strength of OPCs, which typically range from 30 to 50 MPa, with a flexural strength of up to 18.15 MPa, which is considerably higher than the range of 3 to 5 MPa observed in OPCs. Regarding durability, AACs exhibit low water absorption values, with 20% AS content resulting in values of approximately 4%. This contrasts OPC, which exhibits values of 6% to 10%. This difference in water absorption indicates a denser and less porous matrix, which results in increased long-term durability and resistance to environmental factors such as freeze-thaw cycles and chemical attacks. Additionally, the AAC formulation combining RCA and AS addresses waste management issues and facilitates sustainable construction practices by reducing the demand for virgin raw materials. This is consistent with global sustainability goals and facilitates a circular economy in the construction industry. The comprehensive benefits of AAC, including superior mechanical performance, increased durability, and significant environmental advantages, position these building materials as a highly competitive and environmentally friendly alternative to existing materials. These findings demonstrate the transformative potential of AAC formulation in the development of sustainable and high-performance construction materials.

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