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Evaluation of Alkali-Activated Mortar Incorporating Combined and Uncombined Fly Ash and GGBS Enhanced with Nano Alumina

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Abstract

The present research focuses on assessing the fresh and hardened properties as well as the durability performance of alkali-activated mortar in an ambient environment and the impact of integrating nano-alumina (NA) at a 2% ratio as a substitute for binder materials in alkali-activated mortar (AAM). Additionally, it assesses the effectiveness of alkali-activated mortar employing different blends of ground granulated blast furnace slag (GGBS) and fly ash as environmentally friendly substitute building materials. Fly ash (FA), ground granulated blast slag (GGBS), and an equal mixture of GGBS and FA make up these binder ingredients. As a result, the main binders contain GGBS, FA, or a 50/50 mixture of GGBS and FA. The sodium hydroxide (NaOH) concentration is fixed at a 12-molarity level, and the alkali activator solution to binder ratio is kept at 0.5. In the alkali solution, the ratio of sodium silicate to sodium hydroxide is always 2.5. The study evaluates various properties of AAM, such as compressive strength, flowability, unit weight, flexural tensile strength, and durability, under ambient conditions at a steady room temperature of 23±3°C. Results indicate that AAM mixtures devoid of NA exhibit a higher flow rate compared to those containing NA. Nonetheless, the flowability of AAM mixtures aligns well with standard requirements, being modest yet adequate. Significantly, the inclusion of NA enhances the mechanical properties and durability of AAM, demonstrating its beneficial effects.

Keywords: Alkali Activated Mortar; Nano Alumina; Mechanical Properties; Durability; Fresh Properties.

1. Introduction

Concrete is recognized as the world's most extensively utilized cementitious material. Anticipated growth in building material demand is significant in many countries in the near future. Despite the widespread availability and ease of supply of ordinary Portland cement (OPC), it remains the predominant concrete binder, leading to an annual increase in OPC production by approximately 3% [1]. This prominence of OPC, a major contributor to greenhouse gas emissions, places the concrete industry at the forefront of releasing unfavorable greenhouse gases [2]. Technological advancements have spurred the development of building materials that are not only more energy-efficient and environmentally friendly but also less expensive than traditional materials. Among these innovations, the production of cementitious materials stands out. Consequently, comprehensive research has been conducted to enhance their properties. In 1970, Davidovits [3] introduced a novel inorganic polymer known as alkali-activated concrete (AAC), which boasts superior mechanical properties compared to ordinary Portland cement [4].

The geopolymerization process, a form of green technology, plays a pivotal role in reducing global CO_2 emissions. Studies reveal that producing one ton of AAC results in approximately 164 kg of CO_2 emissions, significantly less than the emissions from OPC concrete, thereby contributing to the mitigation of global warming [5–9]. AAC, an inorganic

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alumino-silicate polymer, is synthesized from various alumino-silicate sources, such as metakaolin and red mud, and activated by highly alkaline chemical solutions. These sources also include industrial by-products like fly ash (FA), slag, and others from steel production [5, 7]. Replacing cement-based concrete with AAC can significantly reduce CO_2 emissions. Furthermore, this replacement involves using industrial by-products such as fly ash, ground granulated blast furnace slag (GGBS), metakaolin, and rice husk ash as primary ingredients [8, 10]. Alkali-activated composites, engineered as novel binders rich in aluminosilicate materials, are derived from these raw materials. These composites, capable of synthesizing pozzolan with high alkali-activated solutions, have demonstrated promising results in sustainable development, exhibiting enhanced strength and porosity [11].

Recent studies have explored the partial or complete substitution of cement-based concrete with various nanomaterials. Despite the superior mechanical properties, workability, and durability of conventional concrete, alkali-activated composites integrated with nanomaterials offer greater strength and durability. Most research indicates that the optimal content of binder materials in alkali-activated concrete paste and mortar is around 1-2 percent by weight, with a particle size of 10 nm [12]. Recent studies underscore the significant impact of nanomaterials in enhancing concrete properties, a development attributed to advancements in nanotechnology [13–17]. The quality of concrete is greatly affected by the characteristics of the transition zone (TZ) between the cement paste and aggregate. Incorporating nano-silica (NS) has been shown to densify the microstructure and enhance hydrated phases (C–S–H), counteracting $Ca(OH)_2$ leaching, and serve as an effective nano-filler due to NS's high pozzolanic characteristics [13, 14]. Additionally, the use of nano-silica has been proven to decrease overall permeability in hardened concrete, thereby improving its mechanical and durability characteristics [15, 18–21]. Phoo-ngernkham et al. [22] reported that the inclusion of 3% nano-SiO2 and nano-Al_2O_3 resulted in compressive strengths of 48.1 and 46.1 MPa and flexural strengths of 5.23 and 5.26 MPa, respectively, after 90 days.

Xavier et al. [23] found that the addition of nano-alumina to an AAC mix enhances the geopolymerization process, thereby improving mechanical performance due to the effective participation of nano-alumina in chemical activation. This performance, however, begins to decline with increased alumina content due to a weakened bond effect. The production of C-S-H/C-A-S-H in a fly ash/slag alkali-activated concrete using potassium silicate and potassium hydroxide initiates hardening. The hardening process depends on the availability of calcium ions and the system's pH, with the rapid formation of C-A-S-H, K-A-S-H, and (Ca, K)-A-S-H. Slower calcium ion dissolution rates have been shown to enhance the compressive strength of alkali-activated concrete, as prolonged geopolymerization yields better results [24]. As reported, one billion tons of fly ash are produced annually worldwide as a byproduct of burning coal for electricity [25]. According to previous studies, fly ash is a crucial raw material, often serving as a partial replacement for Portland cement in concrete technology production [26, 27]. Researchers commonly agree that fly ash is rich in aluminosilicate, with sodium hydroxide and sodium silicate being the predominant alkali binder solutions [28–30].

The GGBS slag activity index recorded was 62% after seven days and 108% after twenty-eight days. The slag composition must include at least two-thirds of the total mass of CaO, MgO, and SiO_2, with the remainder primarily comprising Al_2O_3 and a few other oxides [31, 32]. The mass ratio of (CaO + MgO) to SiO_2 should exceed 1.0 [33, 34]. Mallikarjuna & Gunneswara Rao [35] stated that using GGBS and fly ash as source materials enables alkali-activated concrete to achieve significant strength, even when cured outdoors. The higher calcium content in GGBS is believed to enhance compressive strength. Notably, particle size, alkali concentration, shape, calcium content, and the origins of fly ash and slag influence the properties of alkali-activated concrete. Furthermore, calcium content dramatically affects strength and the development of compressive strength, with higher slag content leading to quicker strength development and greater compressive strength at an early stage [36]. Therefore, this study investigates the impact of NA presence on the fresh and hardened properties, as well as the durability performance of alkali-activated mortar in an ambient environment. It also evaluates the performance of alkali-activated mortar using various combinations of fly ash and ground granulated blast furnace slag (GGBS) as sustainable alternative building materials.

2. Sustainable Building Practices: Why Fly Ash and GGBS Outperform PC

Sustainable building practices have gained increasing importance recently as the construction industry strives to diminish its environmental impact and enhance energy efficiency. In this vein, the utilization of sustainable materials is pivotal, as they can help in reducing greenhouse gas emissions, conserving natural resources, and minimizing waste. Fly ash and ground granulated blast-furnace slag (GGBS) are two such materials that have proven to surpass OPC in sustainability aspects [37].

Fly ash, a by-product of coal-fired power plants, consists of finely ground coal particles captured by pollution control equipment. When incorporated into concrete, fly ash enhances the material's strength and durability, decreases its permeability, and augments its resistance to sulfates and acids. Additionally, fly ash has a lower carbon footprint than PC, as it repurposes a waste product and reduces the demand for virgin materials [38-41]. Similarly, GGBS, a byproduct of iron and steel production, when used in concrete, improves material durability and chemical attack resistance. It also boasts a lower carbon footprint than PC, thanks to its origin from industrial waste, thereby reducing the need for virgin materials. Moreover, GGBS has been found to diminish the heat generated during curing, making it ideal for large concrete structures [42-44]. While Portland cement is a fundamental component in concrete and widely used in construction, its production is energy-intensive and generates substantial greenhouse gases, including carbon dioxide. Additionally, the extraction of raw materials for OPC production, such as limestone, clay, and sand, can lead to significant environmental damage, including habitat destruction and soil erosion. OPC is also susceptible to chemical attacks, potentially causing concrete structures to deteriorate over time [44, 45]. Comparing the sustainability of fly ash, GGBS, and OPC involves considering embodied energy, carbon footprint, and resource depletion. In all these categories, fly ash and GGBS outperform PC, being produced from waste products and reducing the need for virgin materials. Furthermore, their application in concrete has demonstrated improvements in material durability and chemical attack resistance, thereby decreasing maintenance and repair needs over time [36, 46, 47].

In summary, the incorporation of fly ash and GGBS in construction presents numerous advantages over using Portland cement. These materials, derived from waste products, diminish the need for virgin materials and decrease the construction industry's carbon footprint. Moreover, they have shown to enhance the durability and resistance of concrete, reducing maintenance and repair needs over time. As the construction industry continues to emphasize sustainability, the adoption of fly ash and GGBS is likely to increase, presenting a sustainable alternative to traditional building materials [48].

3. Research Significance

The significance of this research lies in its exploration of sustainable building materials, specifically the use of fly ash and GGBS as alternatives to OPC in concrete. As the construction industry increasingly focuses on reducing its environmental footprint, the shift towards more eco-friendly materials becomes imperative. This study not only highlights the environmental benefits of using fly ash and GGBS but also sheds light on their practical advantages in terms of enhancing concrete's durability and strength. Firstly, the environmental impact of traditional construction practices, particularly the extensive use of PC, is a growing concern.

The production of OPC is energy-intensive, contributing significantly to greenhouse gas emissions. Additionally, the extraction of raw materials required for OPC causes considerable environmental degradation. In contrast, fly ash and GGBS, being by-products of industrial processes, offer a way to repurpose waste materials, thereby reducing landfill use and the need for virgin material extraction. Their lower carbon footprint is a vital factor in the pursuit of sustainable construction practices. Secondly, the enhanced performance characteristics of concrete made with fly ash and GGBS cannot be overlooked. This research underlines how these materials improve the strength, durability, and chemical resistance of concrete. These properties are particularly important for structures exposed to harsh environmental conditions or heavy usage. The use of these alternative materials can lead to longer-lasting buildings and infrastructure, reducing the need for frequent repairs and replacements. This not only has cost-saving implications but also minimizes the construction-related disruptions and environmental impacts over the lifespan of a structure.

Finally, this study has the potential to influence policy and practice in the construction industry. By providing empirical evidence of the benefits of using fly ash and GGBS, it could encourage policymakers and industry leaders to adopt more sustainable practices. The findings could guide regulations and standards, promoting the use of environmentally friendly materials. Moreover, this research contributes to the broader discourse on sustainable development, demonstrating practical ways the construction industry can adapt to meet global sustainability goals.

4. Material and Methods

4.1. Materials Characteristics

In the current study, nano-alumina (NA) with a ratio of 2% was utilized, characterized by particle sizes ranging from 20–30 nm in gamma shape. Three distinct types of binders were evaluated: high-calcium fly ash (FA) conforming to ASTM C 618 [49] standards, GGBS, and a combination of FA and GGBS used collectively as binding agents. Tables 1 and 2 detail the chemical compositions of these materials, as analyzed by X-ray fluorescence (XRF), and the physical properties of the binders. Furthermore, Figure 1 presents the physical appearance of FA and GGBS as observed under SEM analysis. Table 3 provides a comprehensive overview of the properties of nano-alumina. In this investigation, silica sand, with particles ≥ 500 µm, was employed as the fine aggregate.

The study also utilized a solution of sodium silicate (Na2SiO3) and sodium hydroxide (NaOH) as an alkali activator, maintaining a ratio of 2.5. A local supplier provided sodium silicate with a composition of Na2O at 17.98%, SiO2 at 28.1%, and H2O at 53.92% by mass. This study discovered that the sodium hydroxide was 98% pure, flaky in shape, and had a molarity of 12 M, which was identified as the optimal ratio [26, 50]. Additionally, the superplasticizer Glenium 51 was obtained from the BASF Company.

Table 1. Chemical composition and physical properties of fly ash and ground granulated blast slag

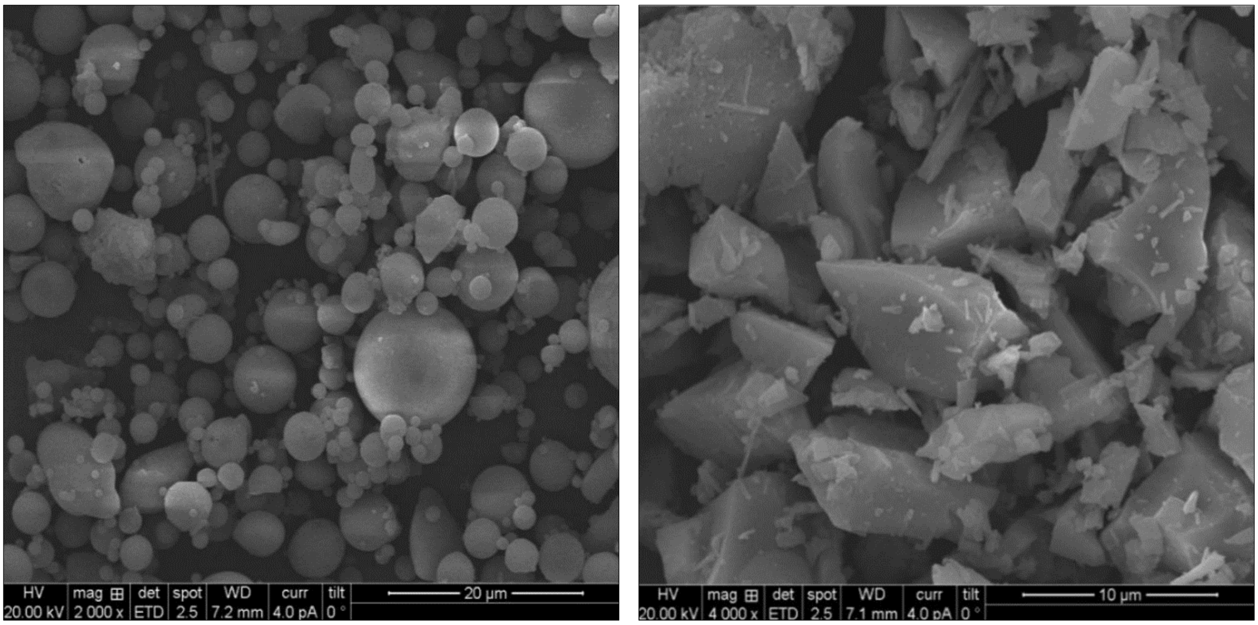
Component	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	TiO_2	SO_3	K_2O	P_2O_3	Mn_2O_3	Na_2O	SrO	LOI
FA (%)	15.48	48.43	17.15	11.96	1.35	2.68	0.82	0.41	0.4	0.17	0.0019	0.2	1.47
S (%)	47.75	28.17	8.6	0.42	3.89	0.94	1.45	0.29	0.06	0.47	0.02	0.076	0.2
NA (%)	-	-	99.9	-	-	-	-	-	-	-	-	-	
NS (%)		99.8											

Table 2. Physical properties of fly ash, ground granulate blast slag

Physical Properties	Specific surface area (m^2/kg)	Size (μm)	Density (kN/m^3)	Moisture content (%)	Color	Length (mm)
S	418	-	2.9	0.1	Light grey	-
FA	360	<45	<2.6	<1.0	gray	-

Table 3. Properties of nano alumina

Additives	Particle size (mm)	Purity	Color	Shape
NA	20–30	99.9%	White	Gama



Fly Ash GGBS

Figure 1. SEM analysis of FA and GGBS [51]

4.2. Mix Design

The mixtures incorporated 100% FA, 100% GGBS, and a 50% FA and 50% GGBS blend, each constituting a consistent total binder content of 650 kg/m^3. Drawing from prior research [50, 52-54], the study affirmed the Na2SiO3/NaOH ratio of 2.5 with 12 molarity of sodium hydroxide as the optimal proportion [55-57], hence adopting this value. The mixing process involved blending the dry materials, silica sand, FA, and GGBS, for 2.5 minutes. The nano-alumina was incrementally added to the mix and stirred for an additional 2 minutes. Subsequently, the alkaline solution and the superplasticizer were gradually introduced over a period of 1 minute to the dry mixture. Finally, the concoction was thoroughly mixed for two more minutes [14, 58]. In this experiment, nano-alumina constituted 2% of the binder's weight. Three identical specimens for each test were meticulously cast. For a visual representation of the sample preparation and testing sequence, please refer to Figure 2, which shows the flow diagram of the study's methodical approach, including how samples were prepared and tests were administered.

Table 4. Quantity of materials of alkali-activated concrete mortar (kg/m^3)

Mix. No	FA	GGBS	NA	Sodium Silicate	Sodium Hydroxide	Fine Aggregate	Superplasticizer
M1	650	-	-	92.9	232.1	1040	13
M2	-	650	-	92.9	232.1	1040	13
M3	325	325	-	92.9	232.1	1040	13
M4	637	-	13	92.9	232.1	1040	13
M5	-	637	13	92.9	232.1	1040	13
M6	318.5	318.5	13	92.9	232.1	1040	13

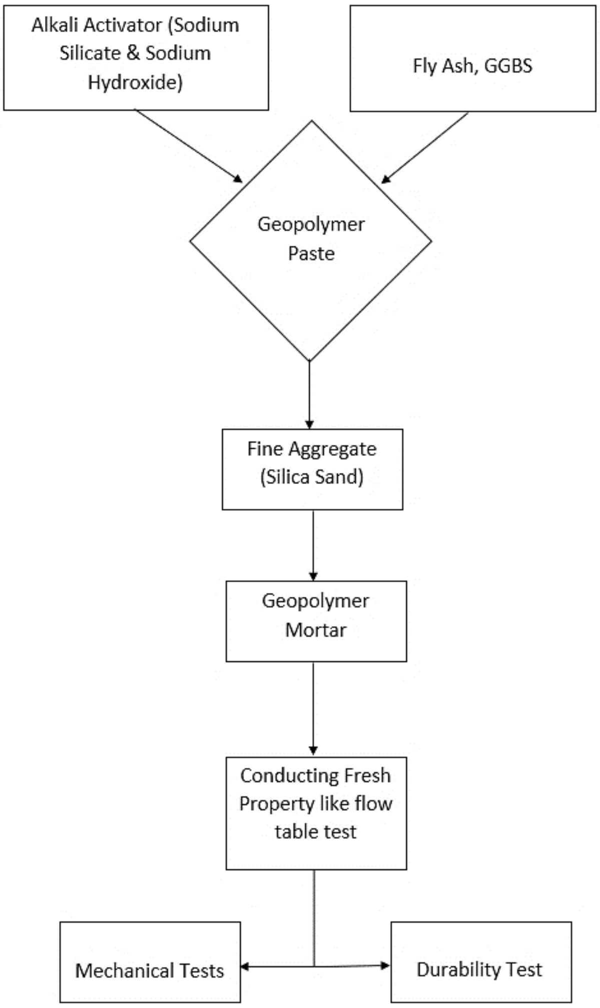


Figure 2. Experimental Workflow: A detailed flowchart that outlines the systematic methods for sample preparation and alkali-activated mortar (AAM) mix testing

4.3. Curing Condition

After casting, the specimens were shielded with plastic sheets to prevent the evaporation of the alkaline solution for 24 hours following the formation of alkali-activated concrete mortar. Post 24 hours, the specimens were carefully demolded and stored in a controlled laboratory environment at 23±3°C and 60% relative humidity for 28 days after casting.

4.4. Hardened Properties Test

The compressive strength of the AAM was evaluated in accordance with ASTM C109 [58, 59]. For each mixture, three identical specimens were tested [59]. The flexural strength was determined following ASTM C348 [60]. Specimens manifestly flawed or exhibiting strengths deviating by more than 10% from the average value of all specimens prepared from the same mix and tested concurrently were deemed non-representative and thus excluded from consideration.

5. Results and Discussion

5.1. Fresh Properties

5.1.1. Flowability

Figure 3 and 4 show the results of the laboratory test that evaluated the flowability of mixes of alkali-activated mortar (AAM). Mixtures that include fly ash (FA) and those that include ground granulated blast furnace slag have quite different flow properties (GGBS). Remarkably, AAM mixes including FA showed more flowability than those containing GGBS. Previous research has set expectations that are contradicted by this flowability discrepancy [61, 62]. The use of high-calcium fly ash as the FA in this investigation may explain why the perceived discrepancy was not as strong.

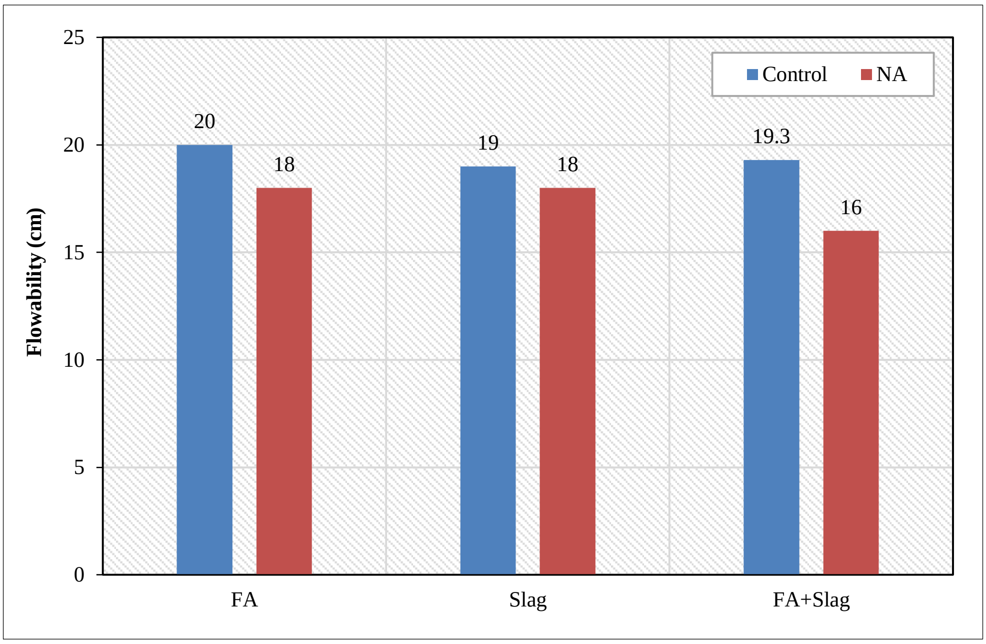


Figure 3. Flowability of AAM mixtures

Figure 4. Execution of Flow Table Test

5.1.2. Unit Weight

Figure 5 illustrates the unit weight results. Consistent with previous findings, AAM mixes with FA had a lower unit weight than those with GGBS, owing to GGBS's higher specific gravity. The addition of NA increased the unit weight of AAM mixes, regardless of the binder type, indicating that NA enhances the mixes' density and concrete microstructure [56, 57]. Research has shown that concrete's unit weight increases with the addition of nano-materials, while its permeability decreases [63].

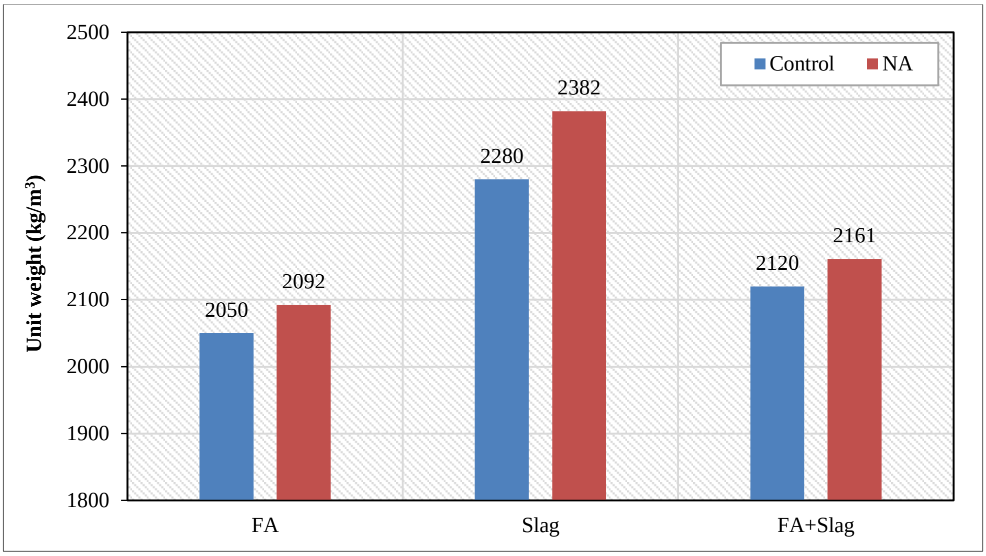


Figure 5. Unit weight of AAM mixtures

5.2. Mechanical Properties

5.2.1. Compressive Strength

Figure 6 shows the compressive strength values of AAM specimens, which show interesting trends in the effect of various binders. Incorporating ground granulated blast furnace slag (GGBS) into AAM mixtures clearly results in higher compressive strength than using fly ash alone (FA). This finding is in line with predictions, considering GGBS's pozzolanic reactivity and additional cementitious characteristics. Figure 7 depicts the sample's compressive test and can be used as an example.

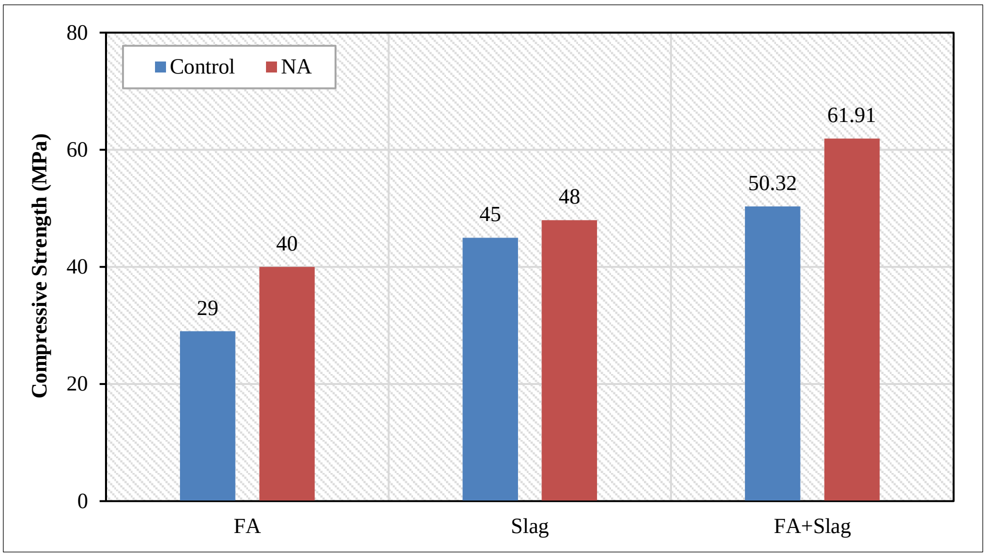


Figure 6. Compressive strength of AAM mixtures

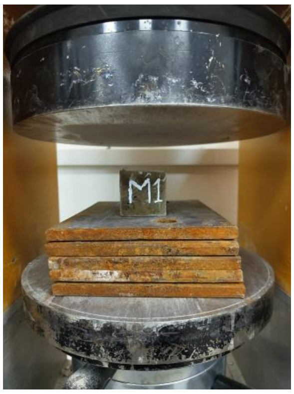


Figure 7. Compressive Testing of AAM Sample

Using a synergistic combination of the two binders, with half FA and half GGBS, produces mixes with the highest compressive strength. All the materials' reactions and activations contributed to this outstanding performance, which is a result of a synergistic impact that improves the AAM's mechanical properties in general.

Furthermore, one of the most important factors in increasing compressive strength is the incorporation of nano-silica (NA) into the AAM matrix. Consistent with other results in concrete investigations [56, 57], this discovery reiterates the positive effect of nano-silica on the mechanical properties of materials activated by alkalis. It should be noted that mixes including FA and the combined binder ingredients exhibit a more pronounced enhancement ratio compared to blends having only GGBS. The significance of taking binder combinations into account when optimizing AAM characteristics is highlighted by this discrepancy, which implies a distinct interaction between nano-silica and the individual binders. Mixes including FA and the combined binder ingredients had a more noticeable enhancement ratio compared to mixes containing only GGBS.

5.2.2. Flexural Strength

The flexural tensile strength of AAM (see Figure 9), shown in Figure 8, also varied with the binder type. Consistent with prior research, AAM specimens with FA had lower flexural tensile strength compared to those with GGBS, attributed to GGBS's higher reactivity [62]. The addition of NA increased the flexural tensile strength of FA-inclusive mixes, but had a detrimental effect on mixes with GGBS. This indicates that NA enhances the bond strength and microstructure of concrete in FA-inclusive mixes [58]. Studies have found that incorporating 2% nano-materials increases concrete's flexural tensile strength and decreases its permeability [14]. Specimens with 2% nano-alumina acted as fillers, occupying pore spaces and enhancing the interaction between binder phases (FA and GGBFS). The AAM matrix's role is significant in enhancing the material's overall strength, as observed in SEM captures where the cohesion between reactive materials and pore spaces is strengthened with the addition of nano-alumina [57].

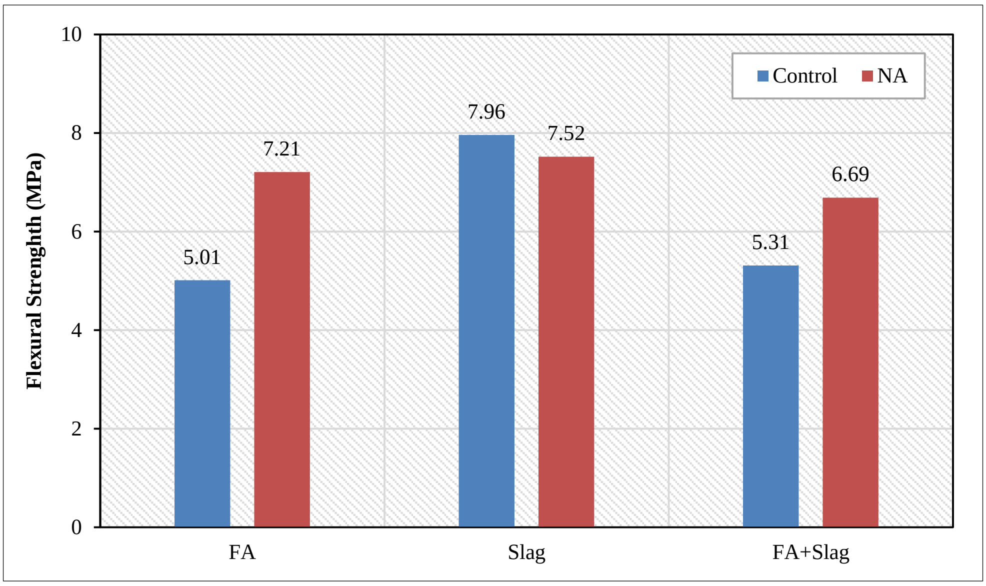


Figure 8. Flexural tensile strength of AAM mixtures

Figure 9. The apparatus used for conducting flexural strength tests, featuring the test devices and samples of alkali-activated mortar (AAM)

5.3. Durability Properties

Indeed, studying the water absorption characteristics in AAM mixtures plays a crucial role in understanding their durability properties. This section discusses the water absorption percentages of various AAM specimens, as shown in Figure 10. In general, the water absorption percentages observed range from 10.04% to 11.66%, indicating a moderate variance influenced by the constituent materials. Specimens with FA show a water absorption of 10.06%, which is relatively lower compared to GGBS at 11.02%. This suggests that FA may impart a denser microstructure to the AAM, consequently reducing the porosity and absorption capacity. In specimens where FA and GGBS are combined, the water absorption percentage is 10.26%, illustrating a slight effect where the combination of both materials does not significantly deviate from the individual values. This indicates that the complementary properties of FA and GGBS in AAM might contribute to an optimized pore structure, balancing the material's overall porosity and density. The addition of NA, particularly in combinations with FA (11.66%) and GGBS (11.15%), results in higher water absorption rates. This increase can be attributed to the high surface area of NA, which potentially increases the porosity within the AAM matrix. The lowest water absorption rate is observed in the FA+GGBS+NA combination at 10.04%, which is intriguing as it suggests that the trio-combination effectively counterbalances the individual effects of each constituent. The enhanced packing density and improved microstructural integrity achieved through this combination could be responsible for this reduced absorption rate.

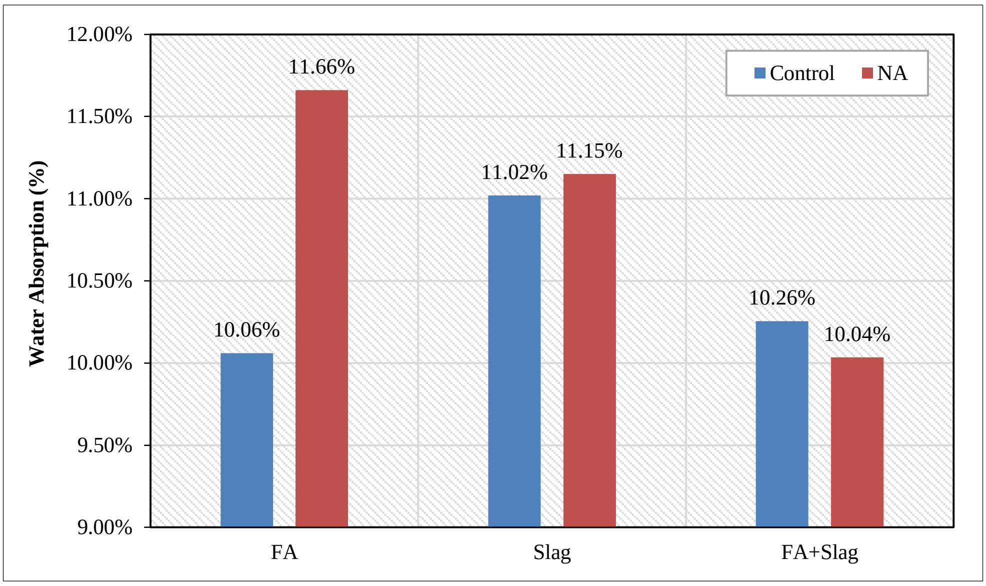


Figure 10. Water absorption of AAM mixtures

6. Conclusions

This study explored the fresh and hardened properties of AAM with an emphasis on the role of NA as a substitute for binder materials. The major findings and implications from this research are as follows, along with identified limitations and directions for future research:

- The incorporation of NA was found to negatively affect the flowability of AAM mixtures. This effect was more pronounced in mixtures that included FA compared to those with GGBS. This suggests a nuanced interaction between NA and different binder types that requires further exploration.
- All AAM mixes, regardless of the binder type, experienced an increase in unit weight with the addition of NA. This finding indicates that NA contributes to a denser mix and potentially enhances the microstructure of the concrete.
- The study confirmed that NA significantly improves the compressive strength of AAM, in line with previous research. Mixtures incorporating FA and combined binders exhibited greater strength improvements compared to those with GGBS alone.
- The flexural tensile strength of AAM specimens increased with the addition of NA in FA mixes, while a decrease was observed in GGBS mixes. This suggests that the pore-filling mechanisms of NA vary depending on the binder type, impacting the overall strength differently.

While this research offers an extensive evaluation of the mechanical and durability aspects of AAM with NA, it is limited by its focus on static conditions and a singular NA concentration of 2%. The absence of dynamic testing leaves a gap in understanding AAM's response to varied loads and environmental stresses, crucial for applications in seismic zones or fluctuating climates. Moreover, the controlled room temperature of the experiments does not reflect the range of climatic conditions AAM might face in real-world scenarios. Future research should, therefore, prioritize dynamic testing, explore the effects of diverse environmental conditions, investigate a broader spectrum of NA concentrations, and delve into the microstructural analysis of AAM with NA to offer a more comprehensive understanding of its properties and applicability.

7. Declarations

7.1. Data Availability Statement

The data presented in this study are available in the article.

7.2. Funding

The author received no financial support for the research, authorship, and/or publication of this article.

7.3. Conflicts of Interest

The author declares no conflict of interest.

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