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Research Article

Accelerated microwave curing of hybrid geopolymers with nano-silica for enhanced physico-mechanical properties

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ABSTRACT

This paper presents the microwave curing method as an alternative to conventional thermal curing of hybrid (fly ash-slag) geopolymer mortars (GMs) to achieve comparable performance with significantly reduced curing times. This study aimed to ascertain the impact of varying nano-silica contents (0.5%, 0.75%, and 1%) on the geopolymer matrix to identify the optimal dosage for enhancing densification and bond improvement phases. Mixture proportions were designed to achieve high mechanical and durability performances. The activator/binder (A/B) ratio was set at 0.71, the sodium silicate to sodium hydroxide ratio at 1.5, and the sand/binder (S/B) ratio at 2.5. This study considered two curing methods: thermal curing at 80 °C for 24 hours and microwave curing at 119 W for 3 minutes. The latter method produces equivalent thermal effects in a significantly shorter time. Physical properties tested after seven days included water absorption, porosity, and mechanical properties related to compressive and flexural strength. The results demonstrated that incorporating NS markedly enhanced the physical and mechanical characteristics. Moreover, microwave curing has been identified as a promising approach for producing hybrid geopolymers, offering a low-energy and high-performance alternative.

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1. INTRODUCTION

Sustainable construction has become the most important focus area of modern research and industrial applications, considering the urgent need to reduce the environmental impacts associated with traditional building materials. Portland cement (PC) remains the backbone of conventional construction. It is well known for its high emission of CO_2 into the environment due to its value chain engagement in intensive energy consumption in its manufacturing process. PC production is estimated to account for about 7% of total CO_2 emissions worldwide, primarily due to the calcination of limestone and high-temperature processes. This ecological footprint and the depletion of non-renewable resources raised the interest in investigating alternative materials with a lower environmental impact. Geopolymer mortars (GMs) synthesized with industrial by-products like fly ash (FA) and ground granulated blast furnace slag (GGBFS) represent a promising class of sustainable construction ma-

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terials. Such binders efficiently utilize wastes and offer improved mechanical, thermal, and chemical resistances, thus finding applications in variants of infrastructure development. GMs are a type of alkali-activated aluminosilicate material, and the mechanism of their synthesis is based on the dissolution and polycondensation of silica and alumina precursors [1–5]. The resulting three-dimensional framework forms a compact matrix with excellent strength and durability. The three most prevalent parameters influencing the mechanical behavior and durability of GMs are composition, type of activator, and curing conditions. Although the raw materials and their chemical formulations are of utmost importance, the curing techniques stand at the core of determination for all properties of the GMs [6–10]. Hence, traditional thermal curing, if applied, is very effective even for a prolonged time under higher temperatures to increase the rate of geopolymerization. It improves the dissolution of aluminosilicate precursors, allowing for easier gel formation and higher matrix densification, improving mechanical properties like compressive strength and flexural strength. However, high energy demand and long processing times for thermal curing have become quite a big barrier regarding scalability and cost-effectiveness. Newly developed curing methods have recently been among the potential alternatives to traditional thermal curing; microwave curing has received increased interest due to its efficiency in energy use and speed of processing. Unlike heat-curing, which relies on outside heat transfers, microwave curing depends upon heat generated internally through the interaction of microwave radiation with polar molecules in the material. This permits uniform and speedy heating that, in many cases, greatly reduces the curing time and produces comparable material properties or even superior to the best current practices. Indeed, it has been demonstrated that microwave curing can enhance early-age strength in GMs, reduce pores, and increase the matrix's general densification. Besides this, the energy consumption from microwave curing is considerably lower than that of conventional thermal curing, hence meeting the bigger principles underlying sustainability and cost efficiency in construction. The other key factor that influences GMs' performance is including supplementary materials such as nano silica. Nanosilica (NS) possesses a high surface area and reactivity, acting in a dual role on GMs. NS acts as a micro filler to fill up the voids among the matrixes, reducing porosity and increasing their density. This inorganic nanofiller agent acts as an additional source of silicate ions during the geopolymerization reaction, increasing the population of cross-linked aluminosilicate gels and, strengthening the matrix and enhancing mechanical properties. NS incorporation has been found to enhance GMs' compressive and flexural strengths while increasing their resistance to chemical and physical degradation. However, the effectiveness of NS is attached to its dosage and dispersion in the matrix, besides the curing conditions. In this respect, incorporating NS and microwave curing shows several synergistic effects that could be applied to develop high-performance geopolymers at lower energies with improved sustainability. Thus, microwave curing reinforces the interaction of nano silica addition by enhancing material strength by fast activating the GM matrix. This combination has the potential to overcome some of the limitations of the currently used curing methods, with the added advantage of offering improved mechanical and physical properties. Notwithstanding the optimistic test results obtained from the few studies that have been performed, comprehensive research is still sorely needed to optimize the interaction between microwave curing parameters with NS content and GM composition [11–13]. The practical application of GMs in construction requires a profound understanding of their mechanical and durability properties under various curing conditions. Compressive strength, symbolic of a material's axial load-carrying capacity, is one of the most vital parameters in structural applications. Similarly, important is the flexural strength, a representative of the material's resistance to bending forces, which is equally vital for usability assessment in load-bearing and thin-section elements. Apart from mechanical properties, porosity, water absorption, and capillarity are considered some of the most important physical properties concerning GMs' durability and long-term performance under aggressive environmental exposure. The development of GMs with superior performance metrics along these parameters can go a long way toward their widespread use in construction. Microwave curing is such a disruptive technology that can help restructure the production aspects of GMs and overcome their inherent inefficiencies. In this respect, the rapid capability of processing reduces its energy footprint in the curing process, apart from reducing the production times. Microwave radiation thus provided uniform heating and maintained the material properties consistent without thermal gradients that might have resulted in microcracking and other defects [14–19]. Because of the prospects of NS addition, microwave curing signifies a paradigm shift in the studies conducted on sustainable and high-performance construction materials.

This paper studies the effects of microwave curing and nano-silica addition on some physical and mechanical properties of GMs made using locally available materials in Turkey. Microwave curing generally provides considerable energy economy and significantly reduces curing time. At the same time, high internal temperatures with limited performance loss were attained compared to conventional thermal curing. NS may act as a micro-filler and a reactive additive to achieve matrix densification through reducing porosity, with increased silicate ions strengthening the geopolymer gel network. Thus, GMs were prepared with the addition of NS at different levels of 0.5%, 0.75%, and 1%, and their mechanical properties like compressive and flexural strengths along with water absorption and apparent porosity were evaluated under ambient and thermal and microwave curing methods. ANOVA test was conducted to interpret the developed trend in these tests at a 95% confidence level.

Table 1. Chemical compositions of materials

Components (%)	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	K_2O	Na_2O	LOI	MnO
GBFS	40.55	12.83	1.10	0.75	35.58	5.87	0.68	0.79	0.03	–
FA	58.75	25.24	5.76	–	1.46	2.22	–	0.60	0.015	–

GBFS: Granulated blast furnace slag; FA: Fly ash.

Table 2. GM mix design (g)

Mixing code	GBFS	FA	Sand	Na_2SiO_3	NaOH	NS
SFA	225	225	1125	255.6	127.8	0
SFA05NS	225	225	1125	255.6	127.8	2.25
SFA075NS	225	225	1125	255.6	127.8	3.375
SFA1NS	225	225	1125	255.6	127.8	4.5

GBFS: Granulated blast furnace slag; FA: Fly ash; NS: Nanosilica.

2. MATERIALS AND METHODS

2.1. Materials

FA was obtained from Zonguldak/Turkey. GGBFS was purchased from Bolu/Turkey, and the chemical properties of both binders are shown in Table 1. The specific gravity of FA and GGBS is 1.96 and 2.91, respectively. The study used sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) as chemical activators. NaOH purity value is higher than 99%, Na_2SiO_3 has a percentage of 27.2 SiO_2, 8.2 Na_2O, and its pH value is between 11 and 12.4.

2.2. Mix Design

The binder is composed of an equal proportion of FA and GGBFS, with NaOH and Na_2SiO_3 acting as activators in a 1.5:1 ratio and an A/B ratio of 0.71. This ensures a balance between the workability and strength of the binder. NS is incorporated at 0%, 0.5%, 0.75%, and 1% by binder weight, resulting in enhanced densification, reduced porosity, and augmented mechanical performance. GMs are designated as SFA, SFA05NS, SFA075NS, and SFA1NS, where SFA represents the control series devoid of NS, while the other codes indicate series with 0.5%, 0.75%, and 1% NS by binder weight, respectively (Table 2). Fine aggregates comprise natural sand with a sand-to-binder ratio of 2.5:1, thereby ensuring the production of GM with a consistent texture. The mixture is combined in a Hobart mixer for five minutes to ensure uniformity. GMs are subjected to three curing regimes: microwave, thermal, and ambient. In the case of microwave curing, the specimens are subjected to microwave energy at 119 W for three minutes immediately following their casting [20, 21]. This process induces the reaction kinetics and partial polymerization necessary for the specimens to undergo the desired chemical changes. In the case of thermal curing, the specimens are initially left at room temperature for 24 hours to achieve the initial setting, after which they are exposed to 80°C for a further 24 hours to maximize polymerization. Ambient curing is employed as a control, simulating standard curing conditions without additional heat treatment. Mixture design balances sustainability, advanced curing techniques, and local material utilization, thereby providing a robust framework for evaluating the effects of NS and curing methods on physical and mechanical properties. Furthermore, statistical analyses are employed to quantify these effects, ensuring a comprehensive understanding of the performance of GMs.

2.3. Methods

Unit weight, water absorption, and porosity tests on GMs were carried out according to ASTM C-642 [22] standard. Assesses the workability of GM using the flow table following ASTM C-1437 [23] standards. GMs were produced in 50x50x50 mm cubes, and their CS was applied in an automatic test device per TS EN 12390-3 [24] standard. Three prism samples with dimensions of 40x40x160 mm were used to determine the FSs (TS EN 12390-5 [25]). GMs were loaded from a single point in the automatic testing machine according to the standard, and the tests were carried out on the 28th day (Fig. 1).

3. RESULTS AND DISCUSSION

3.1. Fresh Properties

Figure 2 represents the relation of NS content to flowability for GMs. It exhibits a regular decline in flowability with an increase in the NS content from 0% (SFA) to 1% (SFA1NS). For the SFA series, the flowability without NS was 15 cm, representing the most workable mix in the series. Adding NS by 0.5% resulted in a fall in flow to 14.2 cm, a loss of 5.33%. With further increases up to 0.75% SFA075NS and 1% SFA1NS, the values fall within the range of 13.5 cm and 12.8 cm, respectively, relating to 10% and 14.67%. These represent the reduction in values due to the direct attack of NS on the viscosity and particle mobility of the GM matrix. Declining flowability is attributed to NS's extremely high surface area and reactive nature; these increase water demand and densify the mix. The absorbed free water by NS particles decreases the effective water content available for lubrication between particles. This increases the viscosity of the mix. Besides, the increase in the particle packing density due to NS decreases the free-flowing ability of the matrix. For instance, at 1% NS, SFA1NS develops considerably higher stiffness than the controlled series SFA. This is one of the trade-offs between matrix densification and workability. This behavior characterizes the challenge of maintaining adequate flowability when high nano-silica proportions are used, especially in practical applications involving large-scale casting and placing. A comparison of the impact of NS in the series evidences that the dependence is nonlinear, while the highest dosage of NS results in the most significant reduction of flowability. From 0% NS (SFA) to 0.5% NS (SFA05NS), the reduction of relative

Figure 1. Curing setup and testing of GMs.

values is less compared with the decrease from 0.75% NS (SFA075NS) to 1% NS (SFA1NS). This means that the NS effect on workability becomes more and more evident with its higher dosages; thus, the measures taken to adjust mix proportions or apply some admixtures like superplasticizers should be more substantial. Although these reductions occur, the inherent advantages of NS addition in mechanical and durability enhancement justify its inclusion due to improved compressive strength, flexural strength, and reduced porosity. For example, mixes with higher NS content, even though less workable, function satisfactorily for a long time under durability and heavy loads. Hence, they can be used for structural components where fluidity during placement is not critical. In practice, the adverse effect of loss of flowability is commonly partly offset by optimization of the water-to-binder ratio or activator proportions. When this is not sufficient, needed flow characteristics can be maintained either by modifying the sand-to-binder ratio or using high-range water-reducing admixtures in manners that do not prejudice the integrity of the matrix. These observations confirm the need for a careful balance between the achievement of adequate workability and the exploitation of the performance benefit of nano-silica, especially in applications where facility of placement and high mechanical strength are both required. Also, it was strongly

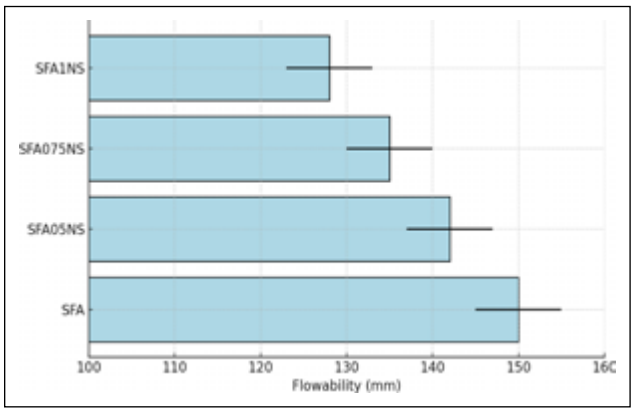

Figure 2. Flowability of GMs under different curing methods.

indicated by the observed trends that complete testing is immensely vital in tailoring the GM design to the intended application, especially in immediate workability and long-term performances [26–30].

3.2. Physical Properties

Figure 3 presents the effects of nano-silica content series SFA, SFA05NS, SFA075NS, and SFA1NS on water absorption and porosity for three different curing methods: thermal, microwave, and ambient. Figure 3 illustrates complex

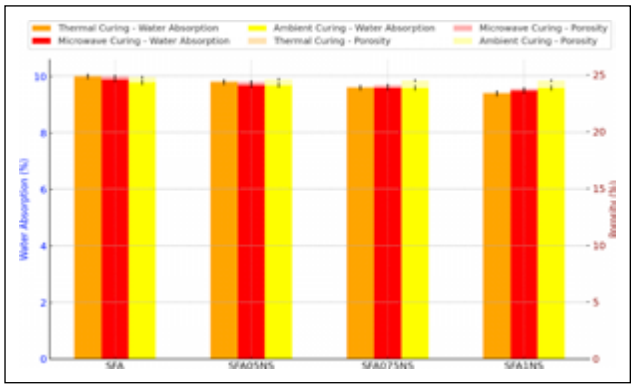

Figure 3. Water absorption and porosity of GMs under different curing methods.

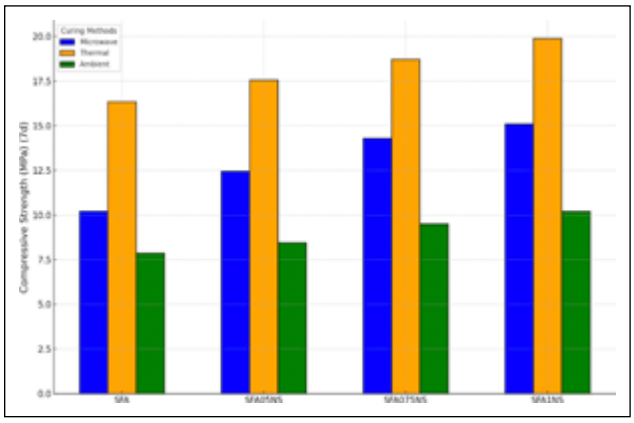

Figure 4. Compressive strength of GMs under different curing methods.

features of the densification and permeability reduction mechanisms. Water absorption trends indicate that thermal curing achieved the maximum reduction from 10.0% for SFA to 9.4% for SFA1NS, constituting a 6% reduction. This trend confirms that long-term high-temperature exposure favorably promotes the dissolution of the aluminosilicate precursors, accelerating geopolymerization and developing a dense, impermeable matrix. Microwave curing shows less effectiveness than thermal curing yet still exhibits a reasonable reduction in water absorption from 9.9% for SFA to 9.5% for SFA1NS, corresponding to a decrease of 4%. This result implied that microwave energy could quickly heat the matrix and promote partial densification, which is nevertheless limited by a three-second curing time compared to thermal curing.

On the other hand, ambient curing presents the least water absorption reduction from 9.8% SFA to 9.6% SFA1NS, only a 2% reduction, because of the slower reaction kinetics and incomplete geopolymerization under room temperature. The porosity trends are also parallel to those of water absorption. Again, thermal curing is performing better when comparing others, as it decreases from 25.0% with SFA to 23.5% for SFA1NS, corresponding to an increase of 6%, showing that superior densification and compactness were achieved via maintained heat exposure. Microwave curing reduces the porosity from 24.9% of SFA to 23.8% of SFA1NS, which accounts for a 4.4% decrease. Though less significant than thermal curing, it reinforces the development of microwave energy use as one of the promising treatment methods, which reduces voids and improves the microstructure. However, when curing by ambient exposition, the porosity decreases only from 24.8% to 24.5%, a very moderate 1.2% reduction, further showing the limited potential of this curing method for achieving significant improvement in densification and structural refinement. Overall, from all the trends, one can notice that with the increase in nano-silica content, higher water resistance and higher porosity reduction are progressively obtained for all curing methods. NS acts as a reactive microfiller, which increases the filler density by reducing the void spaces and provides additional silicate ions to strengthen the gel structure of the GM [26–30]. Among the curing methods, thermal curing offers the best results since it can sustain higher temperatures for longer, aiding complete geopolymerization and densification. Microwave curing is a much more energy-effective treatment that gives results comparable, or near equivalent, to those obtained by thermal curing in much shorter times; further optimizations may ultimately bridge the gap. Ambient curing gave the least effect out of the three methods, but again, this sees improvements with the addition of NS, although less dramatic than microwave curing. The clear evidence of synergy between nano-silica content and advanced curing methods in enhancing durability and the mechanical performance of GMs has shown clear implications for material design and process optimization in different construction applications.

3.3. Mechanical Properties

Results of the compressive strength values of hybrid-GMs were evaluated for different nano-silica ratios and curing methods and are presented in Figure 4. It was indeed found that there was a systematic and progressive increase with increasing NS content, reflecting consistently in the densification of the matrix and mechanical performance. For the baseline mixture, without NS SFA, the thermal curing gave the best result, a value of 16.34 MPa against 10.21 MPa for microwave-cured and 7.88 MPa for ambient-cured samples. These results agree with the performance expected of an unmodified GM under various curing conditions since continuous exposure to a high temperature expedites the reaction kinetics and enhances the consolidation of the GM matrix. Microwave curing reached 62.47% of the strength of thermal curing, testifying to its quickening of geopolymerization reactions even with reduced exposure time. Ambient curing trailed far behind, penalized by the limited response kinetic at room temperature, but it contributed a cost-effective baseline for comparison. All three methods provide increased compressive strength with the addition of SFA05NS, indicating that NS acts catalytically in developing properties for an improved GM matrix. With thermal curing, the improvement was about 7.47%, reaching a value of 17.56 MPa, indicative of NS's ability to enhance gelation and particle packing with long thermal exposure.

On the other hand, microwave curing offered a better improvement of about 21.90%, reaching 12.45 MPa, because NS amplified this method's rapid heat-induced densification characteristics. Ambient curing presented a more modest delivery of 7.23%, reaching 8.45 MPa, indicative of NS's contribution even within low-activation environments. By this stage, the result agrees with values from literature in cases of low NS dosage, as it is common to have incremental improvements in the early stages of NS addition. Increasing the NS addition rate to 0.75% (SFA075NS) induced higher increments; thus, thermal curing attained as high as 18.72 MPa, representing a percentage increase of 14.56% over the control. This result underlines the synergy between high dosage rate and thermal activation, which enhances the development of a more compact and cross-linked-GM matrix. Microwave curing registered a growth of 39.99% at 14.30 MPa, demonstrating the efficiency of such a method in using NS as the accelerator for the consolidation of the matrix. Ambient curing increased by 20.56% to reach 9.50 MPa, which, although far lower than others, constitutes a remarkable enhancement for an ambient condition. These results are within the expected range, though higher values from this dosage of NS for microwave curing could be expected; hence, there may still be room for optimization of either temperature control or curing duration. At 1% NS content, the compressive strength for SFA1NS reached its peak for all methods, having obtained a value through thermal curing of 19.88 MPa, obtaining a cumulative gain of 21.65% over the baseline. This was equal to the highest performance ever reported in NS-reinforced geopolymers with high-temperature curing, as prolonged heat application encourages the complete dissolution of aluminosilicates and maximizes gel formation. Microwave curing, therefore, yielded a compressive strength of 15.10 MPa, an outstanding increase of about 47.87%, and its place was secured as a time-saving, energy-efficient alternative to thermal curing. Ambient curing, while still trailing, chalked up a gain of 29.44% to reach 10.20 MPa, showing the capabilities of NS for mechanical performance improvements even under suboptimal curing conditions.

Although such a set of results follows the trends from GM literature, the values of thermal curing could surpass 20 MPa once the times of heat exposure and activation ratios are optimized, especially at higher dosages of NS—this dual role of NS and a reactive agent-constitutes the backbone for these enhancements. As a micro filler, NS filled the voids in the matrix, which reduced its porosity and increased the density of the GMs. The heat energy supplied under curing thermal and microwave conditions favored dispersion and integration of the NS particles, causing this densification effect to be more evident. NS is an active agent with additional silicate ions that participate in geopolymerization and form strong and interlocked gel structures. Improved integrity of the matrix and reduced micro-defects result in increased compressive strength. The curing by microwave, while shorter, showed the ability to produce properties almost comparable with those of the thermally cured specimens, thus indicating that fast heating was performing its job in accelerating reaction kinetics [26–30].

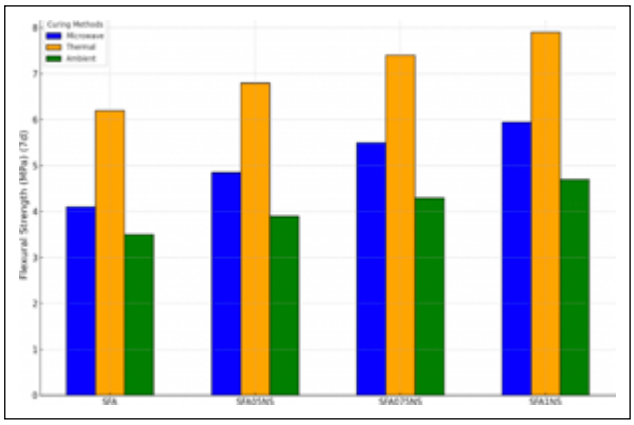

Figure 5. Flexural strength of GMs under different curing methods.

It can be observed from Figure 5 that the flexural strength of hybrid GMs increased significantly and consistently with the gradual addition of NS. Among the various applied curing methods, the highest value of flexural strength for the baseline mixture SFA was recorded through thermal curing at a value of 6.20 MPa, followed by microwave curing at a value of 4.10 MPa, and thirdly, ambient curing method at a value of 3.50 MPa. This result agrees with the expected behavior of the thermally cured geopolymers, which can achieve optimal reaction kinetics conditions with a longer period under high temperatures and improve the tensile bond strength of the aluminosilicate gel. The Microwave curing reached 66.13% of the strength of thermal curing. It showed its capability for rapidly promoting geopolymerization, while the degree of Cure was slightly less than that ofhermal curing. The lowest flexural strength was recorded for the case of ambient curing, naturally due to incomplete tensile-resistant bond formation within the matrix, constrained by the limited reaction rates at room temperature. Adding 0.5% nano-silica produced a detectable improvement in resistance to flexural stresses for all curing methods. In thermal curing, the enhancement was 9.68%, reaching a value of 6.80 MPa, which again evidenced that nano silica could enhance the gel network due to its contribution of reactive silicate species to this strengthening in the tensile integrity of the matrix. On the other hand, microwave curing exhibited a more abrupt enhancement of 18.29% to 4.85 MPa since the accelerated heating mechanism of microwaves amplified nano silica dispersion and interaction within the matrix. Ambient curing exhibited a moderate gain of 11.43% at 3.90 MPa, indicating that nano silica can partly compensate for the slower reaction kinetics under room temperature conditions. At 0.75% nano-silica, the improvement in flexural strengths became more pronounced. Thermal curing recorded a strength of 7.40 MPa, representing an increase of 19.35% over the baseline, reflecting the synergistic effect of higher nano silica content and sustained thermal activation. Microwave curing significantly improved by 34.15% to attain a value of 5.50 MPa since nano silica enhanced the fiber-matrix bonding

Table 3. ANOVA results for physical and mechanical properties of GMs

Property	F-Statistic	p-Value
Water absorption (%)	0.8620639108765783	0.4544251661505388
Porosity (%)	0.003418452169689903	0.9965886774244932
Compressive strength (MPa)	30.847268624182604	9.372489021240787e-05
Flexural strength (MPa)	18.869639794168087	0.0006032845854845374

and reduced microcracking due to the increase in gel cohesion. Ambient curing was better by 22.86%, attaining 4.30 MPa, the lowest among the other two, but still suggesting that nano silica can incrementally enhance tensile properties even under less than ideal cure conditions. Flexural strength reached a maximum in all three curing modes at 1% nano-silica (SFA1NS). The highest, 7.90 MPa, was obtained from thermal curing, representing a cumulative percentage improvement of 27.42% above the baseline. Therefore, thermal curing favors maximum nano silica potential in matrix strengthening through complete gelation and elimination of weak points in tension. The second closest was microwave curing, at 5.95 MPa; very impressively, enhancement of as high as 45.12% was recorded, showing how effective rapid heating is in enhancing tensile properties. Although unimpressive and ineffective, ambient curing was far from an unimpressive improvement ratio of 34.29%, reaching 4.70 MPa and consistently improving tensile performance by nano-silica even in less reactive environments. The improvement in flexural strength with nano silica content is due to its dual role as a microfilter and reactive additive. As a micro filler, it fills up empty spaces in the GM matrix, optimizing its density and reducing the micro defects that can lead to tensile failure. Such an effect is more pronounced under thermal and microwave curing conditions on account of the facilitation provided by heat energy for the uniform incorporation of NS into the gel structure. As a reactive additive, NS provides additional silicate ions that strengthen the aluminosilicate gel, enhancing tensile strength, restricting crack propagation, and improving flexural performance. The reasons behind achieving such high strength by microwave curing can be further elaborated by its ability to cause a heat rise very quickly and, accordingly, assist in developing a more homogeneous matrix. For this reason, microwave curing could be quite feasible as an alternative to thermal curing in those applications where time is of the essence. However, the rather inferior flexural strength concerning the corresponding thermal curing for higher nano silica dosages indicates that full geopolymerization might not have been achieved due to incomplete heat diffusion or insufficient curing time. Ambient curing, though less effective in general, also showed a consistent improvement as nano silica was incorporated, especially at higher dosages. This confirms the trend of nano-silica, adding to improved tensile strength through better gel cohesion and reduced porosity without any fitting external heat. Such improvements make the ambient curing option feasible at low-cost applications where a moderate tensile performance is acceptable [26–30].

3.4. Statistical Properties

ANOVA results provide a comprehensive evaluation of the impact of curing methods on GMs' critical physical and mechanical properties, explicitly focusing on water absorption, porosity, compressive strength, and flexural strength (Table 3). The analysis reveals statistically significant differences for compressive strength ($F=30.85$, $p<0.001$) and flexural strength ($F=18.87$, $p<0.001$), confirming the crucial role of curing methods in enhancing the mechanical performance of these materials. Thermal curing is the most effective method, consistently delivering the highest compressive and flexural strengths due to its prolonged high-temperature exposure, accelerating geopolymerization, and densifying the matrix. Microwave curing shows intermediate performance, leveraging rapid internal heating to improve mechanical properties within shorter durations, while ambient curing, constrained by limited reaction kinetics, results in the lowest strength values. Conversely, the properties of water absorption ($F=0.86$, $p=0.454$) and porosity ($F=0.003$, $p=0.997$) exhibit no statistically significant differences across curing methods, indicating that these durability-related parameters are primarily influenced by the incorporation of nano-silica, rather than the curing method itself. NS acts as a micro filler, uniformly reducing porosity and improving water resistance by minimizing voids and increasing matrix compactness, regardless of the curing approach. This consistency across curing methods suggests that the effects of NS on these properties dominate over the thermal or mechanical energy provided by the curing processes.

4. CONCLUSIONS

- Adding NS at an optimum dosage of 1% provides the maximum gains in compressive strength. It was also reported that the highest value reaches as high as 21.65% under thermal curing and as high as 47.87% under microwave curing. It realized relatively increasing trends through remarkable flexural strength values for thermal and microwave curing, reaching 27.42% and 45.12% accordingly, at 1% NS. This evidences their potential to improve tensile integrity or reduce the matrix's micro-defects.
- All the curing methods proved to yield a significant statistical difference from each other statistically since the p-value is below 0.001.
- Durability, mainly determined by water absorption and porosity in water, was related much to the composition itself.

- Several technical and logistical challenges in scalability regarding microwave curing in industrial applications pertain to how one can maintain consistency and uniform heating across more significant volumes of GMs. In addition, managing costs associated with microwave equipment will be required while meeting the need for energy efficiency to maintain sustainability advantages. Uniform heating becomes particularly critical in such a case because the variation in temperature distribution might result in heterogeneous geopolymerization, leading to weak zones or cracks in the matrix. This problem can, however, be minimized if more sophisticated microwave generators that could provide frequency modulation for homogeneous energy distribution within the material can be used. Modulus designs the curing units in batches of building elements-prefabricated panels or blocks manufactured within the current production flow. Besides, energy consumption by microwave curing, though much below that of conventional thermal methods, needs optimization to balance between rapid curing rates and energy efficiency, which could be attained through exposure times and power settings tailored based on the size and composition of the material concerned. In the case of long-term durability, GMs cured by microwaves are found to show adequate resistance against environmental actions like freezing-thawing, sulfate attacks, and thermal variations due to the dense aluminosilicate gel in the matrix. Long-term durability for many varieties in which these materials would be under continuous exposure to UV radiation, constant moisture, or chemical pollutants has been under ongoing research for several decades in an aggressive environment. The existing gap between the actual results from accelerated aging tests and field trials is necessary evidence to confirm the practical viability associated with structural applications. While its relative effectiveness is apparent for early age strength and densification, ambient curing has high potential in low cost and low energy where considerations about mechanical performance are not immediate. On some occasions, the comparably modest reaction kinetics of geopolymerization under ambient conditions have been balanced by NS content optimization or by using an assistant to boost geopolymers' reactivity. NS dispersion is considered an essential role player in such improvements due not only to its microfilming role, which decreases the voids and loosening, but also due to serving as an active additive by providing extra silicate ions to reinforce such a gel structure. The only prerequisites for accurate uniform dispersion are narrowly defined mixing protocols, using mechanical mixers to allow for the avoidance of particle agglomerations, which would impede the density and mechanical integrity of the base matrix. Although some literature has pointed out the synergistic effects of microwave curing and nano-silica addition, this establishment is undoubtedly required as a key design strategy toward high-performance geopolymer systems since higher rates of heating provided by microwaves could fasten the proper integration of NS into the matrix; improved compactness, reduced porosity, and overall increased durability along with mechanical strength could be noticed. While these integrated approaches offer solutions for the scalability of microwave curing, they also position it as a transformational technology to meet the goals of sustainable construction practices.

ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

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PEER-REVIEW

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