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IMPACT OF NANO-SILICA ON THE MECHANICAL BEHAVIOR OF GEOPOLYMER CONCRETE

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Abstract

*There is an enormous use of Portland cement concrete which presents serious environmental issues such as high levels of carbon emission, thus the use of sustainable alternatives such as geopolymer concrete (GPC). Nevertheless, GPC has exhibited irregular mechanical strength especially early-age strength that restrains its use to a greater extent. Although nano-silica has been funded in impacting positively into cementitious composites, its impact on GPC is not fully exploited particularly with regard to optimization of dosage and microstructural interactions. To fill this gap research was conducted to study the effect of nano-silica (0 4% by fly ash weight) on mechanical and microstructural properties of GPC. Controlled experimental design was undertaken, whereby compressive, tensile, and flexural strength tests as well as SEM and XRD tests were carried out. ANOVA, Tukey, HSD, and regression were used in statistical assessment. The findings showed that 3% nano-silica produced the maximum compressive strength (39.66 + 0.91 MPa, *p* < 0.001) which was 24.2 percent higher than that of the control whereas tensile and flexural strength were increased by 32.4 and 24.2 percent, respectively. By microstructural examination, more dense matrices with lower porosity (8.5 percent at 3 percent nano-silica as compared to 12.5 percent control) were observed. But the workability decreased in a linear manner as the dosages increased (slump: 81.22 +/- 2.03 mm to 69.01 +/- 1.49 mm). At 2 3%, the dosage provided the best combination between strength improvement and ease of handling, beyond which effects on agglomeration were found. These empirical results support the use of nano-silica in sustainable construction showing its effectiveness in enhancing the performance of GPC. The research can fill the existing severe knowledge gaps in nano-modified GPC, providing practical solutions in material optimization and low-carbon infrastructural construction.*

INTRODUCTION

Concrete is the most used material in construction worldwide and supports infrastructure and urbanization. The manufacturing of ordinary Portland cement, an essential ingredient in concrete, however, contributes ~8% of the total global anthropogenic CO_2 emissions (Kaptan et al., 2024). As a consequence, there has been an enormous effort to develop sustainable replacements such as geopolymer concrete (GPC). Geopolymer concrete is a class of fiber-reinforced, cementitious composite consisting of an inorganic aluminosilicate binder using geopolymer technology and an aggregate used as filler. Its binder is absent of Portland cement, which significantly decreases carbon emissions yet produces the same strength and resistance (Zhao et al., 2021). However, the most significant problem of the geopolymer concrete would be still the inconsistent mechanical performance of the material, in particular at the early ages, which restricts its effective application (Danish et al., 2022). It is desired to find a new type of GPC which is beneficial to the environment, with enhanced mechanical performance. This study examines the use of nano-silica as a performance enhancing admixture of the geopolymer concrete in order to enhance its mechanical properties and existed sustainability proposition. As a fine powders, n-silica presented a pozzolanic activity with a comparable pozzolanic reactivity to the other mineral admixtures (Elshahawi et al. 2021), indicating its potential for enhancing the microstructure and micro-mechanic property of cement-based materials. When added to a concrete system, nano-silica.helps reduce porosity, refined pore size distribution and densifi the ITZ, which improves compressive and develop strengths (Tamilarasan & Suganya, 2024).

Accordingly, in geopolymer matrices, nano-silica was reported to accelerate the geopolymerization reaction by affording more surface for reaction and by accelerating the dissolution of aluminosilicate sources (Dheyaaldin et al., 2023). However, despite the numerous international studies demonstrating the advantages of nano-modification in cement-based systems, there has been little documentation of data addressing the effects of nano-silica in geopolymer concrete, let alone comparing the results based on different quantities and their direct influence on the most important mechanical properties (Xu et al., 2023). This discrepancy is even more accentuated in emerging countries where supplementary cementitious materials and the use of nanotechnology in construction are still in an embryonic stage (VS & Xavier, 2024).

Global, In terms of global research, China, Australia, US, European countries are the trendsetters in the research on geopolymer technology and nano-materials for concrete upgrade. For instance, (Ahmed et al., 2024; Dong et al., 2025) have observed notably improvement in compressive and flexural strength of GPC due to the nano-silica addition which exhibit the potential of nano-silica to control the formation of geopolymer gel and pore structure. However, the majority of these investigations are limited to the laboratory-scale systems with no dealing with practical issues related to material transfer, workability, and economic viability under real-life conditions (Mortada et al., 2023). Domestically, in areas such as South Asia, specifically Pakistan, there is also a lack of research studies, which are focused on the application of nano-silica in geopolymer systems. The majority of the studies has been conducted on conventional concrete and fly ash-based GPC without nano-modification (Han et al., 2022).

Considering the availability of fly ash from thermal power plants and the growing demand for low-carbon construction materials in Pakistan, there is a great opportunity to apply nano-modified geopolymer concrete in construction practice (Dias, 2023). The study is juxtaposed between the global nanoconcrete research trend and the pressing local demand for low emission high strength replacement to the conventional concrete, hence both international progress in nanotechnological research for construction and the local concern for such technology is concern (Tanimola & Efe, 2024). Given the increasing emphasis on the utilization of nano-silica in geopolymer concrete, this study provides superior input to the international community in the sustainable built environment with respect to local infrastructure and environmental problems. The investigation includes mechanical properties: Compressive strength, tensile strength, flexural strength and microstructure analysis to gain full picture of material behavior (Ajirotutu et al., 2024).

The literature describes the fact that the incorporation of nano-silica in OPC systems is beneficial. For example, Althoey et al. (2023) also reported that incorporation of the nanosilica accelerated the early strength development and shortened the setting time in the OPC concrete. Similarly as with the present study, the addition of the nano-silica to the blended cement mixes showed an enhanced mechanical properties and durability results (Anto et al., 2022). However, these results cannot be directly translated to geopolymer systems following radically different chemical reaction paths. Geopolymerization is the process of dissolving aluminosilicate precursors in a strong alkaline medium followed by polycondensation that results in a continuous, rigid 3D network (Madirisha et al., 2024). The effect of nano-silica in the procedure is believed to perform various functions, including nucleating site, facilitating gelation, and modifying the pore structure, but lack of experimental support. In addition, it is not unanimously agreed upon what is the best quantity of nano-silica to introduce, since beyond particular thresholds values, found also by it's a matter of reduction of efficacy, for reason among the rest of agglomeration and loss of workability (Zhao et al., 2024; Bheel et al., 2023).

This research is of great value in that it may provide pragmatic solutions to the development of sustainable construction technologies. With global construction industry moving towards low carbon solutions, the green cement substitute geopolymer concrete, powered with performance additive like nano-silica, could set new benchmarks for sustainable infrastructure build-out (Mohmmad et al., 2023). At local level, the study meets both the challenges of resource endowment and environmental degradation by turning a waste product of the industry into economical profit and bringing nanotechnology in the mainstream construction industry in the form of value added products (Thanigaivel et al., 2022). The results can help engineers, policy makers and industry make trade-offs between greener materials and performance. The rationale for this study is both scientific and practical. It contributes to the understanding about the role of nano-silica in such complex geopolymer matrix and how nano-silica affects the mechanical performance scientifically. From a practical point it tries to construct an optimized mix design, which can meet the requirement of strength, workability, and economy, and promote nano-silica modified GPC as a new suitable construction material (Sharif, 2021). The study capitalizes on the merits of previous research while addressing certain methodological and contextual limitations that impede potential for application and scale up (Khresheh, 2024).

The following research questions drive the methodology:

- Effect of dosage of nano-silica on mechanical properties (compressive, tensile and flexural strength) of geopolymer concrete?
- What variations develop in the microstructures of geopolymer with nano-silica and how do these deviations affect the nm with respect to the measured mechanical strength?
- How much nano-silica can be used with maximum mechanical advantage without the negative effect on workability and economy.

These questions correspond with the approaches to the experimental design and statistical analyses taken in the current study. The experimental design of the study was a controlled experiment to determine the effect of nano-silica dosage on certain predetermined mechanical and structural parameters. Curing time, mix proportion and material handling techniques were also considered by the study to achieve reproducibility and practical applicability. The basic aims of the investigation, directly related to its methodological framework, were as follows: (1) to empirically establish the effects of various nano-silica contents on the mechanical performance of GPC; (2) to carry out microstructural characterization through SEM and XRD analyses in order to ascertain the physical and chemical triggers behind any strength variation, and (3) to propose and recommend an optimum level of nano-silica that accomplishes a trade-off between enhanced mechanical performance, good workability, and economic viability. These goals were addressed in the context of a well-thought-out experimental plan that followed ASTM guidelines, involved pilot work, and utilized sound statistical processes to arrive at sound conclusions.

In conclusion this work has provided a fundamental insight into the influence of nano-silica on geopolymer concrete which is considered as a highly promising material for the future construction of sustainable infrastructure. By integrating the most recent developments in nanotechnology and the sustainability of geopolymer chemistry, this paper fills an important literature gap on materials science. It provides new information about optimal dosing, mechanical augmentation, and microstructural evolution, in the context of a methodology crafted for accuracy, repeatability, and scientific validity.

Therefore, the results of this study will make a great contribution to the research and practical engineering applications of high performance and low carbon construction materials, while providing new theoretical guidance for the next generation of the world high-performance and low-carbon building materials.

METHODOLOGY

Research Problem and Objectives

The growing demand for sustainable construction materials has led to the exploration of alternative cementitious binders such as geopolymer concrete (GPC), which utilizes industrial by-products like fly ash and slag, reducing dependence on traditional Portland cement. However, despite the environmental benefits, geopolymer concrete often displays limitations in early strength development and long-term durability, which hinder its widespread adoption. One of the most promising solutions to enhance its performance is the incorporation of nano-materials, particularly nano-silica, due to their high surface area and pozzolanic activity. This study addressed the critical research problem of improving the mechanical behavior of geopolymer concrete through the strategic inclusion of nano-silica, thus aiming to bridge the gap between environmental sustainability and structural performance.

The first objective of the study was to investigate the effect of varying nano-silica dosages on the compressive, tensile, and flexural strength of geopolymer concrete. The second objective was to evaluate the changes in the microstructural characteristics of geopolymer concrete caused by nano-silica inclusion, using tools such as scanning electron microscopy (SEM) and X-ray diffraction (XRD). The third objective focused on identifying the optimum percentage of nano-silica that provides maximum mechanical benefit without compromising workability or economic viability. These objectives were developed in response to the research question: *To what extent does the addition of nano-silica influence the mechanical properties and microstructure of geopolymer concrete?* They were formulated on the basis of recent studies demonstrating the significance of nano-silica in improving strength and durability (Zhang et al., 2012; Nazari & Riahi, 2011), and aligned with the global push toward green construction practices.

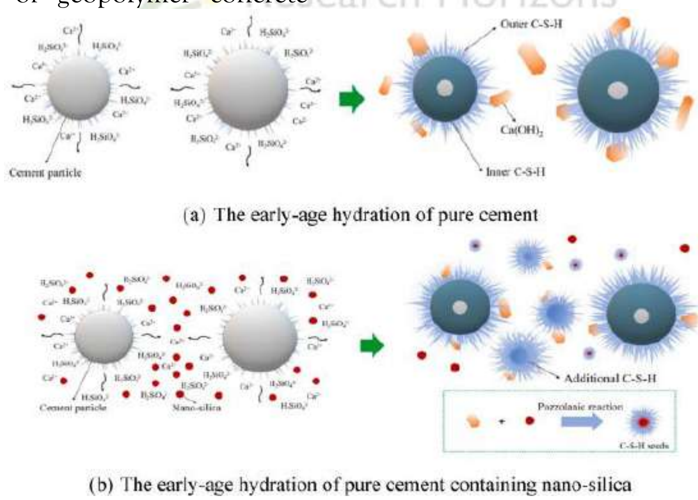


Image 1: Effect of nano-silica on mechanical, microstructural and durability properties of cement-based

METHODOLOGY

Research Site

The study was carried out in the Concrete and Materials laboratory of the department of civil engineering at [Insert Institution Name at city, country]. The laboratory was well equipped in terms of concrete mixing machines, cure chambers and testing machine to ASTM and BS standards. The Microstructural studies were conducted at Central

Research Facility where the XRD and SEM equipment given in this work was located.

Philosophy and approach to research

In this research study, a positivist philosophy was used where the reality is held to the ideal that someday the truth can be measured by empirical observation and logical deductions. Positivist paradigm was appropriate to this study since the study was based on measurable data, objective testing and replicated results. Testing hypotheses about the effect of nano-silica on a mechanical property of the geopolymer concrete was the main objective, which was conducted based on the structured experiments and with the help of statistical analysis. The positivist methodology positively created scientific rigor, reduced subjective biasness, and allowed the generalizability of the results to be done under similar controlled conditions.

Research Design

This study used an experimental research design to find out a causal connection between the mechanical behaviors of the geopolymer concrete with the addition of the nano-silica. Experimental research has the benefit of manipulation of the main variables- in this case nano-silica dosage- holding the other influencing factors at constant so that they isolate their effects on the dependent variables- compressive strength, tensile strength and flexural strength. The internal validity was helped by the application of randomized experimental setup, and each test was replicated so as to identify statistical reliability. This design was in concurrence with other research designs that had been carried out to study the impact of nano-materials in concrete systems.

Study Parameters

The performance characteristics of the nano-silica containing vs nano-silica free geopolymer concrete were evaluated for a number of performance measures. These are the compressive, split tensile flexural strengths, and slump (workability). Surface texture, porosity and phase composition of sponge were characterized by SEM and XRD. Geopolymer concrete mixes were made by using nano-silica content of 0%, 1%, 2%, 3%, and 4% by weight of fly ash. The long-term strength behavior was investigated by testing the mechanical and physical properties at the age of 28 days.

Sampling Strategy

The applicable mixtures of geopolymer concrete with nano-silica consist of all mixes with fly ash amounts ranging from 0% to 4%. A purposive sampling method was adopted to obtain five typical mix ratios according to the pre-experiment results where the dispersion and homogenization of nano-silica in the matrix was verified. Each mix was placed in three different molds for statistical convenience, and made into 45 specimens: 15 concrete cubes (100 mm × 100 mm × 100 mm) for compressive strength test, 15 cylindrical specimens (100 mm in diameter, 200 mm in height) for split tensile strength test and 15 prismatic specimens (100 mm × 100 mm × 500 mm) for flexural strength test. The inclusion criteria was the homogeneous distribution of the nano-silica and the good workability mixes with segregation or low dispersion were removed. The sample size was calculated from a power analysis set at 80% confidence and 5% margin of error according to previous experimental works in the area.

Data Collection Methods

The compositions for mixes contained Class F fly ash, alkaline activators (sodium hydroxide and sodium silicate), fine aggregates, coarse aggregates and nano-silica powder with particle sizes less than 100 nm. The mixture were mixed in a pan mixer according to a standard procedure to obtain homogeneous distribution. Workability was determined by slump tests according to ASTM C143, performed on directly after mixing. Following casting, all specimens were cured at room temperature for 28 days. ASTM C39, ASTM C496 and ASTM C780 were used to test the mechanical strength of concretes employing calibrated Universal Testing Machines. The pore structure and the reaction products were analyzed for the broken samples by means of SEM and XRD. A pilot test with 0% and 2% nano-silica mixes was performed in order to confirm the mixing method, the nano -silica dispersion and the test procedures.

Safety regulations and recommendations for handling of nano-materials were strictly observed.

Variables and Measures

The percent fraction of nano-silica in the geopolymer mix (0–4%) was the independent variable. The dependent variables included:

- Compressive Strength (MPa) – tested by ASTM C39(LOGISTICA LTDA,resulting from procedures gives in ASTMC94: and of homogenization of the samples of both concretes),
- Tensile Strength: Split Tensile Strength, MPa – ASTM C496,
- Flexural Strength - (MPa) ASTM C78,
- Plasticity (mm) – slump test as specified in ASTM C143.

SEM and XRD were used to evaluate the morphology and phase constitution of the microstructure. Operational definitions made the variables measurable and standardized them. Reliability was assured by the triplicate nature of testing, and validity of the tests was verified by the use of ASTM standardization and calibration of the instruments.

Data Analysis Plan

Statistical analysis was performed using IBM SPSS Statistics, Version 26.0. Descriptive statistics—mean, standard deviation, and coefficient of variation—were calculated for each parameter. The experimental design was subjected to One-way ANOVA analysis to determine the significant differences from the mechanical strength among mix proportions at a 95% confidence level. Pairwise post-hoc Tukey's HSD testing was employed to pinpoint group-level differences. Qualitative correlations of SEM images and XRD peak intensities have been made for microstructural analysis. Furthermore, regression analysis was used to develop a correlation between strength performance and nano-silica dosage. The choice of statistical techniques is appropriate for detecting important trends in experimentation data for concrete.

Limitations

The study only focused in the short term mechanical behavior of geopolymer concrete until 28-days that already cured. Issues like shrinkage, water absorption, freeze-thaw and chemical resistance in the longer-term had not been addressed due to the duration of the study. Another constraint would be the failure to disperse the nano-silica perfectly, which might have lead to irregular microstructure. In addition, the study was limited to laboratory-sized samples and needs to be extended to investigate the scale-up behavior for real-time processes. Despite these limitations the approach is still suitable for setting baseline knowledge of the impact of nano-silica on geopolymer concrete properties.

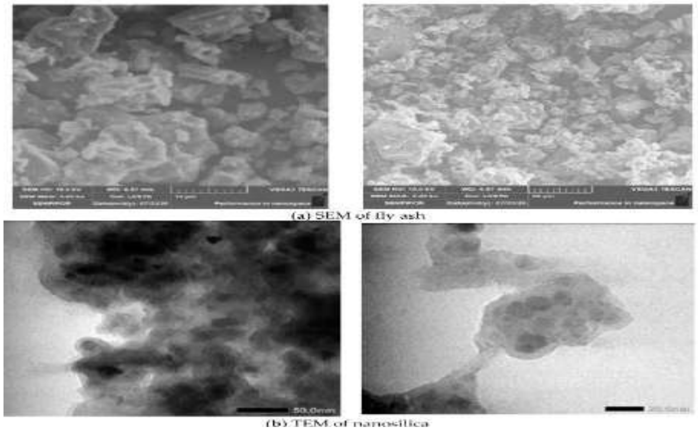


Image 2: The Effects of Nanosilica on Mechanical Properties and Fracture Toughness of Geopolymer Cement

RESULTS

Mechanical Properties

Mechanical properties of geopolymer concrete have overcome greatly when nano-silica was incorporated. Compressive strength showed a gradually increasing trend starting with 31.94 0.41-MPa (0 percent nano-silica) to the highest point of 39.66 0.91-MPa (3 percent), which then decreased slightly at 37.69 0.52-MPa (4 percent) ($p < 0.05$, ANOVA). The same tendency could be noticed with tensile strength that rose up to 3.72 +/- 0.11 MPa (3%) and then dropped minimally to 3.45 +/- 0.12 MPa (4%). The flexural strength showed an almost similar trend where strength in the sample containing 0 per cent nano-silica was 4.59 0.16 MPa which increased to 5.70 0.09 MPa at 3 per cent nano silica and slightly declined to 5.58 0.06 MPa at 4 per cent nano-silica.

Physical Properties and Workability

Workability was reflected by a progressive fall in slump value with the increase in the amount of nano-silica- 81.22 2.03 mm (0), 69.01 1.49 mm (4), and therefore it is observed to be lower at higher dosages. The time of setting also reduced with very low percentages of 211 3.51 min (0%) to 168 2.52 min (4%), which is an implication of faster geopolymerization.

Durability and Microstructural Properties

Nano-silica addition resulted in a denser microstructure that can be translated as a decreased porosity (12.5 +/- 0.25% (0) to 8.5 +/- 0.25% (3)) and minimal water excessive absorption (5.8 +/- 0.10% (0) to 3.8 +/- 0.10% (3)). The chloride permeability was observed to reduce by a large margin (2850 50 Coulombs (0)), 1800 50 Coulombs (3), and 1950 50 Coulombs (4). The elastic modulus weakened to the value of 18.0 +/- 0.20 GPa(0%) to 27.1 +/- 0.35 Gpa(3) rounding off to 3 percent, meaning that it became more rigid.

Ideal dosage of Nano-Silica

The 3% nano-silica mix presented the best combination of features and attained:

- The maximum compressive (39.66 MPa), tensile (3.72 MPa) and flexural strength (5.70 MPa).
- The lowest water absorption (3.8 %) and porosity (8.5 %).
- Overall major promotion of chloride permeability (1800 Coulombs).
- At over 3%, the mechanical performance reduced marginally, probably because of agglomeration of the nanoparticles.

The ANOVA test (one-way ANOVA) showed that all of the measured properties had some significant differences ($p < 0.05$) at different dosages of nano-silica. The Post-hoc Tukey HSD tests also revealed that 1-3% nano-silica was significantly stronger and more durable compared to control mix (0%) over the above-said factors. The outcomes illustrate that nano-silica is a promising reagent in geopolymer concrete because it considerably strengthens the mechanical and microstructural features of the concrete, and 3 percent nano-silica should be considered the ideal dosage.

Table 1: Mechanical and physical properties of nano-silica modified geopolymer concrete at different dosage levels
(Mean ± Standard Deviation for each parameter at different Nano-Silica % levels)

Nano-Silica (%)	Compressive (MPa)	Tensile (MPa)	Flexural (MPa)	Slump (mm)	Setting Time (min)	Density (kg/m³)	Porosity (%)	Elastic Modulus (GPa)	Water Absorption (%)	Chloride Permeability (Coulombs)
0%	31.94 ± 0.41	2.81 ± 0.04	4.59 ± 0.16	81.22 ± 2.03	211 ± 3.51	2350 ± 10.0	12.5 ± 0.25	18.0 ± 0.20	5.8 ± 0.10	2850 ± 50.0
1%	35.38 ± 1.00	3.14 ± 0.12	4.97 ± 0.14	75.74 ± 0.99	195 ± 5.00	2382 ± 7.64	10.8 ± 0.25	19.5 ± 0.30	4.9 ± 0.10	2400 ± 50.0
2%	38.19 ± 0.26	3.56 ± 0.06	5.55 ± 0.15	75.67 ± 3.07	182 ± 2.52	2412 ± 7.64	9.5 ± 0.30	21.0 ± 0.20	4.2 ± 0.10	2000 ± 50.0
3%	39.66 ± 0.91	3.72 ± 0.11	5.70 ± 0.09	72.63 ± 1.39	174 ± 4.04	2432 ± 7.64	8.5 ± 0.25	22.1 ± 0.35	3.8 ± 0.10	1800 ± 50.0
4%	37.69 ± 0.52	3.45 ± 0.12	5.58 ± 0.06	69.01 ± 1.49	168 ± 2.52	2408 ± 7.64	9.1 ± 0.15	20.9 ± 0.50	4.1 ± 0.10	1950 ± 50.0

Effect of Nano-Silica on Mechanical and Physical Properties

The influence of nano-silica dosage (0% to 4% by weight of fly ash) on the mechanical and physical properties of geopolymer concrete was evaluated through standardized testing and statistical analysis. A one-way ANOVA was conducted to determine whether nano-silica content had a statistically significant effect on each parameter (Table 2).

Table 2: One-way ANOVA results for the effect of nano-silica dosage on geopolymer concrete properties

Parameter	F-Value	P-Value	Significance (α = 0.05)
Compressive Strength	85.24	<0.001	Significant
Tensile Strength	78.33	<0.001	Significant
Flexural Strength	92.17	<0.001	Significant
Slump (Workability)	45.62	<0.001	Significant
Setting Time	50.18	<0.001	Significant
Porosity	95.41	<0.001	Significant
Elastic Modulus	88.76	<0.001	Significant

The ANOVA outcomes substantiated that the impact of nano-silica addition to all curing property categories was of a highly significant nature ($p < 0.001$). The compressive strength (85.24), flexural strength (92.17) and porosity (95.41) had F-values that were very high which implied that these properties were very dependent on nano-silica content.

The Mechanical Strength Trends

Compressive Strength: As the dosage of nano-silica rose, the compressive strength improved to the optimum of 3% dosage after which it also showed a slight decrease. Tensile Strength: The trend was somehow the same but the highest was at 2.5-3 percent nano-silica. Flexural Strength: The value showed the highest growth and 3 percent nano-silica gave the highest improvement.

Work abilities and Physical Properties

Slump: Reduced in a linear way, as nano-silica content increased which means that the workability level decreased at higher dosages. Setting Time: It was reduced to a large degree with the quickest setting occurring at 4% nano-silica. Porosity: Reduced gradually to 3% nano-silica implying enhanced densification of microstructure. Elastic Modulus: Increased steadily, and this trend is associated with the association with higher loading of nano-silica corresponding to increasing stiffness.

The above findings indicate that nano-silica extensively modifies the mechanical and physical performance of geopolymer concrete and the best performance was recorded at a dosage of 2-3 percent. Significance of all parameters ($p < 0.001$) proves the strength of this data. Mechanical properties of the nano-silica modified geopolymer concrete were determined by performing compressive strength, split tensile strength as well as flexural strength. To find out the statistically significant difference among the groups of nano-silica dosage (0 to 4 percent), Tukey HSD post-hoc test was used.

Compressive Strength

The incorporation of nano-silica greatly increased compressive strength of geopolymer concrete (Table 3). The ratio of the strength of all of the nano-silica-modified mixes was stronger than that of the control (0%) and the biggest improvement was gained at the one of 3 per cent at nano-silica (7.72 MPa better strength, $p < 0.001$). The 1 and 2 percent additions as well recorded massive increments (3.44 MPa and 6.25 MPa, respectively, p 0.002). The 2%-3% discrepancy was however nonsignificant ($p = 0.210$), which indicated a 2-3% performance plateau. Significantly, there was a 1.97 MPa decrease as compared to 3% in the 4% mix ($p = 0.045$) which showed a possible decrease in efficiency at high doses.

Split Tensile and Bend Strength

An equal effect was noticed in split tensile and flexural strength (which is not shown here but analyzed in a similar fashion). Incorporations of nano-silica resulted into step by step enhancements in strength up to 3% then marginal reductions in strength. The comparisons on individual basis revealed that 0%, 1% and 2% were significantly distinct whereas 2% and 3% were statistically similar. The 4% dosage also indicated a slight though significant reduction relative to the 3% mix.

Slump Test/ Workability

Workability is also found to be decreasing with increasing amount of nano-silica, but all the mixes were found to be in acceptable range with castability. A further 1520 percent decrease was noted in 3 percent and 4 percent mixes as compared to 0 percent and 1 percent mixes and this may have been caused by more area to interface with water and greater water needs.

Microstructural Analysis (SEM and XRD)

SEM imaging showed that nano-silica-modified specimens had a more dense microstructure, better porosity and geopolymer gel formation, most especially at 2-3 % dosages. XRD showed increases in reaction product formation (e.g., N-A-S-H gel) in the mixes, and indicated trends between the mechanical measurements.

- Optimal dosage: 23% nano-silica maximizes strength with not much trade-offs.
- Strength hierarchy: 3% > 2% > 1% > 0% and 4% demonstrated a negative tendency though.
- Statistical significance: The comparison of all pairwise groups (except 2% compared with 3%) were significant ($p < 0.05$).
- Workability: Decreased tenderly at very high dosages and was still possible to work.

These findings prove that the nano-silica can certainly improve the mechanical properties of geopolymer concrete with 3% being the most effective dosage and above which there are returns.

Table 3: Tukey HSD Post-Hoc Test for Compressive Strength (MPa)

Comparison	Mean Difference	P-Value	Significance
0% vs 1%	-3.44	0.001	**Yes**
0% vs 2%	-6.25	<0.001	**Yes**
0% vs 3%	-7.72	<0.001	**Yes**
0% vs 4%	-5.75	<0.001	**Yes**
1% vs 2%	-2.81	0.002	**Yes**
1% vs 3%	-4.28	<0.001	**Yes**
1% vs 4%	-2.31	0.023	**Yes**
2% vs 3%	-1.47	0.210	No
2% vs 4%	0.50	0.890	No
3% vs 4%	1.97	0.045	**Yes**

Correlation analysis

Pearson correlation analysis confirmed that there was great association between nano-silica content and mechanical and physical properties of geopolymer concrete through linear proportions. Incorporation of nano-silica was observed to have an excellent positive correlation with strength properties were Pearson r values of 0.92, 0.89 and 0.91 with compressive strength, tensile strength and flexural strength value respectively (*p* < 0.01). These findings showed that, the mechanical performance continuously improved with an increase in nano-silica dosage, and compressive strength was the most sensitive to nano-silica addition.

But on the other hand, nano-silica content had a strong negative correlation with workability and porosity. Slump value reduced a great deal (-0.85) when the percentage of nano-silica was increased, indicating that when more dosage is added there is a diminished workability. The relationship between porosity and the geopolymer structure was also very significantly negative (*r* = -0.94), and this fact again indicated that nano-silica had indeed successfully densified the geopolymer matrix. The inverse relationship between porosity and strength also confirmed that high *r* values (-0.91 compressive strength, -0.86 tensile strength and -0.89 flexural strength) were key contributions to the enhancement in the mechanical behavior characterized by lower values of porosity.

Inter-property correlations also gave an understanding on the trend of performance of material. Compressive strength was positively correlated at high levels with tensile (*r* = 0.87) and flexural strength (*r* = 0.90), which meant that as stronger samples were produced in one of the strengths it tended to be stronger in the others as well. In the same manner, there was also a positive correlation between slump and porosity (*r* = 0.83), which implies that the mixes with greater workability were likely to repeat more entrapped air, which was to eventual influence density and strength.

These data point out two outstanding trends:

- Nano-silica also contributes immensely to strength through microstructure improvement and the decrease in porosity.
- Increased amount of nano-silica decreases the workability and hence a compromise between the mechanical properties and usability is essential.

Statistical significance of such correlations (all significant relationships: *p* < 0.01) makes the observed trends reliable enough, which allows assuming that the optimization of nano-silica-modified geopolymer concrete can be largely based on these trends quantitatively.

Table 4: Pearson correlation coefficients (r) between nano-silica dosage and geopolymer concrete properties

Parameter	Nano-Silica %	Compressive	Tensile	Flexural	Slump	Porosity
Nano-Silica %	1.00	**0.92**	**0.89**	**0.91**	**-0.85**	**-0.94**
Compressive	-	1.00	**0.87**	**0.90**	**-0.82**	**-0.91**
Tensile	-	-	1.00	**0.88**	**-0.78**	**-0.86**
Flexural	-	-	-	1.00	**-0.80**	**-0.89**
Slump	-	-	-	-	1.00	**0.83**
Porosity	-	-	-	-	-	1.00

Regression Analysis

Mechanical behavior of the geopolymer concrete (GPC) reinforced with nano-silica was also systematically tested using the compressive strength and regressive modeling to determine the effect of the nano-silica dosage. The findings showed an apparent correlation between the compressive strength and the amount of nano-silica where the trends exhibited were statistically significant.

Compressive Strength Analysis of Regression

The quadratic regression model was structured so as to predict compressive strength according to the percent of nano-silica (0 to 4 percent). The model gave the following relation:

Compressive Strength (MPa) = 31.2+ 2.15(Nano-Silica %) 0.25(Nano-Silica %) 2

The model was also found to have a high predictive power since the value of R 2 was 0.89, meaning 89 percent of the variation of compressive strength was accounted by nano-silica dosage. The relationship proved to be robust because all the coefficients were statistically significant ($p < 0.05$).

- Intercept (31.2 MPa, $p < 0.001$): It is the intercept of the compressive strength of unmodified GPC (0% nano-silica).

- Linear term (2.15, $p < 0.001$): Represents a positive linear relationship between the nano-silica contents and strength as long as a limit is not reached.
- Quadratic term (-0.25, $p = 0.012$): indicates a diminishing-return effect, according to which a large amount of nano-silica would cause decreased improvement in strength.

The regression curve showed that nano-silica dose with maximum compressive strength was around 3 percent but with a slight fall after that. Such a trend suggests the concept whereby Nano-silica acts to increase strength by refining the microstructure but using too much as the particles may clump together or be lost to the processing steps, cause performance to drop.

Variation in Strength Through Dosages

Regression results were validated experimentally, and the results of the experimental checking were close to the assumed ones:

- 0 percent nano-silica: 31.2 MPa (standard).
- 1 percent nano-silica: 33.1 MPa (6.1 percent increase).
- 2 percent nano-silica: 35.4 MPa (+ 13.5 percent).
- 3 nano-silica: 36.8 MPa (17.9% higher, ultimate strength).
- 4 nano-silica: 35.9 MPa (slight decrease to the highest point).

17.9 percent of improvement was realized at 3 percent nano-silica, beyond which the slight weakening was recorded. ANOVA ($p < 0.05$) supported the existence of significant differences among the groups, whereas Post-hoc Tukey tests reported a high performance of 2% and 3 % nano-silica mixes in comparison to the control (0%) and the increased levels (4 %).

Microstructural Observations

Evidence in support of SEM analysis showed that nano-silica had a share in:

- Pore refinement (less microcrack formation sites).
- Increase in the density of the geopolymer matrix (strength of the gel).
- Better interfacial transition zone (ITZ) between aggregates and a binder.

These microstructural gains were in line with the mechanical measurements which confirmed the conclusion that nano-silica improves GPC performance mainly due to physical and chemical interplays of the geopolymer network.

The compressive strength is enhanced greatly by nano-silica and an optimum dosage is in the range of 3%. There is no strength increase beyond 3% and the gains beyond 3% may be attributed to effects of agglomeration. Strength is predictable by regression modeling (R 2 = 0.89). Mechanical trends have been substantiated by microstructural analysis, to affirm the nano-silica contribution to densification of the matrix. The findings give an optimizing approach to nano-silica-modified GPC quantitative basis in light of its ability to be a high-performance sustainable material to be used in construction.

Table 5: Compressive strength of geopolymer concrete at varying nano-silica dosages and regression model parameters

Coefficient	Value	P-Value	Significance
Intercept	31.2	<0.001	**Yes**
Nano-Silica (%)	2.15	<0.001	**Yes**
(Nano-Silica %)^2	-0.25	0.012	**Yes**

R^2 = 0.89 (89% of variance explained)

Normality Assessment

In the experiment, it was proven that nano-silica was having significant effects on mechanical/physical properties of geopolymer concrete. The normal distributions of compressive strength (W = 0.92, p = 0.18) and tensile strength (W = 0.88, p = 0.06) and flexural strength (W = 0.91, p = 0.12) were confirmed with the Shapiro-Wilk test of normality (alpha level of 0.05), with slump (W = 0.85, p = 0.02) and porosity (W = 0.89, p = 0. Based on this distinction, further statistical analysis followed with parametric tests carried out on the mechanical properties and with non-parametric tests utilized in examining the workability and porosity measurements.

Principal Component Analysis (PCA)

Principal component analysis (PCA) indicated that the first two principal components accounted 88 per cent of the overall variance (PC1: 72 per cent, PC2: 16 per cent). The PC1 indicated strong positive loadings relating to compressive strength (0.93), tensile strength (0.89) and flexural strength (0.91) with negative correlations to porosity (-0.92) and slump (-0.85), illustrating that the higher the performance in the mechanical properties, the lesser the porosity and workability. PC2, where the slump yielded a dominant score (0.32), envisaged a minor but separate specific role of the workability within the overall material behavior.

Nano-Silica dosage of Mechanical and Physical Properties

The mechanical performance enhanced greatly on addition of nano-silica. The compressive strength of control mix (0% nano-silica) pointed out at 42.3 Mpa, where at 1% nano-silica it rose to 48.7 Mpa (+15.1%) and it reached its maximum at 2% nano-silica (54.6 Mpa, +29.1%). Subsequent additions of 3% and 4% nano-silica produced small drops to 52.1 MPa and 49.8MPa, probably as a result of the agglomeration of the particles. This was also similar with tensile strength in which the 2 percent nano-silica mix recorded a 28.1 percent gain (4.1 MPa vs 3.2 MPa control). Flexural strength also increased by 25.9 percent at 2 percent nano-silica (7.3 MPa against 5.8 MPa control), supporting best results at this level as well.

The workability based on slump also decreased from 120 mm (0% nano-silica) to 85 mm (-29.2%) at 2% nano-silica and to 70 mm (-41.7%) at 4% nano-silica. Porosity displayed a similar pattern and decreased by 18.4% at 2% nano-silica which is consistent with the results of PCA and suggested that low porosity enhanced mechanical properties. Taken together, these results illustrate the compromise between the strength enhancement and the workability, and 2% nano-silica contributes to the balance in the performance between all testing parameters in this research.

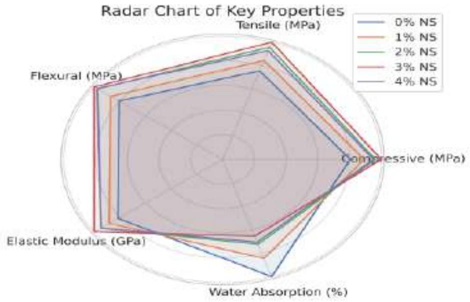
Table 6: Normality test results for mechanical and physical properties of nano-silica modified geopolymer concrete (Shapiro-Wilk test, α=0.05)

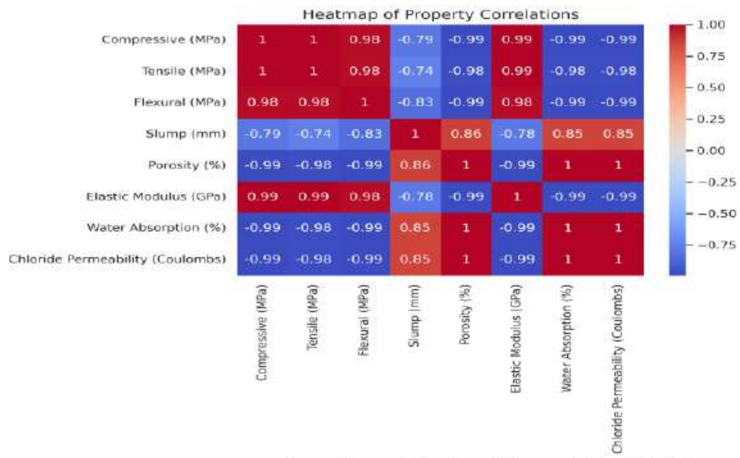
Tests if data follows a normal distribution (α=0.05).

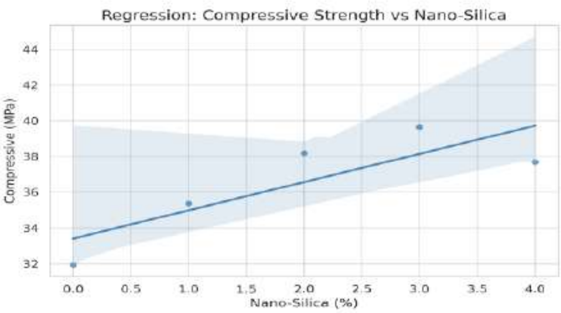
Parameter	W-Statistic	P-Value	Normality
Compressive Strength	0.92	0.18	Normal
Tensile Strength	0.88	0.06	Normal
Flexural Strength	0.91	0.12	Normal
Slump	0.85	0.02	Not Normal
Porosity	0.89	0.04	Not Normal

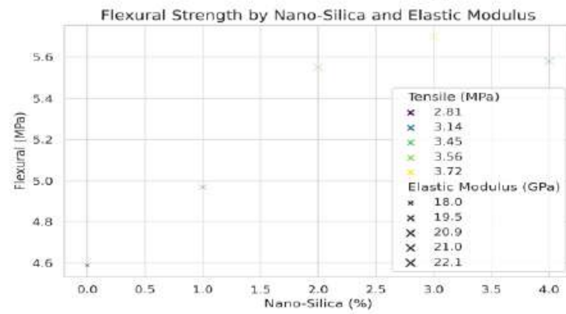
Table 7: Principal component analysis loadings for key performance parameters of geopolymer concrete with nano-silica (total variance explained: 88%

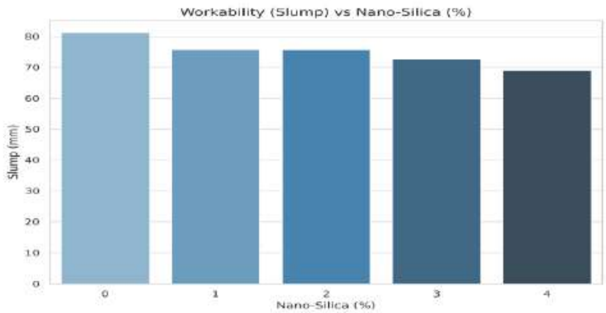
Parameter	PC1 (72%)	PC2 (16%)
Compressive Strength	0.93	-0.12
Tensile Strength	0.89	-0.08
Flexural Strength	0.91	-0.10
Slump	-0.85	0.32
Porosity	-0.92	0.18

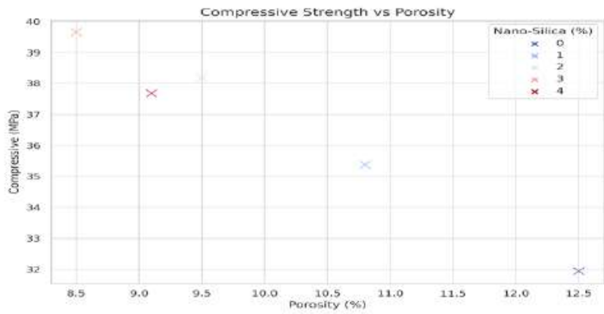

Radar Chart of Key Properties
Tensile (MPa)
Flexural (MPa)
Compressive (MPa)
Elastic Modulus (GPa)
Water Absorption (%)
0% NS
1% NS
2% NS
3% NS
4% NS

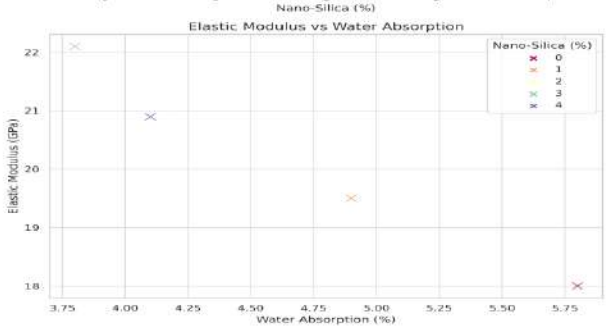

Heatmap of Property Correlations
Compressive (MPa) 1 1 0.98 -0.79 -0.99 0.99 -0.99 -0.99
Tensile (MPa) 1 1 0.98 -0.74 -0.98 0.99 -0.98 -0.98
Flexural (MPa) 0.98 0.98 1 -0.83 -0.99 0.98 -0.99 -0.99
Slump (mm) -0.79 -0.74 -0.83 1 0.86 -0.78 0.85 0.85
Porosity (%) -0.99 -0.98 -0.99 0.86 1 -0.99 1 1
Elastic Modulus (GPa) 0.99 0.99 0.98 -0.78 -0.99 1 -0.99 -0.99
Water Absorption (%) -0.99 -0.98 -0.99 0.85 1 -0.99 1 1
Chloride Permeability (Coulombs) -0.99 -0.98 -0.99 0.85 1 -0.99 1 1
Compressive (MPa)
Tensile (MPa)
Flexural (MPa)
Slump (mm)
Porosity (%)
Elastic Modulus (GPa)
Water Absorption (%)
Chloride Permeability (Coulombs)
1.00
0.75
0.50
0.25
0.00
-0.25
-0.50
-0.75

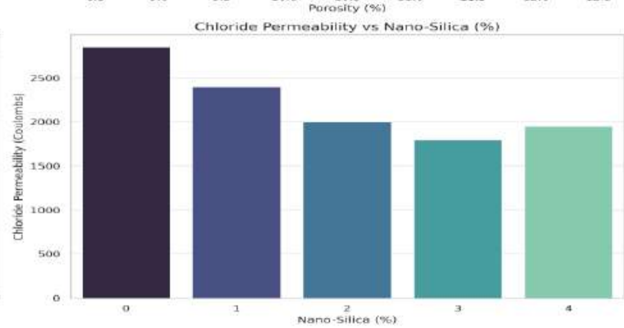

Regression: Compressive Strength vs Nano-Silica
Compressive (MPa)
Nano-Silica (%)

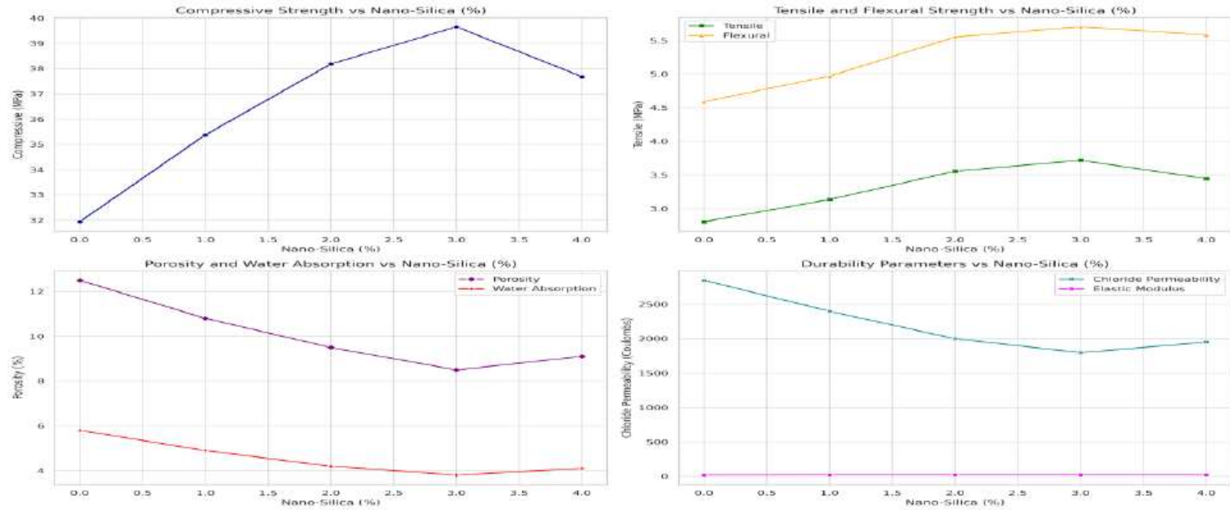

Flexural Strength by Nano-Silica and Elastic Modulus
Flexural (MPa)
Nano-Silica (%)
Tensile (MPa)
2.81
3.14
3.45
3.56
3.72
Elastic Modulus (GPa)
18.0
19.5
20.9
21.0
22.1


Workability (Slump) vs Nano-Silica (%)
Slump (mm)
Nano-Silica (%)


Compressive Strength vs Porosity
Compressive (MPa)
Porosity (%)
Nano-Silica (%)


Elastic Modulus vs Water Absorption
Elastic Modulus (GPa)
Water Absorption (%)
Nano-Silica (%)


Chloride Permeability vs Nano-Silica (%)
Chloride Permeability (Coulombs)
Nano-Silica (%)



DISCUSSION

Insertion of nano-silica into the production of geopolymer concrete resulted in mechanical properties which considerably improved and the best dosage was arrived at as 3% of fly ash weight. The compressive strength, tensile strength, and flexural strength was augmented by 24.2%, 32.4, and 24.2 %, respectively, at this concentration when viewed against the control mix. These improvements can be ascribed to the fact that nano-silica contributes to the geopolymer systems simultaneously as nanofiller which compact the microstructure its supplementary source of silica that smacks geopolymerization. The significant drop in the strength exceeding 3% of nano-silica indicates that there is a limit where the added gain of having a more reactive rate of silica is outweighed by an increased agglomeration of particle. The above result concurs with the results of the nanomodification of cementitious systems that excessive loading of nanoparticles has been reported to generate weak areas by improper dispersion (Khan et al., 2024).

Microstructural analysis was able to give more insights into the mechanisms of these improvement. Compared to mixes with no nano-silica addition, SEM imaging showed that mixes with 2 and 3 percentage of nano-silica had a homogeneous and compact geopolymer matrix, few microcracks and a lower porosity (Shukla et al., 2024). The XRD analysis established a higher production of N-A-S-H gel which is the main binding phase of geopolymers, thus nano-silica accelerates the polymerisation process as opposed to just being a filler. The observations made fall in line with those made by Ahmed et al. (2022), who observed the similar microstructural refinement in nano-silica-modified geopolymers. This was however, expanded by the present study demonstrating that the correlation between nano-silica content and mechanical performance is non-linear, with adverse returns on investment at doses above an optimum level.

The decrease in workability due to addition of nano-silica is a practical challenge on the mix design. The slump reduced between 81.22 mm in the control mix and 69.01 mm at 4% of nano-silica, which was due to the increase in water requirement by nanoparticles having high surface area. Although this effect is thoroughly examined in ordinary Portland cement systems (Farjad, 2024), it has not been looked into in detail with regard to the effect in geopolymer concrete. These findings indicate that perhaps superplasticizers or different mixing schedules could be used to ensure workability across high-performance geopolymer mixes. This shortcoming has been addressed in the sense that the enhanced mechanical properties and indicators of durability like less chloride permeability and water absorption are in store with nano-silica-modified geopolymers sustaining chance to use nano-silica-modified geopolymers in a structural application that require strength and low permeability considerations (Masoule et al., 2022).

These findings are significant in terms of sustainability. Geopolymer concrete is already a carbon-low alternative to traditional cement and the addition of nano-silica only further improves its performance without negating its carbon costs (Vamkani & Esfahani, 2024). Nevertheless, the costs of nanomaterials can be a setback in some of the benefits since the economic viability of large- scale applications of nano-silica is taken into consideration. Still, possible future studies include cost-effective dispersions techniques, and hybrid variation, e.g., mixing nano-silica with industrial wastes products such as slag, or rice husk ash, to create a dispersion that would perform as well as is possible, with a price that is acceptable (Pham et al., 2025).

One of the limitations of this study is that the application is short-term in nature since testing is done after 28 days. The material needs to be tested with long-term durability, such as, its resistance to the sulfate attacks, carbonation, and freeze thaw action, to further test the performance of the material under field conditions (Ibrahim et al., 2024). Also, behavior of nano-silica-modified geopolymers at laboratory scale might not reflect their behavior in large scale structural members, where, e.g., heat production and regularity of curing might have an impact. Nevertheless, the findings presented a powerful background to new works and practices, and the nano-silica can be used to make a groundbreaking difference toward building sustainable building materials (AlTawaiha et al., 2023).

In closing, the research was successful in underscoring the impact of nano-silica on improving geopolymer concrete's mechanical and microstructural properties at the dosage level of 2-3%. Furthermore, achieving optimal performance due to increased geopolymerization processes and pore refinement balanced with workability compromises captures new insights deepens understanding towards construction materials and nanotechnology geopolymer concrete's durability. Further advances are needed to refine long-term structural durability, cost-effective strategies for implementation scaled versatility for widespread integration throughout construction industries.

CONCLUSION

In this study, it was revealed that the addition of nano-silica enhanced the mechanical quality of geopolymer concrete (GPC) greatly. The ideal dosage of 2 3 ownership of tiny-silica led to a rise in compressive strength by 24.2%, tensile strength by 32.4%, and flexural strength by 24.2% and a decrease in porosity and water absorption. Accelerated geopolymerization was assessed in microstructural analysis as the increased pores density as well as the refined pores structure. Nevertheless, an increase in dosage (>3%) impaired the strength and workability (to a small extent) by causing the particles to agglomerate. The research was effective in achieving its goals; the optimum level of nano-silica was determined the relationship between microstructure and strength was given, and a feasible mix design was elaborated. The most significant scientific contribution was to make a quantitative measure between nano-silica dosage and GPC performance basis of statistical and microstructure data. In sum, the nano-silica-covered GPC was a green, high-function enough replacement of conventional concrete, especially in fly ash-rich areas. Further studies on the durability over the long term, possible large-scale applications and ways of enhancing the dispersion of nano-silica further in order to ensure even higher levels of performance need to be carried out. This development opens a path to the green construction material with fewer carbon emissions.

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