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Nano-Silica integration for superior properties in potassium feldspar-based phosphoric acid activated geopolymers: A sustainable approach

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Abstract

This study investigates the potential of Potassium Feldspar-phosphate-based geopolymer concrete as a sustainable alternative to conventional concrete, addressing the environmental concerns associated with CO_2 emissions during cement production. While geopolymer concrete offers a promising path toward sustainability, its performance often falls short of Portland cement concrete. This study investigates utilizing nano-silica (NS) to enhance the performance of geopolymer concrete. Potassium feldspar powder, metakaolin, and rice husk ash were combined to create a ternary mixture that included different amounts of NS. The resulting geopolymer composition's mechanical characteristics were assessed. The mechanical qualities were evaluated using split tensile (STS) and compressive strength tests (CS). The findings revealed that a 4% NS dosage (GC-N4) yielded the most significant improvement in strength and durability. The GC-N4 mix performed superior in all metrics, demonstrating the highest compressive (42.86 MPa) and STS (3.8 Mpa) strengths. Reduction in water absorption and durability aspects were also optimum in GC-N4. These results highlight the potential of incorporating NS into a ternary mix of potassium feldspar powder, metakaolin, and rice husk ash to significantly enhance the overall performance of geopolymer concrete, promoting its wider adoption as a sustainable construction material.

1. Introduction

Geopolymer concrete has emerged as a viable substitute for traditional Portland cement-based concrete due to its enhanced mechanical characteristics, reduced carbon emissions, and ability to utilize industrial waste materials [1,2]. Fly ash, slag, and other natural minerals are examples of aluminosilicate sources that are alkali-activated to create this novel material [3,4]. In recent years, incorporating nanomaterials like nano-silica (NS) has significantly enhanced the geopolymer concrete performance by improving its microstructure and durability [5,6]. One promising development in this field is using potassium feldspar as a source material for geopolymer synthesis, mainly when activated with phosphoric acid [7,8]. This approach leverages the abundant availability of potassium feldspar and creates high-strength, chemically resistant geopolymer matrices [9,10]. Recent studies have highlighted the benefits of NS addition, including refined pore structure and increased CS, making it a pivotal component in advancing geopolymer technology [11,12].

Potassium feldspar and metakaolin play pivotal roles in conventional and geopolymer concrete, offering sustainable alternatives to traditional Portland cement-based materials while enhancing performance across various construction applications. Potassium feldspar, an abundant aluminosilicate mineral, has garnered attention for its potential in geopolymer synthesis, mainly when activated with phosphoric acid or alkalis. This activation process converts potassium feldspar into a reactive binder that can replace or supplement cement in concrete formulations, thereby reducing environmental impact and carbon emissions associated with cement production [13]. Using potassium feldspar in geopolymer concrete not only taps into an ample natural resource but also enhances the material's chemical resistance and mechanical properties, making it suitable for diverse construction needs [14].

Metakaolin, derived from the calcination of kaolin clay, is another crucial ingredient in geopolymer concrete formulations due to its high pozzolanic reactivity. When combined with potassium feldspar, metakaolin further enhances the material's performance by improving its CS, durability, and resistance to chemical attack [15]. This synergistic effect arises from metakaolin's ability to react with alkalis or other activating agents, forming a stable geopolymeric network that binds aggregates and enhances the overall matrix cohesion [16].

In recent years, extensive research has focused on optimizing the proportions and processing conditions of potassium feldspar and metakaolin in geopolymer concrete mixtures to achieve superior mechanical and durability properties. Studies have explored curing conditions, activator types, and particle size distributions to tailor the geopolymer's microstructure and performance characteristics [17]. Incorporating nanomaterials, such as NS, has further advanced these efforts by refining pore structure and enhancing the material's density and strength [18,19]. Geopolymer concrete formulations incorporating potassium feldspar and metakaolin have shown promising results in laboratory tests and practical applications. They exhibit comparable or superior mechanical properties to traditional concrete, including higher CS and lower permeability, which are crucial for infrastructure durability in harsh environmental conditions [20,21]. These materials offer significant environmental advantages over conventional Portland cement-based concrete because they reduce energy usage and greenhouse gas emissions during production [22].

However, despite these advantages, the widespread adoption of geopolymer concrete, particularly in African countries, faces several challenges. These include the availability and quality of raw materials, the establishment of standardized mix design procedures, and the need for specialized equipment for large-scale production [23]. Cooperative endeavours between scholars, industry participants, and policymakers must encourage technology transfer, enhance regional infrastructure, and cultivate inventiveness in sustainable building methods to tackle these obstacles. Research efforts continue to explore novel formulations and applications of geopolymer concrete incorporating potassium feldspar and metakaolin. Current studies focus on optimizing geopolymerization processes, enhancing material properties through nanotechnology, and evaluating long-term performance under various environmental exposures [24]. Integrating digital modeling and simulation techniques also plays a crucial role in predicting material behavior and optimizing structural designs using geopolymer composites [23-25].

Metakaolin and potassium feldspar are two viable substitutes in the search for environmentally friendly building supplies. Combined with geopolymer concrete formulations, they can provide improved performance, less of an adverse effect on the environment, and even financial gains over traditional Portland cement-based materials in order to fully realize the promise of geopolymer concrete in worldwide construction practices, research, and development activities must be sustained in order to overcome technical obstacles and increase market acceptance.

It is an environmentally friendly and innovative construction material where recycled pozzolanic substances entirely substitute conventional cement. Extensive research has underscored the potential of high-performance geopolymer concrete to revolutionize construction practices [26-30]. However, in numerous third-world nations, the practical adoption of such advanced concrete remains constrained by multiple challenges. These include difficulties in refining pozzolanic materials to a satisfactory grade, absence of standardized mix design procedures, lack of field-applicable methodologies, suboptimal utilization of raw materials, and inadequate equipment for producing superior geopolymer concrete. To overcome these hurdles, integrating nanomaterials into production processes offers a promising solution. While previous studies have explored the benefits of nanoparticles in enhancing geopolymer performance, most have focused on single or dual combinations of conventional pozzolanic materials [30-35]. In contrast, current research investigates the formulation of geopolymer concrete using a blend of novel pozzolanic materials: potassium feldspar powder and metakaolin. Moreover, there needs to be more investigation into the durability and geopolymer concrete strength when fortified with NS.

Studies have emphasized numerous advantages of NS in concrete applications. High-volume fly ash and slag concrete's first and final setting times are shortened by NS [36-39]. However, its impact on strength varies over time; while it improves early-age strength in fly ash cement mortar, it may slightly diminish later-age strength. NS has also been successfully integrated into concrete formulations containing waste materials, such as glass powder, overcoming challenges like reduced strength and delayed setting times. Additionally, oil well cement's strength and setting times have been improved and attributed significantly to NS [39-42].

This study combines pozzolanic materials with NS to optimize geopolymer performance. The research evaluates various properties related to strength and durability across the new geopolymer concrete compositions. Incorporating NS is anticipated to enhance geopolymer concrete's specific density and compaction, improving its overall effectiveness, particularly in robustness and longevity. The rigidity of geopolymer concrete could be increased by the refined particle form of NS, potentially reducing structural cracking [43-47].

2. Method

To investigate the impact of nanomaterials, k feldspar, metakaolin, and rice husk ash (RHA) on the mechanical properties of geopolymer concrete, explicitly employing a combination of k feldspar and metakaolin, this study involved the creation of eight different concrete mixes. The main constituents are a pozzolanic combination, naturally existing fine and coarse aggregates, and cementitious materials consisting of 70% metakaolin, 20% k feldspar, and 10% RHA which has been optimized from trial and error method for different ranges. An alkaline solution activates the alumino-silicate source. Varying quantities of NS, ranging from 0% to 6%, were added to the mixes to change the cementitious mixture [48]. SEM imaging was used to characterize NS particles, as shown in Fig. 1.

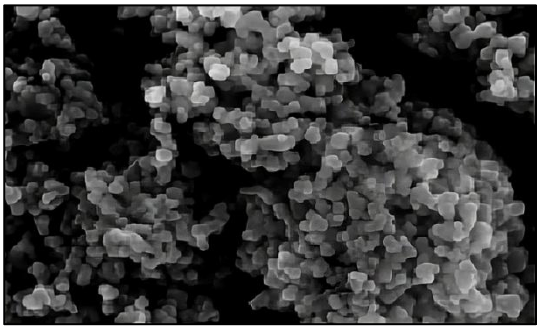

Figure 1. SEM Image of NS

Phosphoric acid was employed as an activator in the polymerization process. Commercially available in liquid form, phosphoric acid was diluted with distilled water to prepare solutions with a molar concentration of 12 mol/L, which stabilized for 24 hours before use. A ratio of 1:0.35 was maintained between the ternary blended pozzolanic material and the alkaline activator solution. A homogenization procedure was applied to guarantee that the nanoparticles were distributed uniformly throughout the fluid. the nano-silica was dispersed in the alkaline activator solution prior to its addition to the dry ingredients. This dispersion was performed using a magnetic stirrer for 10-15 minutes to ensure that the nanoparticles were uniformly suspended in the solution. This step significantly reduced the risk of nano-silica clumping together when added to the geopolymer mix. Table 1 provides the mix proportions for the geopolymer concrete.

Table 1 Mix proportion of experiment groups

Sample ID	Metakaolin (kg)	K feldspar (kg)	RHA (kg)	FA (kg)	CA (kg)	Nano silica (kg)	H3PO4 (kg)	Water (l)
GCC	323.8	80.95	0	595	1176	0	147	1009
GC-N0	283.325	80.95	40.5	595	1176	0	147	1009
GC-N1	283.325	80.95	40.5	595	1176	4.05	147	1009
GC-N2	283.325	80.95	40.5	595	1176	8.1	147	1009
GC-N3	283.325	80.95	40.5	595	1176	12.15	147	1009
GC-N4	283.325	80.95	40.5	595	1176	16.2	147	1009
GC-N5	283.325	80.95	40.5	595	1176	20.25	147	1009
GC-N6	283.325	80.95	40.5	595	1176	24.3	147	1009

Initially, the dry ingredients—fine aggregate, coarse aggregate, and ternary blended pozzolanic materials—were well combined. Following this, the prepared activator was added to the mix. After all the materials were blended in their natural state, the workability was assessed using a slump cone test. The desired cubes and cylinders were then cast from the mixture, with the samples being de-moulded after 24 hours and subsequently cured in an oven at 90 degrees Celsius and tested up to 90 days. Every concrete mix combination had three samples cast to facilitate laboratory testing corresponding to the thermal curing periods.

Several experiments were carried out on fresh and hardened concrete to assess the impact of nanoparticles on the concrete's performance. The slump cone test measures the cohesiveness of freshly mixed concrete and observes its behaviour under gravity. The CS Test ascertains the most significant axial compressive load a concrete sample can sustain before fracture. The STS strength test determines the concrete's lateral tensile strength under axial compressive force. The RCPT (Rapid Chloride Permeability Test) measures how well concrete resists the infiltration of chloride ions. The water absorption test evaluates the microstructure improvements of various concrete mixtures and quantifies the porosity of water-accessible concrete. In order to gain a deeper understanding of the concrete hydration process, the ingredients are identified using XRD (X-ray diffraction). This study prepared concrete samples for XRD analysis by grinding them into fine powders. This process is critical to ensure uniformity and reduce sample loss. Grinding was performed under a liquid medium such as ethanol or methanol to minimize structural damage and ensure accurate measurement of crystalline phases. The finely ground powders were then pressed into sample holders with smooth surfaces, positioned at a 45° angle relative to the incident X-ray beam for optimal diffraction.

The XRD experiments were conducted using CuKα radiation from a diffractometer operating at specific parameters: 45 kV and 40 mA. The diffractometer was configured in a Bragg–Brentano θ–2θ geometry, standard for analyzing crystalline materials. A linear position sensing X-ray detector was employed for data collection. It was able to precisely record diffracted X-rays over a range of 2θ angles, from 8° to 60°, with a step size of 0.017°. These tests aimed to get detailed information on the improvements brought about by adding nanoparticles to the geopolymer concrete mixture.

3. Result and Discusion

The impact of NS and bagasse ash on the strength and durability of k feldspar-metakaolin-based geopolymer concrete was studied. This study introduces two key ingredients: rice husk ash, which replaces pozzolanic material up to 10% of the original amount, and NS, which is supplied externally to the pozzolanic mixtures in proportions as high as 6%. The geopolymer concrete's pozzolanic ingredient was a mixture of metakaolin and k feldspar.

There were two primary findings: The first examined how rice husk ash affected metakaolin and k feldspar's pozzolanic activity. The second finding examined how NS might improve the geopolymer concrete's packing density. Experiments were conducted on freshly mixed geopolymer concrete using fresh and hardened concrete to get thorough insights. Below is a detailed discussion of the test findings, emphasising the contributions of NS and rice husk ash to the overall performance of the geopolymer concrete.

3.1. Slump and Density

The relative slump values of the designed geopolymer concrete mixes, based on a flow test involving 25 tamps, are presented in Table 2. It is essential to highlight that all mixes demonstrated excellent flowability, regardless of their composite types. Introducing NS and rice husk ash into the geopolymer mixtures significantly enhanced the relative slump values.

Table 2 Slump test results of mixes

Sample ID	Relative Slump	Density (kg/m^3)
CGC	-	1778
GC-N0	1.49	1760
GC-N1	1.71	1753
GC-N2	2.26	1781
GC-N3	2.55	1768
GC-N4	2.71	1739
GC-N5	2.25	1719
GC-N6	2.20	1639

When 10% of the pozzolanic material was replaced with rice husk ash, the slump height increased by 50%. Reduced flocculated pozzolanic particles in the blend and an enhanced ball-bearing action in the geopolymer concrete are responsible for this improvement. Moreover, the blend's slump height increased by 69% when 1% NS was added. This rise results from increased packing density; fine NS particles filled in the blend's voids, lowering porosity and decreased the mix's workability.

Up to 4% of NS was added, maintaining the trend of rising slump height. The pozzolanic mix's overall surface area was decreased, the packing density was increased, and the higher NS concentration noticeably decreased the flowability of the concrete.

The granular form of micro silica enhances mobility during the mixing process by functioning as a ball-bearing between the combined particles. However, because rice husk ash and NS have lower specific gravity than k feldspar and metakaolin, adding them to the concrete gradually reduces its density. Higher nanoparticle content lightweight geopolymer composites had decreased flowability. Table 2 shows that compared to the mix containing 4% NS, the mix slump with 5% NS was 20% lower. More nano silica further reduced the slump height, indicating that more than 4% can result in more voids in the geopolymer concrete. Because of its tiny particle size, nano silica is more water-retentive than other nanoparticles, which impedes the mortar's flow. This is explained by the nanoparticles' hydrophilic nature, which allows them to absorb water and have a large surface area. The decrease in flowability was further influenced by the NS's non-uniform particle size and the pozzolanic materials' direct interaction with the NS.

3.2. Compressive Strength

Figure 2 displays the CS of geopolymer concrete specimens at 7, 28, and 90 days with varying NS concentrations (0% to 6%). The mixed geopolymer concrete with and without nanosilica showed an increase in CS over time. Specifically, after 28 days of thermal curing, the CSs of conventional and geopolymer concrete incorporating rice husk ash (GPC-RHA) were determined at 42.86 MPa and 40.87 MPa, respectively. One per cent of the mixture's CS was enhanced by NS, and the material was enhanced by four per cent.

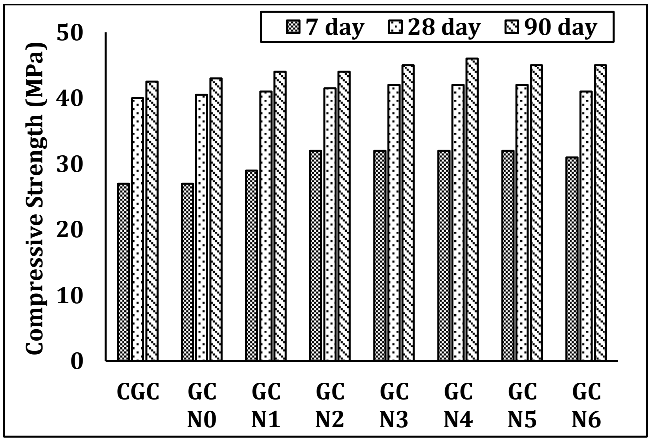

Figure 2. Compressive strength of GC-NS mixes

The key ingredients are natural fine and coarse aggregates, an alkaline solution with 70% metakaolin, 20% k feldspar, and 10% RHA, and cementitious materials made from alumino-silicate sources. This strength increase can be attributed to the increased availability of nano silica for reaction as its volume fraction increases in the composite. The higher NS content accelerates reaction rates than combinations without NS. Reactive silica is the reason for this acceleration since it controls the polymerization reaction and promotes the creation of alumina-silica gel, a crucial step in developing material strength. Particularly apparent in ternary blended geopolymer concrete is potassium aluminosilicate hydrate (K-A-S-H) gel production. By improving the microstructure and matrix packing, more K-A-S-H gel is produced by interacting with the potassium in the feldspar by adding NS. Following 7, 28, and 90 days of heat curing, the geopolymer concrete cubes' absorbance capacity and CS improvements increased by 15%, 12%, and 6%, respectively, due to these interactions. These findings suggest that nano silica is essential for the early-age strength development of concrete. Nanosilica accelerates the polymerization process by functioning as nucleation sites and improving the formation of gel phases. This fast reaction results in a denser, more connected aluminosilicate network that lowers porosity and improves mechanical properties [49].

However, the benefits of nano silica addition have a threshold. They surpass the ideal threshold for the amount of NS, which lowers CS. This decline is primarily due to the aggregation of excessive NS particles, which can create defects like pores or unreacted particles within the matrix. These defects result from components in the specimen that were not reacted to after the reaction. Additionally, the decline in CS observed beyond a 6% NS addition can be attributed to the replacement of more robust materials such as K-feldspar and metakaolin with weaker materials like rice husk ash, which lacks significant pozzolanic activity in the ternary mix.

Furthermore, unhydrated cement coated with excess phosphoric acid, produced by adding more than 4% NS, may slow the hydration process. This excess phosphoric acid can impede the adequate hydration of cementitious components, thereby reducing the strength properties of the geopolymer concrete. The unreacted phosphoric acid forms a coating around the cement particles, preventing complete hydration and leading to a weaker matrix structure.

In conclusion, including nano silica in geopolymer concrete significantly enhances CS, particularly at early ages, by promoting the formation of additional K-A-S-H gel and improving the microstructure. However, careful optimization is required to avoid excessive NS content, leading to aggregation, defects, and reduced strength. The balance between the reactive components and the optimization of nano silica content is crucial for achieving the desired mechanical properties in geopolymer concrete.

3.3. Split Tensile Strength

Figure 3 displays the split tensile strengths of many geopolymer concrete samples (GC-N0 to GC-N6) after seven and 28 days, with tensile strengths ranging from 3.49 MPa to 3.89 MPa after 28 days and 2.5 MPa to 3.3 MPa after seven days. Interestingly, as the dose of nanoparticles rose, the tensile strength of geopolymer concrete increased in a manner comparable to that of CS; after seven days, the GC-N4 mix showed the most significant gain (18.9%). In a detailed study involving metakaolin, rice husk ash, and K-feldspar, these materials were used in proportions of 70%, 10%, and 20%, respectively, with varying nanoparticle dosages. The STS of these geopolymer composites followed a similar increasing trend. Specifically, the GC-N4 sample, which comprised 70% metakaolin, 10% rice husk ash, 20% K-feldspar, and 4% nanoparticles, exhibited the highest strength increase. This mixture increased STS by 26.87% and 27.4% after 7 and 28 days.

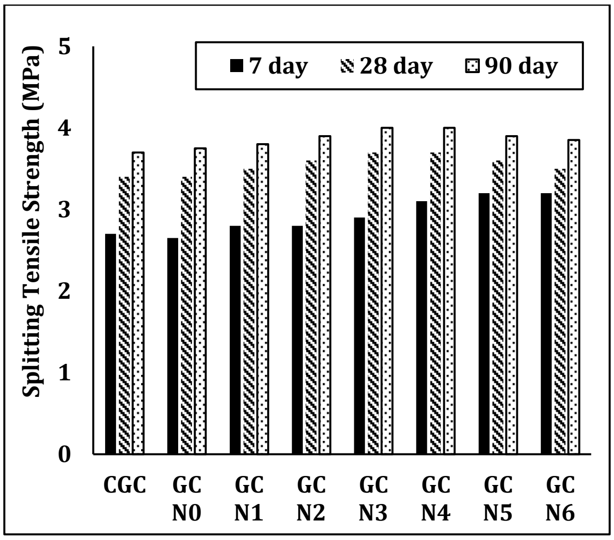

Figure 3. Split Tensile Strength of GC-NS Mixes

The observed increase in tensile strength up to a 4% addition of NS is attributed to several synergistic factors. NS, known for its high reactivity and large surface area, is crucial in enhancing geopolymerization. NS is added to the geopolymer matrix as a source of reactive silica, which helps the aluminosilicate network to become denser and more linked. This improved network structure is critical for enhancing the geopolymer concrete's mechanical properties and durability.

Moreover, NS particles serve as nucleation sites for forming gel phases, accelerating the polymerization process. This results in faster setting and hardening of the geopolymer concrete, contributing to its early-age strength development. The presence of NS also leads to a more homogeneous and densely packed microstructure, significantly reducing porosity and improving the overall integrity of the material.

The advantages of adding NS, however, are not infinite. Tensile strength reduces as the NS level rises above 4%. This decrease is mainly caused by the inhomogeneity produced in the uncured resin zones by the aggregation of NS particles. Weaker areas inside the matrix result from these agglomerations, which increase the material's porosity. This harms the geopolymer concrete's STS and reduces the NS's effectiveness. The influence of NS on the water-binder ratio in geopolymer concrete is another essential factor to consider. By lowering this ratio, NS creates a denser mortar matrix with a more clearly defined interfacial transition zone. When NS is added optimally, this zone—usually the weakest link in concrete composites—becomes more resilient. However, because of the increased porosity and inhomogeneity brought on by particle agglomeration, this zone becomes vulnerable to crack formation when more than 4% NS is utilized.

Including NS in geopolymer concrete significantly enhances STS, mainly when used in optimal amounts. The combination of metakaolin, rice husk ash, and K-feldspar, with an optimal 4% NS addition, results in a robust geopolymer matrix with superior mechanical properties. However, exceeding this optimal dosage leads to diminishing returns due to agglomeration and increased porosity, highlighting the importance of precise material optimization in geopolymer concrete formulations.

3.4. Rapid Chloride Permeability Test (RCPT)

The study focused on assessing the impact of Nanosilica on the resistance of geopolymer concrete to chloride penetration, a crucial factor for concrete durability in corrosive environments. Results indicated a notable improvement in chloride resistance with the inclusion of Nanosilica compared to conventional mixes. For instance, without Nanosilica and bagasse ash, the control mix exhibited a charge transmission of 1058 coulombs, indicating a low level of chloride penetration. In contrast, mixes containing Nanosilica showed significantly enhanced performance, with a charge transmission of 956 coulombs, categorized as extremely low chloride penetration. This represented a 28.61 percentage point increase in resistance compared to the control.

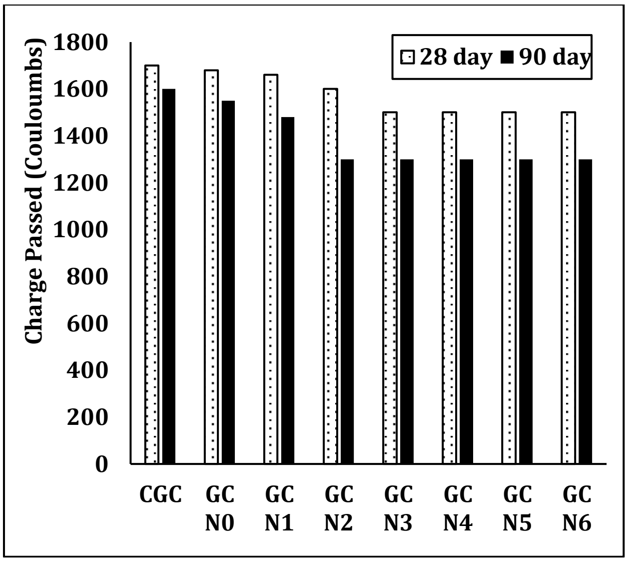

Figure 4. RCPT Test results on mixes

The observed enhancement aligns with established literature [50-56], highlighting Nanoparticles' role in bolstering concrete's resistance to chloride diffusion. This improvement is attributed to Nano silica's nucleation effect, which enhances mechanical properties. The study also noted that well-dispersed nano dispersions improved particle packing within the geopolymer matrix, resulting in a microstructure characterized by increased compactness and density. The spherical morphology of the bagasse ash and NS increased the packing density.

Furthermore, the study found that 90-day cured geopolymer concrete exhibited lower charge transmissions than those cured for 28 days across all NS mixes. This can be attributed to the ongoing densification of the microstructure over time due to adding NS, refining pore structures, and compacting the matrix. Previous research supported these findings, demonstrating NS's efficacy in reducing chloride ion penetration and improving concrete durability [50-5].

Furthermore, because NS contains more crystalline components, the RCPT values in the geopolymer mortar based on k feldspar and metakaolin were also lowered. These methods improve the material's resistance to chloride diffusion by aiding in fracture arrest and crack bridging.

The findings highlight how NS may improve geopolymer concrete's resistance to chloride penetration. The findings highlight improved resistance from enhanced mechanical properties, optimized particle packing, and refined microstructure. These insights emphasize NS's role as a promising additive in geopolymer concrete formulations that extend service life and enhance performance in harsh environmental conditions rich in chlorides.

3.5. Water absorption

Water absorption is critical in assessing concrete's long-term durability, impacting its structural integrity and the longevity of embedded reinforcements. This test assesses the concrete's resistance to moisture infiltration, which is significantly impacted by capillary suction and pressure head. The water absorption coefficient found in these tests is a prediction indicator for the service life of concrete structures since it shows how resistant the structure is to moisture infiltration.

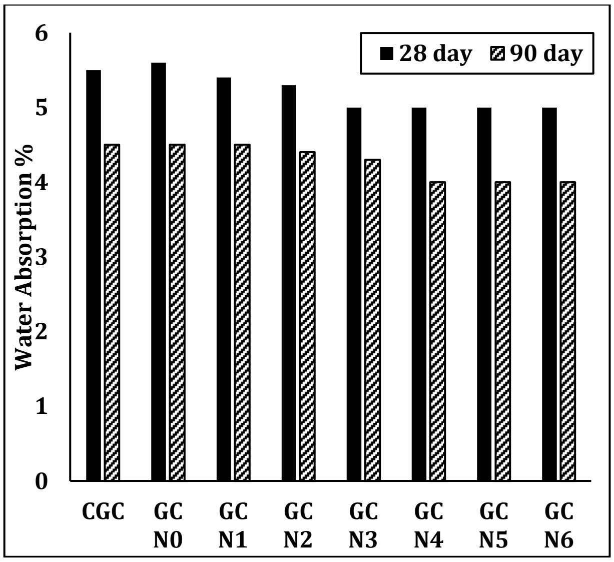

Figure 5. Water absorption test results on mixes

Using bagasse ash and NS in geopolymer concrete in Figure 5 provides exciting insights into the variations in water absorption rates. Water absorption is steadily reduced as the amount of NS rises. Specifically, significant differences were observed when comparing blends using k feldspar and metakaolin as binders versus blends incorporating rice husk ash and NS. For instance, during 28 days of thermal curing, the GC-N0 mix showed a 5.5% water absorption, which decreased to 4.5% after 90 days. Interestingly, this trend was reversed when rice husk ash replaced 10% of metakaolin and k feldspar in blending, indicating a slower hydration reaction at 28 days but subsequent pore filling with K-A-S-H gel at 90 days, reducing water absorption.

The introduction of NS further improved water resistance in geopolymer concrete. With NS levels reaching up to 6%, water absorption decreased consistently at 28 and 90 days of thermal curing compared to controlled geopolymer concrete. This reduction amounted to 0.5% and 0.8% decreases in water absorption, respectively, highlighting the additive's effectiveness in densifying the concrete matrix. The pozzolanic activity of rice husk ash and NS filled the pore structure of geopolymer concrete with fine-grained particles, minimizing capillary pores and improving overall compactness, hence facilitating densification.

The fine particle size of NS played a crucial role in filling the bulk pozzolanic paste's pores, contributing significantly to the reduction in capillary absorption and consequent strength gains. Moreover, higher doses of NS correlated with improved concrete density, a primary factor influencing lower water absorption rates. This phenomenon underscores the pivotal role of NS in minimizing water ingress, thereby enhancing concrete durability.

Overall, this experiment underscores the beneficial impact of NS and rice husk ash on mitigating water absorption in geopolymer concrete. By refining the pore structure and enhancing overall compactness, these additives contribute to a more resilient concrete matrix capable of withstanding moisture-induced degradation over prolonged periods [49]. The findings emphasize the potential of NS as a strategic additive in optimizing concrete performance in various environmental conditions, ultimately supporting sustainable infrastructure development through enhanced durability and longevity.

3.6. Sulphate resistance test

The sulfate resistance test assessed the impact of Na_2SO_4 exposure on geopolymer concrete specimens, measuring gradual mass loss over increasing immersion durations. Figure 6 illustrates that higher percentages of NS corresponded to reduced mass loss. Introducing rice husk ash into k feldspar and metakaolin mixes resulted in a 2% lower mass loss in blends. However, the addition of NS further decreased mass loss in concrete mixes. For instance, 4% NS in ternary concrete mixes reduced mass loss to 6%.

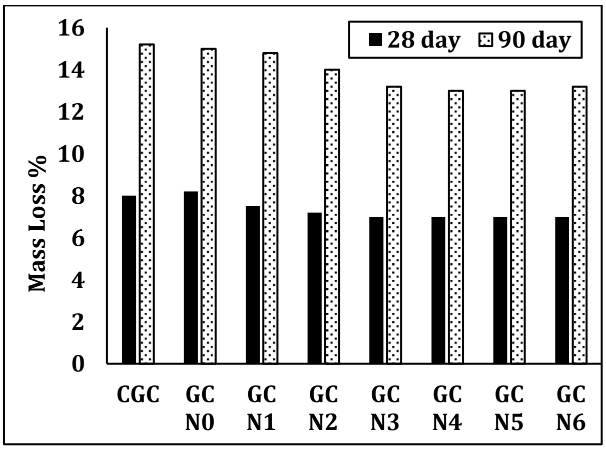

Figure 6. Mass loss % on GC-NS mixes

The large surface area and excellent grain size of geopolymer concrete incorporating NS are responsible for its exceptional strength and longevity. In order to encourage the development of a denser structure, NS successfully filled in the tiny spaces between pozzolanic materials like metakaolin and k feldspar. During hydration, phosphoric acid interacted with nano silica and husk ash to further promote the production of K-A-S-H gel. This subsequent gel reinforced the geopolymer concrete, stopping sulfate ion penetration by enhancing the microstructure's surface.

Further additions of NS did not significantly alter mass loss beyond 6%, suggesting a threshold effect in enhancing sulfate resistance. Acid attacks can break Si–O–Al/Si bonds within the geopolymer network structure. Geopolymer concrete specimens cured at elevated temperatures may exhibit reduced density, potentially facilitating acid penetration and increasing surface area vulnerability to damage. Including up to 10% rice husk ash increased the reactive phase content, enhancing its effectiveness. Additionally, metakaolin contributed to higher thermal curing temperatures, generating internal heat during hydration and geo-polymerization dissolution, which is crucial for binder phase formation. The GC-N6 variant demonstrated superior resistance to acidic media than GC, indicating a denser and more robust matrix.

This experiment underscores NS's pivotal role in augmenting sulfate resistance in geopolymer concrete. By optimizing microstructure density and enhancing chemical interactions among constituents, NS effectively mitigates mass loss under sulfate exposure. These findings highlight NS as a promising additive for improving geopolymer concrete's durability and performance in harsh environmental conditions, supporting sustainable infrastructure development. Future research may explore optimal NS dosages and additional additives to enhance geopolymer concrete's resilience against chemical degradation, extending its service life in challenging applications.

3.7. X-ray diffraction

The XRD analysis revealed several crystalline phases present in the geopolymer concrete samples. Quartz (SiO_2), traces of Potassium Feldspar ($KAlSi_3O_8$), mullite ($Al_6Si_2O_{13}$), and hematite (Fe_2O_3) were among the identified phases. Each phase was characterized by its distinct diffraction pattern, represented by peaks at specific 2θ angles. For instance, quartz typically peaks at approximately 34.73° (CuKα).

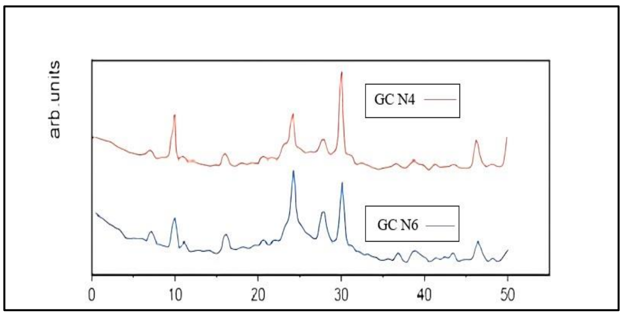

Figure 7. XRD test results for different mixes

The addition of NS to geopolymer concrete mixes significantly influenced the crystalline phase composition and microstructure. NS, characterized by its ultrafine particle size and high surface area, improved the concrete's performance. One notable observation from the XRD results was the increase in quartz content by adding NS. Quartz is a crystalline phase known for its inert and durable nature, contributing to the concrete's mechanical strength and chemical resistance. The denser microstructure resulting from NS addition contributed to reduced permeability and enhanced durability against chemical attacks, such as sulfate ions.

The hydration process, influenced by adding alumina silicate materials like metakaolin and k feldspar, proceeded differently in NS. Traditionally, aluminum silicates react with alkalis to form geopolymer gels, but NS accelerated these reactions, promoting additional hydration products. This evident phenomenon filled voids and improved the concrete's mechanical properties. The XRD results underscored the positive impact of NS on geopolymer concrete's durability and mechanical strength. By enhancing hydration kinetics and promoting the formation of dense microstructures, NS mitigated pore formation and reduced permeability. This reduction in permeability is critical for resisting chloride and sulfate ion penetration, which are common causes of concrete deterioration in aggressive environments.

Moreover, the mineral phases improved chemical resistance and minimized mass loss when exposed to aggressive substances like sodium sulfate (Na_2SO_4). The findings suggest that optimizing NS dosages and combining them with suitable alumino silicates can tailor geopolymer concrete formulations for specific environmental conditions, enhancing their service life and sustainability.

4. Conclusion

Geopolymer concrete compositions using a ternary blend of k feldspar, metakaolin, and rice husk ash exhibited superior performance compared to blends like k feldspar and metakaolin alone. This ternary combination promoted the formation of secondary K-A-S-H gel, crucial for enhancing the concrete's strength and durability properties.

1. NS Enhancement: Up to 6% in the ternary geopolymer concrete significantly improved packing density. This enhancement accelerated the performance of the concrete, making it more robust and durable.
2. Consistency Improvement: NS acted as bearings within the concrete matrix, improving the workability and slump value. This allowed for easier placement and compaction during construction.
3. Optimal Dosage: Geopolymer concrete formulations with a ternary blend of k feldspar, metakaolin, and rice husk ash, combined with 4% NS, demonstrated the best results in terms of compressive and split tensile strengths after both 7 and 28 days of curing.
4. Low Resistivity: The electrical resistivity (RCPT values) of geopolymer concrete with the ternary blend and 4% NS was significantly lower. This indicates reduced penetration of coulomb charge, suggesting enhanced durability and resistance to chloride ion penetration.
5. Water Absorption Reduction: Increasing NS content in ternary geopolymer concrete reduced water absorption. This was attributed to accelerated hydration kinetics and the filling of capillary pores with additional K-A-S-H gel, leading to a denser and less permeable concrete structure.
6. Microstructural Improvements: Ternary geopolymer concrete mixes containing 4% or more nano silica exhibited notable improvements in surface microstructure. These enhancements improved performance against sulfate attacks and reduced mass loss over time, indicating superior durability.
7. Long-term Durability: The incorporation of NS not only improved immediate mechanical properties but also enhanced the long-term durability of geopolymer concrete. This is crucial for ensuring sustainable construction practices and minimizing maintenance costs.
8. Environmental Benefits: Compared to conventional Portland cement-based concrete, geopolymer concrete offers environmental advantages like a lower carbon footprint, especially when optimized with NS. This supports the objectives of global sustainability.
9. Structural Applications: The enhanced properties of NS-modified geopolymer concrete make it suitable for various structural applications, including bridges, buildings, and infrastructure exposed to aggressive environmental conditions.
10. Technological Advancements: The study underscores technological advancements in concrete materials science, highlighting nanomaterials' role in improving concrete performance and longevity.
11. Quality Control: NS addition in geopolymer concrete necessitates rigorous quality control measures to ensure uniform dispersion and optimal performance during production and construction.
12. Economic Viability: Despite potentially higher material costs, NS-enhanced geopolymer concrete offers economic benefits through reduced maintenance and extended service life, offsetting initial investment costs over the structure's life cycle.
13. Global Applications: The findings have implications for global applications of NS in geopolymer concrete, promoting sustainable construction practices worldwide and addressing infrastructure challenges.
14. Challenges: One of the main challenges in using nano-silica in geopolymer matrices is achieving uniform dispersion. Due to its high surface area and small particle size, nano-silica has a tendency to agglomerate, which can affect the consistency of the mixture, leading to uneven distribution of strength and durability properties. The can been addressed by use of dispersing agents or surfactants that help reduce the surface tension and promote better dispersion of nano-silica within the geopolymer matrix. Implementation of advanced mixing

techniques such as high-shear mixing or ultrasonic dispersion to ensure uniform distribution of nano-silica. Optimization of nano-silica content to avoid overloading, which may increase the risk of agglomeration.

15. Future Research Directions: Future research could optimise NS dosages, explore new nanomaterials, and investigate the long-term behavior of NS-modified geopolymer concrete under varying environmental conditions to advance its application and performance further.

In summary, incorporating NS in ternary geopolymer concrete formulations showed promising results across various performance metrics. It enhanced mechanical properties, reduced chloride ion penetration, lowered water absorption, and improved resistance to chemical attacks. These findings underscore the potential of NS to optimize the properties of geopolymer concrete, making it a viable alternative in sustainable construction practices. Future research could explore optimal NS dosages and their long-term effects on concrete durability under different environmental conditions.

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Author contributions

Nanthini Murugesan: Conceptualization, Methodology, Software **Ganesan Ramachandran:** Data curation, Writing-Original draft preparation, Software, Validation. **Jaganathan Venugopal:** Visualization, Investigation, Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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