

**Synergistic effect of metakaolin and nano-silica in concrete:
A comprehensive experimental study on concrete properties
thermal stability and eco-efficiency**



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by

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Chapter 8

Conclusion

8.1 Introduction

This chapter presents a comprehensive analysis of the outcomes derived from investigations into MK and NS binary mortars, as well as concrete compositions, compared against reference concrete. The evaluation encompasses mechanical and durability properties, thermal stability, microstructural studies, eco-efficiency, and cost indices. The comparative study sheds light on the nuanced impacts of incorporating metakaolin and nano-silica in both binary and ternary formulations, providing valuable insights into the performance and sustainability aspects of these materials.

8.2 Mortar

8.2.1 Compressive strength

The compressive strength of the reference mortar slightly (0.1%) exceeded that of the binary mortar with 10% metakaolin at 28 days. However, by the 56th day, the compressive strength of the metakaolin mortar surpassed that of the reference mortar. This observation indicates that the pozzolanic reaction between metakaolin and CH persisted even in the later stages, contributing to the enhanced compressive strength of the metakaolin mortar over time.

At a 10% dosage, a substantial part of metakaolin engaged in the pozzolanic reaction. However, at higher doses of metakaolin, the cement hydration rate was insufficient for a proper pozzolanic reaction on metakaolin surfaces. This resulted in a significant amount

of unreacted metakaolin particles remaining in the cement-water matrix, not contributing to mortar strength by forming hydrates like CSH and CASH.

The compressive strength of the binary mortar increased with the rising nano-silica dosage up to 4.5%. This improvement can be attributed to the combined effects of the pozzolanic reaction and the influence of nanoparticles on the ordering of the CSH gel structure induced by nano-silica. However, the marginal strength increment observed at a higher nano-silica dosage of 4.5% might result from the uneven distribution and agglomeration of high surface area nano-silica particles during manual preparation.

Nano-particle, possessing a high surface area of 150 m²/g and an average diameter of 18.1 nm, exhibit higher concentrations in the cement-water matrix than metakaolin particles. This results in a significantly larger total surface area of the active pozzolan introduced by SiO₂

nanoparticles, leading to a substantial increase in pozzolanic reaction, CSH volume, and compressive strength in cement mortars at SiO₂ dosages between 1.5 and 4.5 wt.%.

Ternary blends with 10% metakaolin and nano-silica up to 4.5% exhibited higher compressive strength than their binary counterparts. However, higher metakaolin proportions reduced strength, as observed in binary mixtures. At 10% metakaolin, a significant pozzolanic reaction occurred, with low unreacted metakaolin and nano-silica manifesting pozzolanic and structural effects. With constant metakaolin, strength increased linearly with nano-silica dosage. In all 10% metakaolin and nano-silica compositions, compressive strength surpassed MK10 binary mortar and CM at all ages.

Additionally, in ternary blends of MK15 and MK20, nano-silica compensated for the strength reduction associated with increased metakaolin dosage.

The packing effect of metakaolin can fill the interstitial voids in the hardened microstructure of cement mortar, increasing strength and density. The pozzolanic effect combined glass-like silicon and alumina in metakaolin with calcium oxide and hydroxide in cement to improve the bonding strength and solid volume, resulting in higher compressive strength of cured ternary blended cement mortar.

The presence of nano-silica in the ternary blends increased the pozzolanic activity, which was indicated by the higher relative strength values compared to the binary blends. The highest k-factors were observed in nano-silica binary blends with 3% nano-silica. The approach of determining the k-factor of blended cement mixtures has limitations due to factors such as mineral compositions, curing conditions and age, type of cement, pozzolan-cement ratio, etc., but it still provides increased assurance in designing mixtures with high efficiency.

The TGA weight loss observed in CM, MK10, NS4.5, and MK10NS4.5 mortar powders during hydration product dehydration (110-650°C) increased with decreasing OPC content, indicating more hydration products in blended mortars. The weight loss aligns with compressive strength results, and XRD patterns support TG analysis, showing lower CH peaks for MK10, NS4.5, and MK10NS4.5, reflecting pozzolanic activity.

Morphological analysis highlighted variations in hydration product formation. The CM paste displayed ettringite and long CH crystals. MK10 hydrates exhibited AFm, CH, and

ettringite. NS4.5 showed a uniform, denser microstructure with ettringite and AFm. MK10NS4.5 had significant ettringite and CSH.

8.2.2 Thermal stability

The compressive strength at elevated temperatures exhibited a consistent trend of strength gain at 200°C, followed by gradual strength loss at higher temperatures. Binary blends of MK and NS showed higher strengths at 200°C than the CM, with the combination of 10% MK and 3% NS demonstrating the highest strengths. Ternary blended mortars consistently exhibited higher strengths across all temperatures, with the blend MK10NS3 displaying the highest strengths.

Furthermore, the study evaluated the thermal resistance of mortars and found that the blend MK10NS1.5 exhibited the highest thermal resistance, followed closely by MK10NS3. Incorporating 10% MK and 1.5% NS, the mortar composition enhanced its ability to withstand high temperatures while preserving its compressive strength. Conversely, higher dosages of MK and NS decreased the mortar's thermal resistance.

While MK10NS3 and MK10NS4.5 also demonstrated significant heat resistance, MK10NS3 exhibited less heat resistance than MK10NS1.5 despite displaying superior residual compressive strength. This reduction is attributed to vapour entrapment within its denser structure, resulting in elevated pressure and explosion.

The mortar specimens did not exhibit any visible cracks until they were exposed to temperatures of 350°C. However, cracks and pitting became evident above this temperature, with larger cracks observed at 650°C. Spalling occurred due to internal vapour pressure and thermal stresses surpassing the concrete's tensile strength. Notably,

the mortar containing 10% MK and 3% NS had a significantly higher frequency of spalling, which can be attributed to its denser pore structure

8.3 Concrete

8.3.1 Mechanical properties

The binary and ternary blends of MK and NS consistently outperformed conventional concrete, showcasing enhanced compressive strength at different curing durations. The synergy between MK and NS, with their distinct mechanisms, contributed significantly to the concrete's overall strength development.

The examination of compressive strength in binary blends of metakaolin and nano-silica and their ternary blends demonstrated distinct advantages over reference concrete. Notably, at the early ages (3 days), the binary blend MK10 exhibited an 11% increase in compressive strength, highlighting a positive effect of metakaolin on early strength development. In nano-silica binary concrete, NS3 composition demonstrated significant strength enhancement, with a 29% increase compared to the reference concrete. The synergistic effect of metakaolin and nano-silica was evident, significantly contributing to the early-age compressive strength, reaching a peak enhancement of 38% in the ternary combination MK10NS3 at 3 days.

At the crucial 28-day evaluation, MK10 sustained its strength advantage with a 13% increase over the reference concrete, reaching 61 MPa. NS3 achieved the highest strength at 65 MPa, surpassing the reference concrete by around 21%. Ternary blends consistently outperformed binary counterparts, with MK10NS3 reaching the highest compressive strength at 69.7 MPa, signifying nearly a 30% improvement over the reference concrete.

This underscores the enduring and substantial synergistic effect between 10% MK and 3% NS particles on overall strength development. This sustained superior performance persisted at 56 days, 90 days, and even 180 days, highlighting the prolonged pozzolanic activity of metakaolin and the high reactivity of nano-silica particles contributing to the enduring advantage of ternary blends.

The 180-day compressive strength test revealed sustained strength development in binary mortars, with MK10 exhibiting a 7.4% increase over the normal concrete. NS binary blends, especially NS3, demonstrated progressive improvements, up to 19.4% compared to CC. Ternary concrete, benefitting from metakaolin and nano-silica synergy, outperformed all, with MK10NS3 showing a remarkable 26% strength increment over the reference concrete.

The integration of metakaolin in concrete has yielded a substantial increase in compressive strength, attributed to its remarkably high surface area—100 times greater than that of cement. This characteristic provides abundant pozzolanic active sites for interaction with CH, generating additional CSH and CASH. The finely dispersed metakaolin particles effectively filled the voids between cement particles, leading to a more compact and less porous microstructure. This structural refinement has, in turn, positively impacted the mechanical and durability properties of the concrete.

Nano-silica, characterised by a large surface area ($150 \text{ m}^2/\text{g}$) and a small average diameter (18.1 nm), exhibited a higher concentration in the cement-water mix than metakaolin. This translated to a significantly larger surface area of active pozzolan introduced by nano-silica. Within the optimal range of 1.5 to 3% nano-silica, a substantial portion

contributed to the pozzolanic reaction, augmenting the volume of CSH and, consequently, the compressive strength of the concrete. However, at higher doses of nano-silica (4.5%), a proportional increase in hydration rate was not observed, potentially due to inadequate cement hydration facilitating a pozzolanic reaction on the highly reactive surfaces of nano-silica. Agglomeration of nano-silica particles at higher doses also emerged as a probable cause for reduced strength.

Ternary concrete incorporating 10% metakaolin and 1.5 to 3% nano-silica surpassed their binary counterparts, benefiting from synergistic effects. Metakaolin, with its extensive surface area, facilitates abundant pozzolanic reactions, while the unique properties of nano-silica, even at lower concentrations, contribute to an active pozzolan, collectively optimising particle packing. This synergy fosters a highly compact and less porous concrete structure, ultimately translating into enhanced mechanical strength and durability properties.

The combinations of metakaolin and nano-silica demonstrated notable improvements in both split tensile strength and flexural strength, registering a substantial increase of 15.6% and 31%, respectively, in MK10NS3 compared to the reference concrete. The notable increase in tensile strength observed in ternary concrete, where metakaolin and nano-silica are incorporated, can be attributed to reduced voids. This reduction occurs due to the refinement of pores at the interfacial transition zone (ITZ), a process facilitated by the high reactivity of nano-silica particles coupled with the filler effect and pozzolanic action of metakaolin. The increased flexural strength in the MKNS ternary composition is linked to an improved adhesion between the cement paste and aggregate, particularly at the optimal 3% dosage of nano-silica.

8.3.2 Microstructural studies

XRD analysis of 28-day cured cement pastes highlighted the consistent presence of portlandite and revealed its crucial performance indicator at a 2θ angle of 18° . Incorporating MK and NS in concrete showcased enhanced CSH formation potential, with MK10 demonstrating a 49% higher portlandite consumption than the reference sample. Binary blends with NS significantly increased portlandite consumption by 50, 62 and 57% in NS1.5, NS3 and NS4.5 blended pastes, respectively, compared to the reference paste. Ternary blends MK10NS1.5, MK10NS3, and MK10NS4.5 displayed a substantial rise in CH consumption by 76, 88 and 75%, respectively, compared to the reference paste. This emphasises the synergistic impact of MK and NS in fostering elevated pozzolanic reactivity for augmented CSH gel formation, and these results are in line with the strength performance.

The TGA/DSC analysis revealed that MKNS ternary blends exhibited the highest weight loss, particularly notable between 110°C and 650°C . This signifies extensive dehydration of hydration products, indicating the formation of additional hydrated compounds. MK10NS3 demonstrated a significant 22.8% weight loss, emphasising its superior performance in generating hydrated products.

The microstructural analysis through SEM provides valuable insights into the compressive strength of the concrete blends. The presence of gel-like CSH and plate-like CH phases is evident in the reference concrete, along with ettringite and micropores. MK10 demonstrates a denser morphology, reducing CH and ettringite while forming CSH and CASH, indicating a refined pore structure. Introducing NS in binary pastes leads to densification, attributed to high pozzolanic activity and the filling effect. NS1.5 shows

needle-like ettringite, calcite crystals, and PCE influence. NS3 exhibits honeycomb-like CSH structures, highlighting the synergistic effect with PCE in reducing pore size. The 4.5NS mix shows scattered CSH, increased CH, and more pores, indicating potential agglomeration issues. MK10NS1.5 demonstrates refined pores and enhanced CSH gel, while MK10NS3 displays a denser, uniform matrix with refined pores, emphasizing the blend's effectiveness. MK10NS4.5 reveals a favourable structure but a higher CH presence, possibly due to incomplete reactions. Overall, ternary blends of MK and NS significantly enhance microstructure, promising improved strength and durability through refined pore structures and denser matrices.

The N₂ adsorption test results demonstrated that including metakaolin and nano-silica consistently reduces pore volume in cement paste powders. Ternary mixtures, specifically MK10NS1.5 and MK10NS3, exhibit lower percentage porosity, complementing mechanical and durability test outcomes. This aligns with the positive influence of metakaolin and nano-silica on cement paste pore characteristics.

8.3.3 Durability performance of concrete

At 28 days, CC exhibited a 67% increase in carbonation depth compared to its 14 days depth. MK10 showed a 10% reduction, compared to CC, attributed to denser microstructure from MK's pozzolanic activity. NS binary mixes demonstrated increased resistance, with up to 31% less carbonation depth in NS3. Ternary MK10NS blends outperformed CC, with MK10NS3 showing a remarkable 35% reduction at 28 days, highlighting the synergistic influence of MK and NS in creating a densified microstructure. This enhanced resistance reaffirms reduced pore volumes and finer pore structure of MKNS blends.

The study revealed that the interaction between concrete and water initially results in a high absorption rate, gradually diminishing until saturation at 6 days. MK10 showcased a 4% decrease in water absorption compared to the reference concrete, while NS1.5 and NS3 displayed a 4.7% reduction. In MK10NS3 concrete, the least water absorption was evident, with a notable decrease of 21% compared to the reference concrete. The diminished initial water absorption rate in MK10NS3 points to reduced capillary porosity attributed to a highly refined pore microstructure. These outcomes align with the observed strength properties and carbonation depth, affirming the enhanced durability of MK10NS3 composition. However, higher absorption in NS4.5 compositions suggests potential limitations in excessive nano-silica contribution.

Normal concrete exhibited a high 11.7% mass loss, indicating vulnerability in a 5% sulfuric acid solution in 28 days of immersion. Blended concrete mixes, however, displayed reduced mass loss, showcasing enhanced resistance attributed to decreased permeability from pozzolanic activity. Ternary MK10NS3 mix exhibited the lowest mass loss at 5.08%, outperforming binary counterparts (MK10: 8.16%, NS3: 7.75%). This highlights the potential of MKNS blended concrete, particularly in ternary formulations, to improve acid resistance significantly.

8.3.4 Microstructural studies on carbonated concrete

The TGA/DSC analysis of carbonated concrete samples unveiled distinct CaCO_3 content variations. The weight loss, occurring between 550°C and 950°C and attributed to CaCO_3 decomposition, correlates with carbonation depths. The reference concrete demonstrated

the highest weight loss, equivalent to 28.7% CaCO₃, whereas MK10NS3 exhibited the lowest, representing 16.16% CaCO₃.

8.3.5 Thermal stability of concrete

i Residual compressive strength

At elevated temperatures, the compressive strength of normal concrete increased up to 500°C. This increase can be attributed to internal autoclaving within the concrete caused by steam, leading to additional hydration of previously unhydrated cement grains. Likewise, the compressive strength of MK10 and NS1.5 compositions also increased until the temperature reached 350°C. This can be attributed to the temperature-induced hydration of unhydrated MK particles and the continued hydration of unreacted cement particles with NS particles, improving the concrete microstructure.

MKNS ternary blends exhibited increased strength up to 200°C, attributed to a denser microstructure resulting from the synergistic effect between metakaolin and nano-silica. The highest strength was recorded in MK10NS3 at 81.1 MPa at 200°C, followed by MK10NS1.5 at 78.7 MPa. However, with rising temperatures, compressive strength declined due to hydrate dehydration, leading to complete degradation of the concrete at 650°C and a loss of binding efficiency in the hydrates (CSH). Elevated temperatures also induced increased porosity through pore structure coarsening. The heightened temperature, particularly at 650°C and 800°C, resulted in diminished strength due to the development of high vapor pressure within the compact concrete structure. This pressure triggered the formation of microcracks, potentially compromising the overall strength of the concrete.

Since compressive strength is closely associated with aggregate property, compressive strength deterioration can also be closely linked to aggregate breakdown, where thermal stress beyond yield strength triggers the development of microcracks. This thermal rupture phenomenon initiates microcracks at 200°C, progressing to interconnect as the temperature rises to 300°C, forming a network of cracks. Ultimately, this interconnected network led to aggregate cracking at 500°C.

ii Mass loss

A proportional increase in mass loss in concrete with rising temperatures was observed. Notably, a significant rise of mass loss occurred between 27°C and 350°C, attributed to the expulsion of evaporated water and the liberation of free capillary water. Beyond 400°C, decomposition of carboaluminate hydrates and chemical bonds depletion contributed to mass reduction. Above 600°C, CSH gel breakdown and difficult evaporation of chemically combined water occurred, resulting in a comparatively lower mass loss. Additionally, at 573°C, the transformation of low quartz to high quartz induced quartz aggregate expansion, causing interface cracking and subsequent mass loss in the concrete.

iii Thermal resistance

The thermal resistance was assessed by comparing the area under the relative residual compressive strength curves. MK10 exhibited the highest area, indicating superior thermal resistance, closely followed by NS1.5. Remarkably, MK10NS1.5 surpassed ordinary concrete, with a value of 546.92, emphasising the effectiveness of MK10, NS1.5, and their combination in preserving strength under elevated temperatures. The diminished

relative strength of MK10NS3 can be ascribed to its denser microstructure, leading to the build-up of high vapour pressure and subsequent formation of microcracks within.

iv Surface cracking and spalling

Concrete samples subjected to temperatures up to 200°C displayed no visible surface cracks, consistent with previous findings. At 350°C, slender crack networks appeared, affecting normal and blended cement concrete. Exposure to 500°C resulted in minor scratches and visible cracks. As temperatures rose to 800°C, cracks expanded due to internal vapour pressure. MK10NS4.5 showed reduced surface cracking at 650 and 800°C, with spalling observed at 650°C, indicating internal vapour pressure accumulation. At 800°C, all samples experienced surface layer ablation due to high thermal compressive stress. These observations underscore the complex interplay of temperature and concrete composition.

v Microstructural studies

The XRD analysis reveals distinct patterns in blended cement samples compared to the reference CC, indicating significant effects on hydration products with temperature variation. The decline in portlandite peak, particularly pronounced in ternary MKNS mixes, suggests increased pozzolanic reaction, leading to CH consumption. The rise in portlandite peak within 350-500°C in certain samples, attributed to late hydration, aligns with the temperature-induced disintegration of CSH. Variations in portlandite peaks among MK10, NS1.5, NS3, NS4.5, and MK10NS1.5 samples correlate with residual compressive strength. The observed increase in CaCO₃ peak at higher temperatures aligns with the decomposition of CH into CaO and potential CaCO₃ formation.

The TGA/DSC curves at 90 days reveal distinctive mass loss peaks in cement and blended paste samples. Peaks at 30–300°C signify CSH and CAH decomposition, linked to moisture evaporation. The 400–500°C peak indicates CH decomposition, while the 600–900°C peak corresponds to water loss from CSH and CaCO₃ decomposition. MK and NS inclusion accentuates moisture evaporation, highlighting their high absorption capacity. A reduced mass loss in the second peak, notably in MK10NS3, suggests CH consumption by MK and NS, enhancing strength. The final peak indicates optimized replacements decrease CaCO₃, particularly in MK10NS3, showcasing the benefits of ternary blends.

The high-resolution scanning electron microscopy (HR-SEM) images provided insights into the morphological changes in hydration products under varying temperatures. After a 90-day curing period at 27±2°C, the concrete exhibited a densely packed microstructure correlating with the observed compressive strength. Blended cement paste, especially in ternary blends, displayed a more compacted microstructure due to heightened pozzolanic activity.

At 200°C, minor morphological changes occurred, including increased CSH phases and persistent micropores, attributed to capillary and adsorbed water evaporation. Some samples displayed microcracks linked to hydration product dehydration. As the temperature reached 350°C, complete water evaporation initiated CH decomposition, weakening the microstructure and leading to clearer pores and gaps compared to samples at 200°C.

Beyond 350°C, there was a significant increase in pore volume, impacting compressive strength. At 500°C, pore coarsening and increased cracks were observed due to the breakdown of pore walls. At 650°C, decomposition led to a fragmented microstructure, disrupting the dense CSH gel and CH crystals and impacting strength. At 800°C, substantial hydrate disintegration resulted in increased pores and wider cracks, causing a marked deterioration in concrete strength. Unexpectedly, decomposed CSH gel was observed at 800°C, challenging conventional understanding. Overall, temperature-induced morphological changes significantly influenced the concrete's microstructure and, consequently, its strength at elevated temperatures.

8.3.6 Eco-efficiency

In evaluating eco-efficiency, the study assessed binder intensity for compressive strength (B_{iCS}) and CO₂ intensity for compressive strength (C_{iCS}). The MK10NS3 concrete exhibited superior performance in both metrics, with the lowest B_{iCS} values (6.5, 5.9, 5.8 kg m⁻³ MPa⁻¹) and C_{iCS} values (5.2, 4.8, 4.6 kg CO₂ m⁻³ MPa⁻¹) at 28, 90, and 180 days. This indicates an impressive eco-efficient profile, aligning with international benchmarks. The consistent decline in B_{iCS} and C_{iCS} values underscores the sustainable advantages of the MK10NS3 composition, establishing it as the most efficient in terms of compressive strength and reduced CO₂ intensity.

In evaluating binder intensity and CO₂ intensity for carbonation (B_{iCARB} and C_{iCARB}), MK10NS3 stood out with the highest values of both B_{iCARB} and C_{iCARB} , indicating superior environmental efficiency due to reduced cement content. These findings collectively underscore the eco-efficiency of ternary concrete mixes, particularly at 10%

MK and 3% NS proportions, demonstrating a promising avenue for sustainable construction practices with reduced environmental impact.

8.3.7 Cost index

In conclusion, the economic viability of concrete mixes was assessed through the cost index, considering production expenses and compressive strength. MK10NS3 emerged as a standout performer, boasting the highest compressive strength and a commendable cost index of 0.0053, closely rivalling that of normal concrete at 0.0055. While other blends demonstrated varying cost efficiencies, MK10NS3 exhibited a compelling balance between strength and economic viability. The study underscores the critical link between economic efficiency and concrete durability. MKNS ternary blends, notably MK10NS3, showcased superior carbonation, water absorption, and acid resistance performance, aligning with sustainability goals and offering long-term economic benefits through reduced maintenance and extended service life.

In general the study concludes that the incorporation of MK and NS in both binary and ternary mortar and concrete formulations significantly enhances mechanical properties, durability, and thermal stability compared to conventional concrete. The binary mixes with 10% MK and up to 4.5% NS demonstrated higher compressive strengths, with the optimum performance observed in ternary blends with 10% MK and 3% NS, yielding up to a 30% strength increase over the reference concrete. The synergistic effect of MK and NS improved the microstructural properties, leading to denser matrices, reduced pore volumes, and enhanced resistance to carbonation, water absorption, and sulfuric acid attack. Thermal studies revealed that the ternary blends maintained superior compressive strengths up to 200°C and exhibited better thermal resistance compared to both

conventional and binary mixes. However, higher dosages of MK and NS led to reduced thermal resistance due to vapor entrapment and cracking at elevated temperatures. Overall, the study highlights the potential of MK and NS as supplementary cementitious materials that can significantly improve the performance and sustainability of concrete, particularly in high-performance and durable construction applications.

8.4 Author's contribution

The research presents a novel comparative analysis of the effects of MK and NS on the performance of cement mortars and concretes. The author contributes to the field by demonstrating the significant enhancement of compressive strength and durability in both binary and ternary blends of MK and NS. This study introduces new insights into the optimal dosages of MK and NS, particularly emphasizing the superior performance of ternary blends with 10% MK and 3% NS. Additionally, the research delves into the microstructural evolution and thermal stability of these blends, providing a detailed examination of how the synergistic effects of MK and NS contribute to improved concrete properties under various conditions. The author's work also contributes to eco-efficiency by highlighting the potential of MK and NS to replace a portion of ordinary Portland cement (OPC), thereby reducing the environmental footprint of concrete production. This comprehensive analysis offers valuable guidance for the development of high-performance, sustainable concrete materials.

8.5 Future scope of studies

In light of the current findings, the following areas are recommended for further research:

1. Field Application and Performance Studies: One of the critical future areas of research is the field application of MKNS-based concrete mixes. It is essential to conduct both short-term and long-term performance evaluations under real-world conditions. These studies will provide invaluable insights into the practical challenges and advantages of using MKNS mixes in various construction environments.

2. Durability Studies under Diverse Environmental Conditions: Further studies should be conducted to assess the durability performance of MKNS-based concrete under diverse environmental conditions, including varying humidity, temperature fluctuations, freeze-thaw cycles, and chemical exposure. Understanding the behavior of MKNS-based concrete in different climates and settings will be crucial for widespread adoption.

3. Optimization of Mix Design for Specific Applications: Research should focus on optimizing the mix design of MKNS-based concrete for specific structural applications. This includes investigating the potential for fine-tuning the proportions of metakaolin and nano-silica to achieve targeted properties, such as high early strength, enhanced durability, or improved thermal resistance.

4. Life-Cycle Assessment (LCA) and Sustainability Studies: A detailed life-cycle assessment of MKNS-based concrete mixes should be undertaken to quantify their environmental impact comprehensively. This includes evaluating the potential reductions

in CO₂ emissions, energy consumption, and overall sustainability benefits compared to conventional concrete.

5. Economic Feasibility and Cost-Benefit Analysis: While the current study has provided initial insights into the cost indices of MKNS-based concrete, further economic feasibility studies are necessary. These should include a cost-benefit analysis considering long-term durability, maintenance costs, and potential savings from improved performance.

6. Advanced Microstructural Analysis and Modeling: Advanced microstructural analysis techniques, coupled with computational modeling, should be employed to gain a deeper understanding of the interactions between metakaolin, nano-silica, and cement particles at the nanoscale. This will help in optimizing the pozzolanic reactions and enhancing the overall performance of the concrete.

7. Development of Standards and Guidelines: As MKNS-based concrete mixes show promise, developing standards and guidelines for their use in construction is critical. These should be based on extensive research and field data, ensuring the reliable and safe application of these materials in the industry.

These future research directions are expected to significantly contribute to advancing MKNS-based concrete mixes, enabling their broader adoption in the construction industry while enhancing the durability, sustainability, and economic efficiency of concrete structures.

