Sustainable Concrete Performance Using Nano-Silica and Industrial Waste Materials: A Comprehensive Research

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ABSTRACT

This study evaluates the performance of green concrete prepared by using nano-silica and industrial waste materials as partial replacement of conventional cement. The main objective is to improve concrete strength and durability while reducing environmental impact. Industrial waste materials such as fly ash, GGBS, silica fume, and waste foundry sand help in minimizing cement consumption and waste disposal problems. Nano-silica improves the microstructure of concrete by filling pores and increasing calcium silicate hydrate formation. The results indicate that the optimum mix with nano-silica and industrial waste provides better compressive strength, reduced water absorption, and improved durability.

Keywords: *Green Concrete, Nano-Silica, Industrial Waste, Sustainable Construction.*

I. INTRODUCTION

Green concrete has emerged as an important sustainable construction material because the construction industry is one of the major consumers of natural resources and one of the significant contributors to carbon dioxide emissions through cement production. Ordinary Portland cement is widely used as the main binding material in concrete, but its manufacturing process requires high energy consumption and releases large quantities of greenhouse gases into the atmosphere. At the same time, rapid industrialization has generated huge amounts of industrial waste materials such as fly ash, ground granulated blast furnace slag, silica fume, rice husk ash, waste foundry sand, quarry dust, and other by-products, which create serious disposal and environmental problems if not properly utilized. In this context, green concrete provides an effective solution by partially replacing conventional cement or natural aggregates with suitable industrial waste materials, thereby reducing environmental pollution, conserving natural resources, and lowering the overall cost of construction. The use of industrial waste materials in concrete not only supports waste management but also improves certain engineering properties due to their pozzolanic and filler effects. However, the performance of green concrete depends on the type, percentage, particle size, chemical composition, and compatibility of waste materials used in the mix. To further enhance the strength and durability performance of green concrete, nano-silica has gained special attention in recent years. Nano-silica is an extremely fine material with high surface area and high pozzolanic reactivity, which helps in improving the microstructure of concrete. It reacts with calcium hydroxide produced during cement hydration and forms additional calcium silicate hydrate gel, which is mainly responsible for strength development in concrete. Due to its nano-size particles, nano-silica also acts as a pore-filling material and reduces the voids within the concrete matrix. As a result, concrete containing nano-silica generally shows improved compressive strength, split tensile strength, flexural strength, density, and durability characteristics. The combination of nano-silica with industrial waste materials can produce a high-performance and environmentally friendly concrete by balancing sustainability and structural efficiency. Industrial waste materials such as fly ash and GGBS may improve long-term strength and durability, while nano-silica can compensate for early strength reduction often observed in mixes with high cement replacement levels. This makes the study of green concrete using nano-silica and industrial waste materials highly relevant for modern construction practices, especially in developing durable infrastructure with reduced environmental impact. The performance evaluation of such concrete usually includes the study of fresh properties, mechanical properties, and durability properties. Fresh properties such as workability, slump value, and compaction ability are important because the addition of nano-silica may reduce workability due to its high surface area and water demand. Therefore, the use of superplasticizers may be required to maintain proper flow and placement of concrete. Mechanical properties such as compressive strength, split tensile strength, and flexural strength help in determining the load-bearing capacity of the concrete. Durability tests such as water absorption, acid resistance, sulphate resistance, chloride penetration, and permeability analysis are important to understand the long-term performance of concrete under aggressive environmental conditions. The main purpose of evaluating green concrete with nano-silica and industrial waste materials is to identify the optimum mix proportion that provides maximum strength, better durability, improved microstructure, and minimum environmental impact. Excessive use of nano-silica or industrial waste materials may negatively affect workability and strength; therefore, proper mix design and experimental investigation are necessary. Overall, this study is significant because it promotes sustainable construction, reduces dependence on cement and natural aggregates, utilizes industrial waste effectively, and contributes to the development of durable, economical, and eco-friendly concrete for future infrastructure development.

II. RESEARCH BACKGROUND

El-Wafa (2026) investigated a multi-index performance approach that moved beyond the traditional reliance on compressive strength, aiming to provide a more holistic evaluation of nano-silica-enhanced binders in resource-efficient alkali-activated composites. The study applied the Strength Activity Index (SAI) framework from ASTM C618 and integrated fresh-state flowability with mechanical strength indices to assess overall binder synergy. High-calcium fly ash (HCFA) and low-calcium fly ash (LCFA) were used with a constant 20% fine aggregate replacement, while nano-silica was incorporated at 0, 1, 2, and 3 wt% of the binder to prepare the composites. Fresh-state performance was evaluated using Initial Flow Index (IFI) and Flow Retention Index (FRI), whereas mechanical performance was assessed via compressive, tensile, and flexural indices (SAI, TSI, FSI). Results showed that increasing nano-silica content systematically reduced flowability and workability retention, with LCFA mixtures exhibiting higher fresh-state retention than HCFA systems. Optimal mechanical performance was achieved at around 2 wt% nano-silica, yielding maximum SAI of approximately 120% for HCFA and 118% for LCFA at 28 days, alongside uniform improvements in TSI and FSI. Correlation analyses indicated strong linearity ($R^2 \approx 0.91–0.95$) between SAI and tensile/flexural indices, suggesting compressive strength alone was insufficient to represent total mechanical performance. Mineralogical and microstructural analyses using XRD and SEM demonstrated that performance trends depended on interactions among calcium supply, amorphous aluminosilicate, and nano-silica nucleation effects. Consequently, the study concluded that the multi-index framework provided a practical tool for quantifying binder synergy and optimizing nano-silica dosage, enhancing the development of sustainable alkali-activated composites for infrastructure applications.

Amin et al. (2026) investigated the effects of micro- and nano-scale rice husk ash (RHA) and sugarcane bagasse ash (SBA) on the mechanical, durability, and microstructural performance of ultra-high-performance concrete (UHPC). They examined binary blends with micro-RHA (MRHA) and micro-SBA (MSBA) at 10–50% replacement levels and compared them with ternary blends incorporating nano-RHA (NRHA) and nano-SBA (NSBA) against a control mix. The study measured compressive, tensile, and flexural strengths, as well as the modulus of elasticity, alongside durability parameters including water permeability, chloride penetration, sorptivity, and thermal and sulfate resistance. The authors reported that optimal micro-scale replacements (20% MRHA and 20% MSBA) enhanced 28-day compressive strength by 10.5% and 15%, respectively, while ternary blends achieved compressive strengths up to 177.8 MPa, minimal permeability, and excellent sulfate resistance. SEM analyses were found to confirm matrix densification and improved C–S–H formation, indicating that micro- and nano-ashes provided synergistic benefits as sustainable cementitious replacements in UHPC.

Bharti et al. (2025) investigated the environmental impacts of the building industry, highlighting its significant contribution to natural resource depletion and ecological imbalances due to unregulated mining activities. They examined the potential of industrial by-products, including imperial smelting furnace (ISF) slag, fly ash, and nanosilica, as partial replacements for fine aggregates in concrete to address sustainability challenges. The study assessed the physical and mechanical properties of these wastes and systematically compared their effects on concrete performance. It was reported that ISF slag, owing to its higher specific gravity, considerably enhanced concrete density and mechanical properties, with compressive strength reaching up to 56.17 MPa at a 40% replacement level. Fly ash showed a steady increase in compressive strength, peaking at 40 MPa at 50% replacement, while nanosilica improved compressive strength to 40.22 MPa at the same replacement level. The authors concluded that incorporating these industrial by-products mitigated environmental impacts and produced concrete with superior mechanical properties, underscoring their viability as sustainable alternatives to natural sand in infrastructure applications.

Kallumari and Vijaya (2025) conducted a thorough experimental investigation to optimize and evaluate the performance of nano-silica–incorporated geopolymer concrete (GPC) using fly ash as the primary binder. They observed that, although GPC is a promising sustainable substitute for ordinary Portland cement, limited studies had addressed multi-parameter optimization of two-part GPC under ambient curing conditions. The study aimed to enhance mechanical and durability properties through nano-silica addition and to determine the optimal mix using Taguchi design of experiments combined with grey relational analysis (GRA). Sixteen concrete mixes were prepared by varying fly ash content, Na_2SiO_3-to-NaOH ratio, nano-silica dosage, and water-to-geopolymer solids ratio, and were assessed for flowability, compressive and flexural strength, drying shrinkage, water permeability, water absorption, acid resistance, and rapid chloride permeability. Among the mixes, M7 exhibited the highest compressive strength and excellent workability, whereas GRA identified M11 as the most balanced formulation across all parameters. Early strength development reached 70–80% of 28-day strength within 7 days, indicating accelerated geopolymerization. SEM and XRD analyses confirmed C–S–H, N–A–S–H, and C–A–S–H gel formation, alongside reduced porosity and microcracking due to nano-silica incorporation. Regression modeling validated the optimization strategy with prediction errors within ±2%, supporting the conclusion that nano-silica–enhanced GPC provided a durable, high-performance, and environmentally friendly alternative to conventional cement concrete.

Hamed et al. (2024) investigated the effects of nanomaterials on high-early-strength concrete (HESC) to enhance compressive strength and sustainability. They conducted experimental studies and a 2^3 factorial design to assess three nanomaterials—nano clay (NC), nano silica (NS), and nano cellulose (NCel)—and reported that incorporating these nanomaterials reduced workability, with NCel having the least impact. All nanomaterial-containing HESC mixes exhibited higher compressive strength than the control mix, with optimal enhancements observed at 4.5% NC, 4.5% NS, and 0.0375% NCel. The hybrid mix of 4.5% NC and 0.0375% NCel showed the greatest improvement. Statistical analysis indicated that NCel contributed most significantly to strength enhancement, followed by NC, and mathematical models derived from these analyses were used to predict compressive strength at 3, 7, and 28 days. Contour plots further illustrated optimization of compressive strength across nanomaterial contents. The study highlighted the potential of waste-derived nanomaterials to improve HESC performance, reduce curing times, enhance durability, and minimize environmental impacts in concrete production.

Tran and Phan (2024) investigated high-strength concrete (HSC) incorporating 30% fly ash (FA) and varying nano-silica (NS) contents as supplementary cementitious materials, where FA and NS were sourced from local thermal plants and rice husk ash in Southern Vietnam, respectively. Different NS concentrations (0%, 0.5%, 1.0%, and 1.5%) were incorporated into the base mixture in partial replacement of cement and FA, while maintaining a constant water-to-binder ratio of 0.32. The study reported that the combined binder of cement, FA, and NS satisfied the setting time requirements similar to pure cement, and slump values ranged from 30–40 mm with superplasticizer adjustment. Mechanical properties, including compressive strength, flexural strength, elastic modulus, and abrasion resistance, were evaluated at curing ages of 3, 7, 28, and 56 days, indicating that 1% NS provided optimum performance. A strong correlation between compressive and flexural strengths was observed, and rigid pavement analysis suggested that the inclusion of 1% NS could reduce concrete slab thickness by approximately 30 mm (10.7%), demonstrating that NS incorporation enhanced concrete performance while enabling thinner slabs.

Karlina et al. (2023) investigated the integration of nanotechnology in various industries, noting that it had significantly enhanced product quality and manufacturing technologies for diverse materials. They reported that, within the construction sector, the adoption of nanomaterials had facilitated the development of innovative construction methods. The authors reviewed extensive studies on micro- and nanosilica, particularly their use as partial substitutes for cement in concrete formulations, and aimed to provide a comprehensive overview of silica's impact on concrete properties in civil engineering and road construction. They highlighted that environmental concerns and potential hazards had necessitated strategies for managing industrial by-products, including silica fume, a residue from silicon and ferrosilicon metallurgical processes. Their review indicated that waste silica dust and slurries had proven effective in producing high-strength, high-performance concrete. They also conducted a comparative analysis of microsilica characteristics from different sources, showing that its incorporation in concrete mixes enhanced workability and performance, with particle morphology—smooth and spherical surfaces—playing a key role in influencing concrete properties.

Fallah-Valukolaee et al. (2022, December) investigated the use of pozzolanic materials, specifically nanosilica and silica fume, as partial replacements for cement to produce high-strength concrete (HSC) and examined both the mechanical performance and environmental impacts of the resulting concretes. They evaluated seven mix designs with varying silica fume contents of 0, 8, 10, and 12 % and nanosilica contents of 0, 1, 2, and 3 %, assessing parameters such as compressive capacity, toughness, strain at peak stress, relative energy absorption, and stress–strain relationships. Empirical models were proposed to predict the mechanical behavior of HSC, and atomic force microscopy was employed to study microstructural differences between concretes with and without pozzolans. Environmental assessments were conducted using the CML 2000 and IMPACT 2002+ methods within SimaPro 8.1, considering acidification, eutrophication, global warming potential, human health, ecosystem quality, and natural resource use, and results were validated against the BEES approach. It was found that 12 % silica fume and 2 % nanosilica produced optimal compressive performance, while environmental impact analyses indicated that concretes with higher pozzolan contents exhibited greater damage in multiple categories, whereas HSC without pozzolans showed generally lower environmental indices except for a slightly higher climate change potential.

Qasim et al. (2021) investigated the effects of incorporating plastic waste as coarse aggregates and nano silica sand powder as a partial cement replacement on the mechanical and physical properties of concrete. They reported that industrial and urban development had led to increased plastic waste generation and higher CO_2 emissions from cement production, motivating the development of environmentally friendly "green" concrete. Their study applied 10% and 20% plastic waste replacements and 5% and 10% nano silica sand substitutions by weight, and they found that compressive, flexural, and splitting tensile strengths decreased with increasing plastic content, while these strengths improved with the addition of silica sand. Specifically, compressive strength reductions of 12.10% and 19.23% were observed for 10% and 20% plastic replacements, whereas 5% and 10% silica sand additions increased strength by 12.89% and 20.39% at 28 days. Similar trends were noted for flexural and splitting tensile strengths, and dry density decreased with plastic incorporation but increased with silica sand addition, indicating the potential of nano silica and plastic waste to modify concrete properties.

Sharif (2021) reviewed the role of nanotechnology in construction materials, highlighting that it had emerged as one of the most active research areas with significant technological innovations and practical applications over the preceding two decades. The study indicated that incorporating nanoparticles into construction materials had been increasingly explored to enhance material performance, with particular attention on geopolymer concrete as an eco-efficient alternative to conventional cement-based concrete. The review reported that geopolymer concrete utilized substantial amounts of industrial and agricultural byproducts such as fly ash, ground granulated blast furnace slag, and rice husk ash, and that various methods had been investigated to improve its performance, including the use of nanomaterials to boost chemical reactivity and fill nanopores. Sharif's analysis synthesized findings from recent studies on nano-silica, showing that while its inclusion generally reduced workability, it significantly improved mechanical properties such as compressive, splitting tensile, and flexural strengths up to an optimal dosage.

III. Methodology

The present study was carried out to evaluate the performance of green concrete prepared by using nano-silica and industrial waste materials as partial replacement of cement. First, the required materials such as cement, fine aggregate, coarse aggregate, water, nano-silica, and industrial waste materials such as fly ash or GGBS were collected and tested for their basic properties. The physical properties of aggregates, including specific gravity, water absorption, and grading, were examined before mix preparation. A control concrete mix was prepared without nano-silica and waste material, while other mixes were prepared by replacing cement with different percentages of industrial waste materials and adding nano-silica in varying proportions. The concrete mixes were designed for the selected grade of concrete, and all ingredients were weighed accurately. Dry mixing was done first, followed by the addition of water and superplasticizer to obtain proper workability. The fresh concrete was tested using the slump test to determine workability. Cubes, cylinders, and beams were then cast for compressive strength, split tensile strength, and flexural strength tests. The specimens were demoulded after 24 hours and cured in clean water for 7, 14, and 28 days. After curing, mechanical strength tests were conducted using standard testing machines. Durability properties were evaluated through water absorption and resistance tests. Finally, the results of modified green concrete mixes were compared with the control mix to identify the optimum percentage of nano-silica and industrial waste material for improved strength, durability, and sustainability.

IV. RESULT

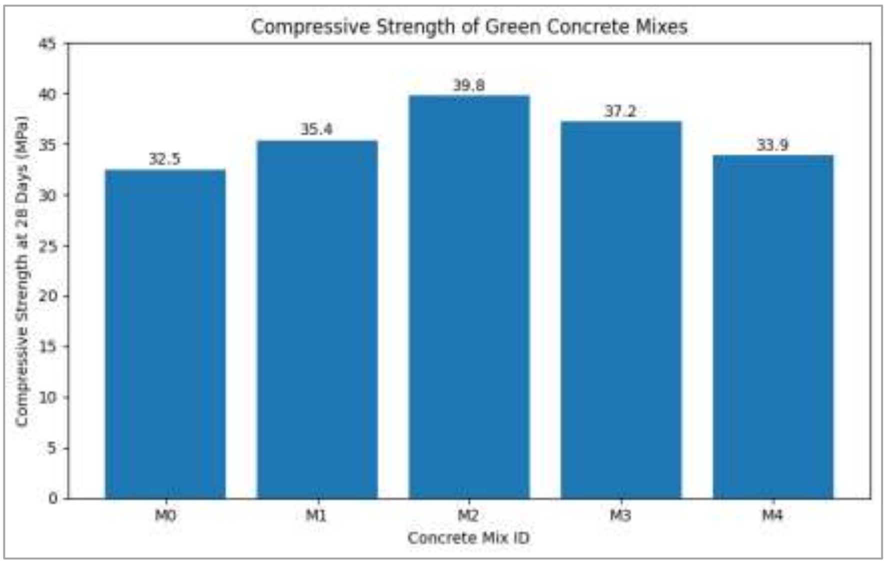
The performance evaluation of green concrete using nano-silica and industrial waste materials showed that the addition of suitable waste materials and nano-silica improved the strength and durability properties of concrete when used in optimum proportions. The control mix without nano-silica and industrial waste showed normal strength development, while modified mixes showed better performance due to the combined pozzolanic reaction and pore-filling effect. The use of industrial waste materials such as fly ash, GGBS, silica fume, or waste foundry sand helped in reducing cement consumption and improving sustainability. Nano-silica improved the microstructure of concrete by filling micro-pores and producing additional calcium silicate hydrate gel, which increased the bonding between cement paste and aggregates. The results indicated that concrete containing about 2% nano-silica with 20% industrial waste replacement performed better than other mixes. This mix showed higher compressive strength, improved split tensile strength, better flexural strength, and lower water absorption compared to conventional concrete. However, when the percentage of nano-silica and waste replacement was increased beyond the optimum level, the workability decreased and strength improvement became limited. This may be due to high water demand, particle agglomeration, and insufficient cementitious material for proper bonding.

Table: Performance Result of Green Concrete Mixes

Mix ID	Industrial Waste Replacement	Nano-Silica Content	Compressive Strength at 28 Days (MPa)	Split Tensile Strength (MPa)	Water Absorption (%)	Performance
M0	0%	0%	32.50	3.10	4.80	Normal
M1	10%	1%	35.40	3.35	4.20	Improved
M2	20%	2%	39.80	3.85	3.40	Best
M3	30%	3%	37.20	3.60	3.70	Good
M4	40%	4%	33.90	3.25	4.30	Moderate

From the above results, it was observed that the M2 mix gave the best overall performance. The compressive strength increased from 32.50 MPa to 39.80 MPa, showing a clear improvement over normal concrete. The split tensile strength also increased, while water absorption decreased, indicating better durability. Therefore, the optimum use of nano-silica and industrial waste materials can produce strong, durable, economical, and eco-friendly green concrete suitable for sustainable construction.

Bar Graph



The graph shows the compressive strength of green concrete mixes at 28 days. The control mix M0 recorded the lowest strength of 32.50 MPa. With the addition of nano-silica and industrial waste materials, strength increased gradually in M1 and reached the highest value in M2 at 39.80 MPa. This indicates that 20% industrial waste replacement with 2% nano-silica was the optimum mix. After M2, the strength decreased in M3 and M4 due to excessive replacement and higher nano-silica content, which may reduce workability and cause particle agglomeration. Therefore, M2 showed the best overall performance.

V. CONCLUSION

The study concluded that green concrete prepared with nano-silica and industrial waste materials can be an effective alternative to conventional concrete. The use of industrial waste materials such as fly ash, GGBS, silica fume, or waste foundry sand helped in reducing cement consumption and minimizing environmental pollution. Nano-silica improved the internal microstructure of concrete by filling pores and forming additional calcium silicate hydrate gel, which enhanced strength and durability. The experimental results showed that the mix containing 20% industrial waste replacement and 2% nano-silica gave the best overall performance. This mix achieved higher compressive strength, improved tensile strength, and lower water absorption compared to the control mix. However, excessive use of nano-silica and waste materials reduced workability and strength due to high water demand and poor particle dispersion. Therefore, it can be concluded that the optimum use of nano-silica and industrial waste materials produces strong, durable, economical, and eco-friendly concrete. This approach supports sustainable construction by conserving natural resources, reducing cement usage, and utilizing industrial waste effectively.

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