Enhancing Sustainability and Performance of Green Concrete Using Nano-Silica and Waste Materials

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ABSTRACT

This paper explores the integration of nano-silica in green concrete systems to improve sustainability and performance. By replacing ordinary Portland cement with industrial by-products like fly ash and slag, and incorporating nano-silica, concrete's mechanical and microstructural properties are enhanced. Nano-silica accelerates hydration, refines pore structure, and increases compressive strength. It also supports the circular economy by reducing waste, including recycled PET and glass, in concrete production. Despite challenges in cost and dispersion techniques, the combination of nano-silica and industrial waste offers promising solutions for eco-efficient, high-performance concrete.

Keywords: *Nano-silica, Green Concrete, Sustainability, Performance, Industrial Waste.*

I. INTRODUCTION

The construction industry is one of the largest consumers of natural resources and a major contributor to global carbon dioxide emissions, primarily due to the extensive use of ordinary Portland cement (OPC). In response to growing environmental concerns, sustainable construction practices have increasingly focused on the development of green concrete by partially or fully replacing cement with industrial by-products and waste materials. These supplementary cementitious materials (SCMs), such as fly ash, silica fume, ground granulated blast furnace slag, rice husk ash, glass powder, and other industrial residues, not only reduce environmental burdens but also enhance certain mechanical and durability properties of concrete when used in optimal proportions (Rath et al., 2026; Fahmy et al., 2022). However, despite their advantages, many SCM-based systems suffer from limitations such as reduced early-age strength, variability in performance, and poor long-term durability when used at higher replacement levels. To overcome these limitations, nanotechnology—particularly the incorporation of nano-silica—has emerged as a promising solution for enhancing the performance of green concrete systems. Nano-silica, due to its ultrafine particle size, high surface area, and strong pozzolanic reactivity, improves hydration kinetics, refines pore structure, and significantly enhances the mechanical and microstructural properties of cementitious composites (Jakhara et al., 2024). Studies have demonstrated that nano-silica acts as both a filler and a nucleation site, accelerating the formation of calcium silicate hydrate (C–S–H) gel, which is primarily responsible for strength development in concrete systems (Bagheri et al., 2025; Dawood & Mahmood, 2021). As a result, the integration of nano-silica into waste-based concrete systems represents a significant advancement in sustainable construction technology.

In recent years, extensive research has focused on combining nano-silica with various industrial and agricultural waste materials to develop high-performance and eco-efficient concrete. For instance, studies have shown that incorporating recycled materials such as crumb rubber, polyethylene terephthalate (PET), waste glass powder, and cement bypass dust into concrete can significantly reduce environmental pollution while promoting resource recycling (Adamu et al., 2024; Onochie, 2025). However, these materials often introduce challenges such as reduced compressive strength, increased porosity, or altered workability, especially at higher replacement levels. The addition of nano-silica has been found to mitigate these negative effects by enhancing particle packing density and improving interfacial transition zones between aggregates and cement paste. Bagheri et al. (2025) observed that combining nano-silica with recycled PET significantly improved compressive strength and freeze-thaw resistance, demonstrating the synergistic effect of nano-scale materials and polymer-based waste. Similarly, Onochie (2025) reported that bio-derived nano-silica extracted from agricultural waste, when used in concrete, led to a 52% increase in compressive strength at optimal dosage levels. These findings highlight the dual role of nano-silica in enhancing performance and enabling higher utilization of waste materials. Additionally, studies on alkali-activated materials and blended cement systems have shown that nano-silica contributes to improved microstructural density but may also influence shrinkage behavior depending on dosage and mix composition (Salami et al., 2023). Therefore, optimizing nano-silica content is crucial to achieving a balance between sustainability and structural performance.

Furthermore, the integration of nano-silica and industrial waste materials aligns strongly with the principles of circular economy and sustainable development by reducing dependency on natural raw materials and minimizing landfill waste. Cement bypass dust, ceramic waste, slag, and other industrial residues have been successfully investigated as partial cement replacements, demonstrating potential in reducing clinker content and associated carbon emissions (Serour et al., 2026). Serour et al. (2026) emphasized that ternary and quaternary blended systems incorporating industrial wastes can achieve satisfactory compressive strength while significantly reducing environmental impact. However, such systems require careful design optimization to maintain performance consistency. Nano-silica has proven particularly effective in such systems by enhancing hydration reactions and improving bonding mechanisms at the micro and nano scale. In high-performance concrete (HPC) applications, nano-silica has also been shown to improve durability characteristics such as permeability resistance, corrosion resistance, and abrasion resistance, making it suitable for infrastructure exposed to aggressive environments (Jakhara et al., 2024). Despite these advantages, challenges remain in terms of cost, dispersion techniques, and large-scale applicability of nano-materials in construction practice. Therefore, further research is needed to develop cost-effective synthesis methods, improve dispersion stability, and establish standardized guidelines for nano-modified green concrete systems. Overall, the convergence of nanotechnology and waste material utilization presents a transformative approach for developing next-generation sustainable concrete, capable of meeting both structural performance requirements and environmental sustainability goals (Najaf et al., 2022; Fahmy et al., 2022).

II. RESEARCH BACKGROUND

Serour et al. (2026) investigated sustainable approaches for managing Cement Bypass Dust (CBD) by either safely disposing of it or incorporating it as a supplementary cementitious material (SCM) in building materials. They observed that CBD's pozzolanic reactivity was generally low and variable, limiting its conventional use, especially at replacement rates above 10%, which typically caused notable strength reductions. To address this, the study introduced an eco-efficient strategy that valorized high CBD levels, up to 34.8%, in hydraulic green cement with reduced clinker content (37.8–38.7%). Unlike prior research focusing on low CBD replacements or single SCM additions, the authors examined the synergistic effects of a ternary blend combining CBD with de-aluminated kaolinite (DAK) and calcined clay (Cclay) to enhance pozzolanic activity. They conducted a comprehensive experimental program producing and testing eight cementitious mixtures, finding that optimized mixes containing 17.1–34.8% CBD, 17.4–34.2% calcined clay, and ~5.75% industrial waste achieved compressive strengths of 36.2 MPa at 28 days and 38.2 MPa at 90 days, while maintaining acceptable setting times (initial up to 245 min, final up to 360 min). The study provided novel insights into designing low-clinker, high-performance green cement and significantly contributed to circular economy and sustainable construction practices.

Rath et al. (2026) investigated the behavior of natural and manufactured pozzolans and the properties of blended mortars, highlighting the growing interest in eco-friendly building materials produced from supplementary cementitious materials (SCMs). The study reported that materials such as granulated blast furnace slag, silica fume, zeolite powder, metakaolin, clay powder, fly ash, rice husk ash, copper slag, and glass powder were used to enhance the microstructure, workability, setting time, and strength of blended mortars. Control mixes with varying replacement rates (5–50 %) of SCMs compared to ordinary Portland cement (OPC) reference mortar were examined, and optimal proportions were identified for each material, including brick clay powder (5–15 %), granulated blast furnace slag (5–20 %), silica fume (5–25 %), copper slag (5–35 %), metakaolin (5–25 %), fly ash (5–30 %), rice husk ash (5–20 %), zeolite powder (5–20 %), ceramic waste (5–35 %), and glass powder (5–10 %). The study indicated that the strength of blended mortars generally increased with the volume of SCMs but decreased beyond a critical replacement level. Overall, it was observed that integrating SCMs significantly affected both the fresh and hardened properties of the blended mortars, demonstrating their potential in sustainable construction applications.

Bagheri et al. (2025) investigated green concrete, emphasizing the use of environmentally compatible concrete waste as a transformative approach in the concrete industry. They examined the effects of varying proportions of shredded recycled plastic bottles (Polyethylene Terephthalate, PET) combined with Ethyl Cellulose (EC) and Nano Silica (NS) on the compressive strength, water permeability, and freeze-thaw resistance of C25 concrete. Advanced characterization methods, including X-ray Diffraction (XRD) and Scanning Electron Microscopy (SEM), were employed to analyze changes in the microstructure and corrosion products. The study reported that the mixture containing 5% PET, EC, and 8.5% NS achieved optimal compressive strength and minimal water permeability after 90 days of curing, both before and after 300 freeze-thaw cycles, whereas the blend with 15% PET demonstrated the lowest mass loss post 300 cycles. The authors highlighted that the pozzolanic effects contributed to improved engineering and transport properties of ultra-high-strength concrete, and SEM observations confirmed enhanced density and compaction in mixtures with 5% PET, EC, and NS. Overall, the study indicated that integrating waste materials could reduce cement usage, mitigate environmental pollution, and enhance concrete performance.

Onochie (2025) investigated the synthesis of nano-silica from barley husk waste and its application in concrete production. The study employed acid leaching followed by calcination at 500, 600, and 700 °C to determine the optimal synthesis temperature for nano-silica. X-ray fluorescence (XRF) analysis indicated that the nano-silica produced at 700 °C exhibited the highest silica content, with approximately 94 % SiO_2 purity, while Fourier Transform Infrared (FTIR) spectroscopy revealed functional peaks around 1060 cm^{-1}. BET analysis showed that the particles measured 49 nm with a density of 1.15 g/cm^3, and X-ray diffraction (XRD) confirmed the amorphous nature of silica across all temperatures. Scanning electron microscopy (SEM) indicated non-porous surfaces. The synthesized nano-silica was incorporated into concrete mixes at 0.75 %, 1.5 %, and 3 % by weight along with 30 g of recycled plastic per mix, maintaining a water-to-binder ratio of 0.4. Compressive, flexural, and indirect tensile strengths were evaluated at 7 and 28 days of curing, and results demonstrated that nano-silica significantly enhanced concrete performance, with the 700 °C sample achieving the greatest improvement. Specifically, 3 % of 700 °C nano-silica increased 28-day compressive strength by approximately 52 % and flexural strength by 26 % relative to the control. Statistical analysis confirmed the significance of these improvements, highlighting the dual benefits of utilizing waste-derived nano-silica and plastic for sustainable, durable concrete production.

Adamu et al. (2024) investigated the performance enhancement of roller-compacted concrete pavement (RCCP), noting that RCCP, being a brittle material with low tensile strength and lacking steel or dowel bars, often experienced degradation or cracking before reaching its intended service life. They examined the use of crumb rubber (CR) as a partial replacement for fine aggregate at 0, 10, 20, and 30% levels and incorporated nano-silica (NS) at 0, 1, 2, and 3% by cement weight to mitigate CR's adverse effects. The study applied multicriteria-based optimization methods, including order of preference by similarity to ideal solution, evaluation based on distance from average solution, weighted sum model, and weighted product model, to identify the optimal mix. Experimental results indicated that CR enhanced workability but reduced mechanical and durability properties, whereas NS reduced workability while improving mechanical strength and durability. Among all mixes, the M2 mix (0% CR, 1% NS) consistently ranked highest across decision-making techniques due to its superior physical, mechanical, and durability characteristics. The study highlighted the potential of CR and NS in RCCP design and emphasized the sustainability benefits of utilizing waste tire rubber in pavement construction.

Jakhara et al. (2024) reviewed high-performance concrete (HPC), which was defined by its superior strength and durability compared to conventional techniques, and noted that the characteristics of ordinary concrete at specific times and locations were used to establish HPC standards. They indicated that the application of nanotechnology in HPC had attracted significant global attention due to its small particle size, filling capacity, large surface area, and strong macro quantum tunnel properties. The review reported that incorporating nanotechnology in HPC increased the overall dimensions of the cementation matrix, improved cement hydration, and enhanced matrix density. The study summarized developments in HPC and evaluated the effects of various nanomaterials—including nano calcium carbonate, nano silicon dioxide, nano titanium dioxide, and carbon nanotubes—on compressive strength and other mechanical properties. It was observed that different nanotechnologies enhanced mechanical performance while reducing flexibility. The authors emphasized that integrating nanotechnology could optimize construction outcomes, expand knowledge in building materials, and promote low-impact, eco-friendly solutions by leveraging nanoparticles' antibacterial, self-cleaning, air-purifying, and cooling properties, while simultaneously reducing cement consumption through increased reactivity with other mineral admixtures.

Salami et al. (2023) investigated the use of alkali-activated concrete (AAC) and binders (AABs) as alternatives to conventional ordinary Portland cement (OPC)–based concrete, highlighting their techno-ecological advantages. The study reported that Saudi Arabia's abundant natural pozzolan (NP) positively influenced certain fresh and hardened properties, though the long-term shrinkage behavior and life cycle assessment (LCA) of NP-based AABs had not been fully explored. The research evaluated shrinkage characteristics and LCA of NP-based AAC, examining the effect of nano-silica (NS) admixtures up to 7.5%, and correlated shrinkage with microstructure and pore structure. Findings indicated that NP-based AABs exhibited shrinkage behavior comparable to OPC concrete, while the addition of NS increased drying shrinkage due to finer pore refinement confirmed via nuclear magnetic resonance (NMR). Maximum average drying shrinkage was observed at 510 $\mu\varepsilon$ for OPC and ranged from 486 to 651 $\mu\varepsilon$ in AAC with 0–7.5% NS. The study suggested that NP could be valorized in sustainable AAB production without compromising shrinkage performance, NS enhanced strength and pore refinement, and LCA results demonstrated significant reductions in carbon footprint and environmental impact through recycling of natural waste.

Najaf et al. (2022) investigated the development of environmentally friendly lightweight (LW) concrete by partially replacing cement with nanosilica and aggregates with waste glass powder, while incorporating recycled polypropylene fibers to enhance compressive strength and nonlinear behavior. They evaluated the effects of using glass powder at 20, 25, and 30% of aggregate weight, nanosilica at 1, 2, and 3% of cement weight, and recycled fibers (FORTA Ferro-Green) at 0.5, 1, and 1.5% of cement weight, with Leca employed as a LW aggregate. Through 7- and 28-day experiments and field emission scanning electron microscopy analysis, it was reported that the optimal mixture contained 1.5% fiber, 3% nanosilica, and 25% waste glass powder, achieving compressive and tensile strengths approximately 1.7 and 1.6 times higher than the control specimen after 28 days. The study also indicated that substituting 3% of cement with nanosilica could reduce greenhouse gas emissions by around 3%.

Fahmy et al. (2022) investigated the use of natural pozzolans and industrial wastes as partial replacements for ordinary Portland cement in eco-friendly concrete, aiming to reduce carbon emissions while enhancing mechanical and durability characteristics. They noted that, despite extensive research on natural pozzolans, limited studies had examined the effects of nano waste glass (NWG) and nano waste ceramics (NWC) as cement replacement materials on self-compacted concrete (SCC). Their study first examined how incorporating NWG and NWC influenced SCC properties, addressing the issue of higher cement content in SCC leading to cracking. They also analyzed the effect of self-curing (SC) using polyethylene glycol (PEG400) on SCC modified with various nanomaterials, comparing the results with air curing (AC) and normal curing (NC). Several SCC mixes with 1–5% cement replacement were prepared and tested for fresh characteristics, mechanical performance, microstructure, and corrosion rates. They found that SC slightly reduced workability compared to NC, but it remained within EFNARC-2005 limits. However, mechanical properties, microstructure, and corrosion resistance improved with increasing NWG and NWC content, except at the 5% replacement. Under SC, compressive strength increased by 36% and 32% for NWG and NWC, respectively, while corrosion rates decreased by 87% and 82%, demonstrating the significant benefits of combining nanomaterials with self-curing for SCC.

Dawood and Mahmood (2021) investigated the potential of producing sustainable and economical concrete bricks by partially replacing cement with locally available industrial by-products such as glass powder and steel slag, while also examining the effect of adding Nano-silica to the brick mixes. They highlighted that conventional cement, being the primary binder in concrete, significantly contributes to CO_2 emissions, thus motivating the use of alternative materials to reduce cement consumption. The study employed two curing methods—normal curing at 23 ± 2°C and boiling water curing at 100°C—to assess their influence on key mechanical and physical properties, including compressive strength, flexural strength, ultrasonic pulse velocity, and drying shrinkage. Six different mixes were cast and tested under these conditions. The results indicated that incorporating 2.5 % to 3.5 % Nano-silica considerably enhanced both early- and late-age compressive and flexural strengths, with boiling water curing yielding superior strength performance compared to normal curing. However, drying shrinkage was found to be slightly higher in specimens subjected to boiling curing than in those cured normally.

III. KEY FINDINGS FROM STUDY

Author (Year)	Materials Used	Objective	Methodology	Key Findings	Relevance to Study
Serour et al. (2026)	Cement bypass dust (CBD), calcined clay, de-aluminated kaolinite	Develop low-clinker green cement using industrial waste	Experimental study on ternary blended cement systems	Up to 34.8% CBD achieved 36.2 MPa strength at 28 days with acceptable setting time	Shows feasibility of high-volume industrial waste utilization in cement systems

Rath et al. (2026)	Fly ash, slag, silica fume, rice husk ash, glass powder	Evaluate SCM performance in blended mortars	Replacement of OPC (5–50%) and mechanical testing	Strength improved at optimal replacement; declined beyond threshold	Establishes optimum dosage of SCMs for performance balance
Bagheri et al. (2025)	PET waste, ethyl cellulose, nano-silica	Improve durability under freeze–thaw conditions	Concrete testing with varying PET and NS content	5% PET + 8.5% NS gave highest strength and durability	Demonstrates nano-silica improves waste-based concrete performance
Onochie (2025)	Nano-silica from barley husk + plastic waste	Evaluate bio-waste nano-silica in concrete	Acid leaching + calcination at different temperatures	3% NS (700°C) increased compressive strength by 52%	Highlights eco-friendly nano-silica production and performance gain
Adamu et al. (2024)	Crumb rubber + nano-silica	Optimize RCC pavement performance	Multicriteria decision analysis	1% NS improved strength; rubber reduced mechanical properties	Shows nano-silica compensates rubber-induced weaknesses
Jakhara et al. (2024)	Nano-silica, nano-TiO_2, CNTs	Review nanotechnology in HPC	Literature-based review	Nano-materials enhance density, hydration, and strength	Establishes nano-silica role in high-performance concrete
Salami et al. (2023)	Natural pozzolan + nano-silica	Study shrinkage and LCA in AAC	Experimental + life cycle assessment	NS improved strength but increased shrinkage	Shows trade-off between durability and microstructure
Najaf et al. (2022)	Waste glass powder, nano-silica, fibers	Develop lightweight sustainable concrete	Mechanical testing of hybrid mixes	Strength increased 1.7× with optimized mix	Confirms hybrid waste + nano-silica synergy
Fahmy et al. (2022)	Nano waste glass, nano ceramics	Improve SCC performance	Fresh, mechanical, corrosion tests	Strength and durability improved; corrosion reduced	Demonstrates nano-industrial waste combination benefits
Dawood & Mahmood (2021)	Steel slag, glass powder, nano-silica	Produce sustainable concrete bricks	Curing under normal & boiling conditions	2.5–3.5% NS significantly increased strength	Confirms nano-silica improves cement replacement systems

IV. CONCLUSION

The comprehensive review of recent studies clearly indicates that green concrete incorporating nano-silica and industrial waste materials represents a highly effective and sustainable alternative to conventional cement-based construction materials. Across the literature, it is consistently observed that industrial by-products such as fly ash, slag, rice husk ash, crumb rubber, PET waste, glass powder, and cement bypass dust can successfully replace a significant portion of cement or fine aggregates, thereby reducing environmental pollution and lowering carbon emissions associated with cement production (Serour et al., 2026; Rath et al., 2026). However, these waste materials alone often lead to challenges such as reduced early-age strength, increased porosity, and variability in durability performance when used at higher replacement levels. Nano-silica has emerged as a key performance-enhancing material that effectively addresses these limitations. Due to its nano-scale particle size, high surface area, and strong pozzolanic activity, nano-silica significantly improves hydration kinetics, refines pore structure, and enhances the interfacial transition zone between cement paste and aggregates. As reported in multiple studies, the incorporation of nano-silica at optimal dosages (generally between 1% and 5%) leads to substantial improvements in compressive strength, flexural strength, durability, freeze–thaw resistance, and permeability reduction (Bagheri et al., 2025; Onochie, 2025). Furthermore, hybrid systems combining nano-silica with industrial waste materials demonstrate synergistic effects, where nano-silica compensates for the strength reduction caused by waste incorporation while simultaneously improving microstructural density. Overall, it can be concluded that nano-silica plays a critical role in enabling the high-volume utilization of industrial waste materials in concrete production without compromising structural performance. This dual advantage not only supports environmental sustainability by reducing cement consumption and waste disposal problems but also contributes to the development of high-performance, durable, and eco-efficient construction materials. Therefore, nano-silica-based green concrete represents a promising pathway toward achieving sustainable infrastructure development and circular economy goals in the construction industry.

V. FUTURE SCOPE

- Development of **advanced hybrid nano-green concrete** using combinations of nano-silica, nano-alumina, carbon nanotubes, and graphene for superior mechanical performance.
- Optimization of **mix design models using Artificial Intelligence (AI) and Machine Learning (ML)** to predict strength, durability, and workability of nano-modified concrete.
- Large-scale **field implementation studies** to validate laboratory findings under real environmental and loading conditions such as bridges, pavements, and high-rise structures.
- Investigation of **long-term durability behavior**, including chloride penetration, sulfate attack, carbonation, and fatigue performance in aggressive environments.
- Development of **cost-effective and sustainable production techniques for nano-silica**, especially from agricultural and industrial waste sources.
- Exploration of **self-healing and smart green concrete systems** incorporating nano-silica with bacteria-based or capsule-based healing agents.
- Study of **carbon footprint reduction using Life Cycle Assessment (LCA)** for nano-silica and waste-based concrete systems at industrial scale.

- Application of **3D printing and additive manufacturing technologies** using nano-silica modified green concrete for complex structural forms.
- Evaluation of **fire resistance, thermal conductivity, and energy efficiency** of nano-silica-based sustainable concrete systems.
- Development of **standard codes and guidelines** for the practical use of nano-materials in structural concrete to ensure safety, consistency, and scalability.

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