



Investigation on Strength and Durability Characteristics of High-Performance Concrete Containing Hybrid Nanoparticles

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ABSTRACT

Modern construction frequently uses high-performance concrete (HPC) because of its exceptional strength, resilience, and enhanced performance in harsh environmental circumstances. However, more advancements in HPC's microstructure, deterioration resistance, and long-term mechanical qualities are needed to create sustainable and long-lasting HPC. By improving the interfacial transition zone between cement paste and aggregates, pore refinement, and particle packing, the addition of hybrid nanoparticles to concrete has shown promise in improving its performance.

Depending on the material chosen for the experimental program, the current study focuses on examining the strength and durability properties of high-performance concrete containing hybrid nanoparticles, specifically nano-silica (NS) and volcanic or mineral-based nano-additives like VKC. The purpose of the study is to assess how various nanoparticle ratios affect the fresh properties, compressive strength, split tensile strength, flexural strength, and durability HPC performance.

As part of the experimental program, control and modified concrete mixes are prepared with nanoparticles added or partially replaced at predetermined percentages. To evaluate changes in mechanical performance and durability-related characteristics, specimens are tested at predetermined curing ages. The goal of the results is to find a suitable hybrid nanoparticle combination that enhances concrete performance without negatively impacting workability. The results could help create concrete that is strong, long-lasting, and resource-efficient for use in sustainable building.

Keywords: High-performance concrete, hybrid nanoparticles, nano-silica, compressive strength, tensile strength, flexural strength, durability, microstructure.

1. Introduction Literature survey & background

Because of its higher compressive strength, better workability, decreased permeability, and increased durability when compared to conventional concrete, high-performance concrete has become increasingly important in the construction industry. High-rise buildings, bridges, industrial structures, and other infrastructure subjected to harsh loads and environmental conditions frequently use it. However, the quality of HPC's cementitious matrix, pore structure, and interfacial transition zone determine its long-term performance. In order to enhance the qualities of concrete, researchers have investigated additional cementitious materials, chemical admixtures, and nanomaterials.

Nanotechnology has introduced new opportunities for modifying cement-based materials. Nanoparticles possess a high specific surface area and can participate in physical and chemical processes that influence cement hydration and microstructure. Nano-silica is one of the most extensively investigated nanomaterials because of its fine particle size, filler effect, and pozzolanic activity. It can react with calcium hydroxide released during cement hydration to form additional calcium silicate hydrate (C-S-H) gel. This process can contribute to a denser cement matrix, improved particle packing, and reduced pore connectivity. However, excessive nano-silica may increase water demand, cause agglomeration, and reduce workability if the mix proportions and admixture dosage are not properly controlled.

The use of hybrid nanoparticles involves combining two or more nanoscale materials to obtain complementary benefits. Different nanoparticles may improve concrete through pore filling, accelerated hydration, and modification of the microstructure. When an appropriate combination is used, the resulting cementitious matrix may exhibit improved strength and resistance to the penetration of harmful substances. However, the effectiveness of hybrid nanoparticles depends on their chemical composition, particle size, dispersion, dosage, water-to-binder ratio, and compatibility with the chemical admixture.

Previous investigations into nano-silica-modified concrete have generally reported improvements in compressive strength and matrix compactness at suitable dosages. Some studies have also indicated improvements in tensile and flexural strength due to enhanced bonding within the cementitious matrix. Nevertheless, the benefits are not always proportional to the nanoparticle content. Higher dosages may lead to poor dispersion, increased water demand, and the formation of agglomerates, which can create weak zones in the concrete.

Research on durability has focused on properties such as water absorption, sorptivity, chloride-ion penetration, sulphate resistance, and resistance to chemical attack. A refined pore structure can reduce the movement of water and aggressive ions through hardened concrete, potentially improving its service life. However, improvements in compressive strength alone cannot establish long-term durability; dedicated durability tests and appropriate exposure conditions are necessary to confirm the performance of modified HPC.

Even though individual nanoparticles have been thoroughly studied, more research is required to comprehend the combined effects of hybrid nanoparticles on durability and strength. Mechanical performance, fresh-state workability, durability, and material efficiency must all be balanced in the ideal combination. Thus, the current study examines how specific hybrid nanoparticle combinations affect the durability and strength properties of high-performance concrete.

2 Literature survey & background

Sharma et al. (2026) conducted an advanced experimental investigation on High-Performance Concrete (HPC) incorporating hybrid nanoparticles consisting of nano-silica and graphene oxide. The study focused on optimizing nanoparticle dosage to enhance both mechanical and durability characteristics. Results indicated that the hybrid system improved compressive strength by nearly 30–35% compared to control mixes, primarily due to enhanced pozzolanic reactions and nucleation effects. Microstructural analysis using SEM revealed a dense C–S–H gel formation and significant reduction in microcracks and voids. Additionally, durability tests such as Rapid Chloride Penetration Test (RCPT) showed a marked reduction in chloride ion ingress. The authors concluded that hybrid nanoparticles exhibit a synergistic effect, outperforming individual nanoparticle systems and providing a viable solution for durable infrastructure in aggressive environments.

Kumar and Singh (2025) investigated the combined influence of nano-alumina and nano-silica on the durability performance of HPC under aggressive chemical exposure. Their study emphasized sulfate resistance, acid resistance, and permeability characteristics. The researchers observed that nano-alumina improved early hydration kinetics, while nano-silica contributed to pore refinement and long-term strength development. The hybrid combination resulted in a 25% reduction in water absorption and significant improvement in resistance to sulfate attack.

Zhang et al. (2025) focused on graphene oxide-based nanomodification of cementitious composites. Their research highlighted the role of graphene oxide as a nano-reinforcement material capable of improving tensile strength and crack resistance. The study demonstrated that graphene oxide sheets act as bridges across microcracks, preventing their propagation and enhancing ductility. Experimental results showed an increase in flexural strength by approximately 20–25% and improved resistance to shrinkage-induced cracking. Durability parameters such as permeability and water absorption were significantly reduced.

Ahmed et al. (2024) conducted a comprehensive study on the effect of nano-silica on the mechanical and durability properties of HPC. The research revealed that nano-silica significantly enhances early-age strength due to its high pozzolanic activity and ability to accelerate hydration. The compressive strength increased by up to 28% at 28 days. Durability tests indicated reduced chloride ion penetration and improved resistance to chemical attack. SEM analysis confirmed the formation of a dense microstructure with reduced porosity.

3 Objective of research work

- . To study the influence of hybrid nanoparticles on the fresh properties and workability of high-performance concrete.
- To evaluate the compressive strength of HPC containing different proportions of hybrid nanoparticles at specified curing ages.

4 Result

4.1 Slump Cone Test

The workability of fresh concrete was evaluated using the slump cone test in accordance with relevant Indian Standards. The slump value indicates the ease with which concrete can be mixed, transported, placed, and compacted without segregation. The results of the slump test for various concrete mixtures containing Nano Silica (NS), Veli Karuvelam Charcoal (VKC), and their combined replacements are presented Figure 1

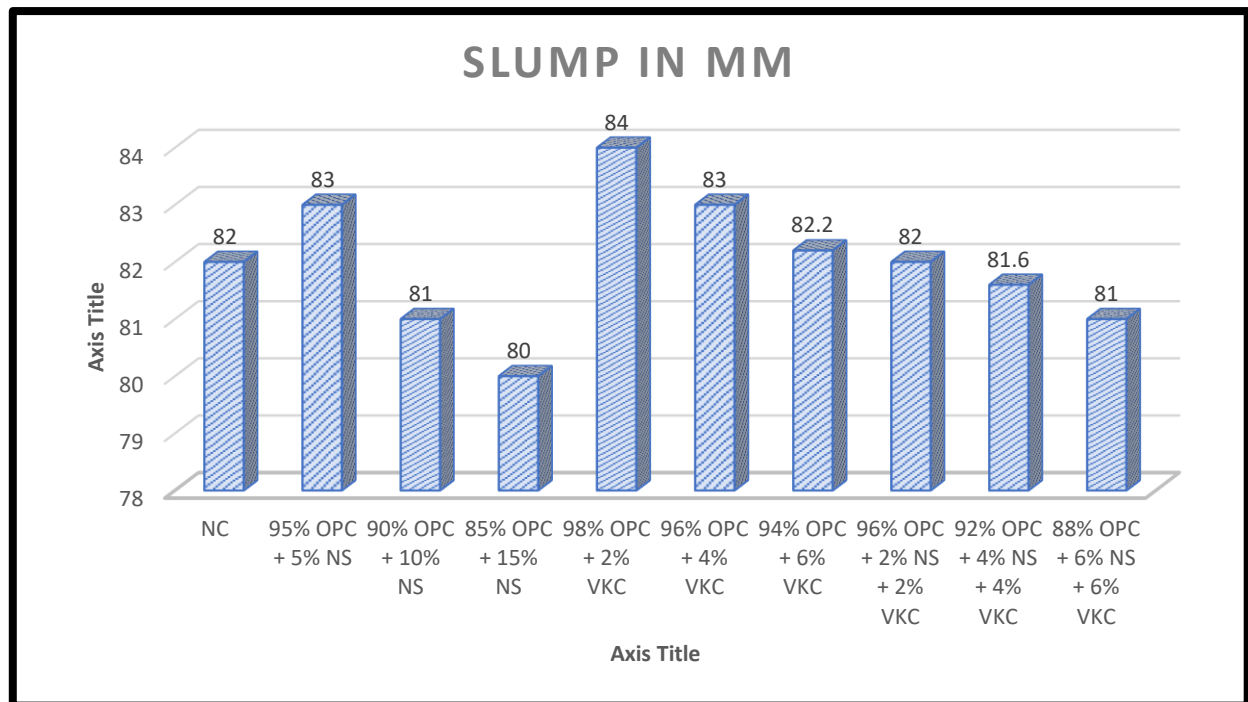


Figure 1 Slump value of M50 grade concrete

The slump values of all concrete mixes varied between 80 mm and 84 mm, indicating medium workability suitable for normal reinforced concrete construction works. The control mix (NC) exhibited a slump value of 82 mm, which served as the reference for comparison.

For concrete mixes incorporating Nano Silica (NS), a gradual reduction in slump was observed with increasing NS content. The slump decreased from 83 mm at 5% NS to 80 mm at 15% NS. This reduction can be attributed to the extremely fine particle size and high specific surface area of nano silica, which increases water demand and absorbs free water from the cement paste, thereby reducing the fluidity of the concrete mixture.

In the case of Veli Karuvelam Charcoal (VKC) replacement, the slump values initially increased to 84 mm at 2% VKC, indicating improved workability due to the filler effect and better particle packing. However, further increases in VKC content resulted in a slight reduction in slump, reaching 82.2 mm at 6% VKC. The porous nature of charcoal particles may have contributed to higher water absorption at elevated replacement levels.

For the combined NS and VKC mixes, the slump values ranged from 81 mm to 82 mm, showing only a marginal decrease compared with the control mix. The synergistic interaction between nano silica and VKC appears to have maintained adequate workability despite the higher surface area of the supplementary materials. Even at the highest replacement level of 6% NS + 6% VKC, the slump remained at 81 mm, demonstrating that the concrete possessed sufficient consistency for practical applications.

4.2 Compression Strength Test

The compressive strength test results of concrete mixes containing Nano Silica (NS), Volcanic Kaolin Clay (VKC), and their combinations are presented in Table X. The compressive strength was evaluated at curing ages of 7, 21, and 28 days to assess the influence of supplementary cementitious materials on the strength development of concrete.

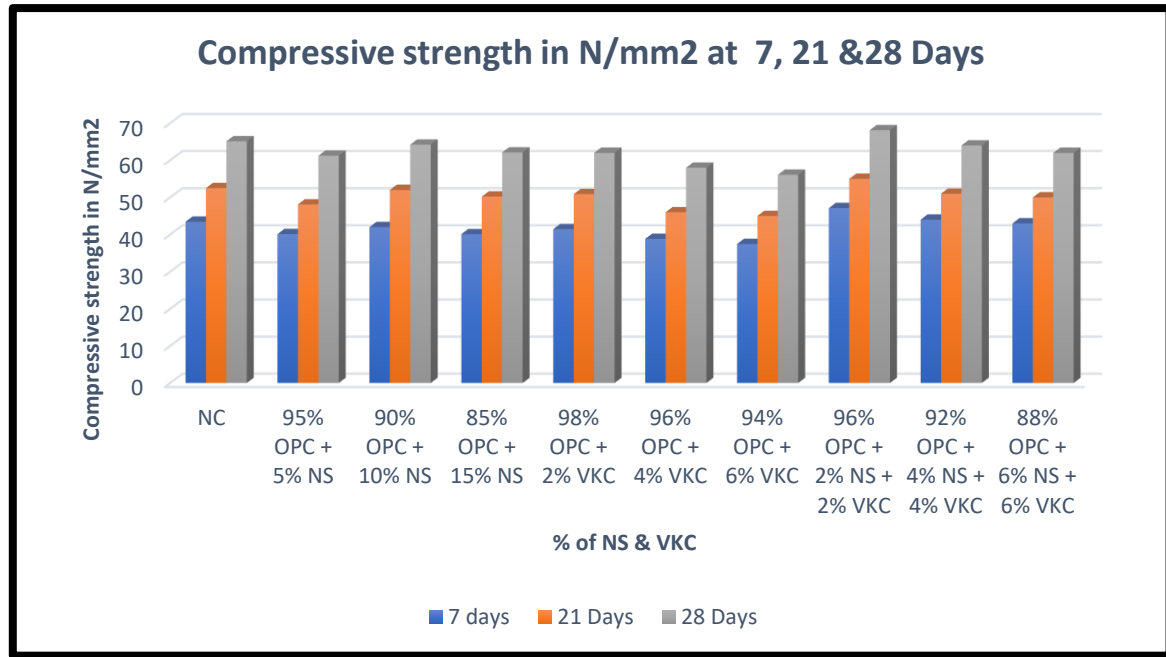


Figure 2 Compressive strength test of M50

The compressive strength results indicate that the incorporation of Nano Silica (NS) and Volcanic Kaolin Clay (VKC) significantly affects the mechanical performance of concrete. The control mix (NC) achieved compressive strengths of 43.45 N/mm², 52.50 N/mm², and 65.12 N/mm² at 7, 21, and 28 days, respectively.

For concrete mixes containing only Nano Silica, the compressive strength initially decreased at 5% NS replacement, recording 61.23 N/mm² at 28 days. However, increasing the NS content to 10% resulted in a substantial improvement, achieving a 28-day compressive strength of 64.23 N/mm², which is very close to that of the control mix. Further increase in NS content to 15% led to a slight reduction in strength, indicating that excessive Nano Silica may cause particle agglomeration and reduce the effectiveness of the pozzolanic reaction.

In the case of VKC-incorporated concrete, a gradual reduction in compressive strength was observed with increasing VKC content. The mixes containing 2%, 4%, and 6% VKC attained 28-day strengths of 62.00 N/mm², 58.00 N/mm², and 56.10 N/mm², respectively. This reduction can be attributed to the lower cement content and the slower pozzolanic activity of VKC compared to Nano Silica.

The combined use of Nano Silica and VKC produced superior results compared to their individual applications. The mix containing 96% OPC + 2% NS + 2% VKC exhibited the highest compressive strength among all mixes, recording 47.12 N/mm² at 7 days, 55.00 N/mm² at 21 days, and 68.10 N/mm² at 28 days. This value represents an increase of approximately 4.58% over the control concrete. The enhanced strength can be attributed to the synergistic effect of Nano Silica and VKC, where Nano Silica accelerates hydration and fills micro-voids, while VKC contributes to secondary calcium silicate hydrate (C-S-H) formation through pozzolanic reactions.

However, further increases in the combined replacement levels to 4% NS + 4% VKC and 6% NS + 6% VKC resulted in reduced compressive strengths of 64.00 N/mm² and 62.00 N/mm², respectively. This suggests that higher replacement percentages may dilute the cementitious matrix and adversely affect strength development.

Overall, the results demonstrate that the optimum replacement level for achieving maximum compressive strength is 2% Nano Silica combined with 2% Volcanic Kaolin Clay. The findings confirm that a carefully selected combination of NS and VKC can enhance concrete performance, improve microstructural densification, and increase long-term strength characteristics.

5 Conclusion

The investigation of high-performance concrete containing hybrid nanoparticles provides an opportunity to improve the mechanical properties and durability of cement-based construction materials. The combination of suitable nanoparticles may enhance particle packing, promote cement hydration, refine the pore structure, and improve the quality of the interfacial transition zone. These effects can potentially increase compressive, split tensile, and flexural strength while reducing water absorption and the penetration of harmful substances.

However, the overall effectiveness of hybrid nanoparticles depends on the type of nanoparticles used, their proportion, dispersion, and compatibility with the concrete mix. An excessive dosage may adversely affect workability and lead to particle agglomeration, making optimization essential. Therefore, a systematic experimental investigation of fresh properties, strength development, and durability performance is necessary to determine the most effective nanoparticle combination.

The present research is intended to establish the relationship between hybrid nanoparticle content and the performance of high-performance concrete. The experimental findings will help identify a suitable mix proportion and provide useful guidance for developing durable, high-strength, and resource-efficient concrete for modern construction. The final conclusions regarding the optimum dosage and percentage improvement should be established from the actual experimental results rather than assumed in advance.

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