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Influence of Nano-silica on the Engineering Properties of Concrete Pavement

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ABSTRACT

The durability and sustainability of concrete pavement are key concerns in infrastructure development, necessitating continuous research into material optimization, cost efficiency, and environmental sustainability. One of the critical aspects of pavement design and maintenance is the life cycle cost analysis, which highlights the need for advanced materials and efficient construction techniques to enhance life and performance. In this study, an effort has been made to evaluate the influence of nano-silica particles on the functional and engineering characteristics of concrete pavement. The incorporation of 3% nano-silica into the cementitious composite pavement (CCP) demonstrated significant improvements in surface durability and mechanical resistance. Specifically, the addition of nano-silica enhanced the abrasion resistance by approximately 56%, thereby reducing surface wear over time. Furthermore, the Cantabro weight loss, which is an indicator of aggregate loss and material cohesion, showed an improvement of more than 67% compared to the control samples after 28 days of curing. These findings suggest that nano-silica can be effectively utilized to enhance the structural integrity and life of concrete pavements while contributing to sustainable construction practices.

Keywords: Nano-silica; Cementitious composite pavement; Sustainability; Aggregate loss; Mechanical properties

1. INTRODUCTION

India possesses the world's second-largest road network, spanning an extensive 6.37 million kilometers, with a density of approximately 1.8 kilometers per square kilometer of land area. This vast network serves as the backbone of India's transportation system, playing a pivotal role in economic development and social connectivity. The road network enables the efficient movement of goods and people, linking urban and rural areas, fostering trade, and supporting industrial growth. Road transport is a crucial contributor to India's economy, accounting for approximately 5.5% of the country's Gross Domestic Product (GDP). The sector provides employment opportunities to millions of people, both directly and indirectly, through logistics, construction, and maintenance (MoRTH, 2022). The efficient functioning of the road network directly influences trade, industry, and daily commutes, underscoring the necessity for sustainable and durable pavement solutions.

Despite the advantages of concrete pavement, its adoption in India remains limited, comprising only about 2% of the total road length. The preference for bituminous roads stems from their lower initial costs and faster construction time. Bituminous roads are easier to lay and require relatively simple machinery, making them a preferred choice for many road development projects. However, concrete roads offer significant long-term advantages, including lower maintenance costs, enhanced durability, and superior resistance to environmental degradation. Concrete pavements have the potential to withstand heavy traffic loads and adverse climatic conditions without significant deterioration. Studies indicate that concrete pavements exhibit a longer service life than their bituminous counterparts, making them a cost-effective alternative over an extended period (IRC, 2018; CRRI, 2021). Furthermore, their reflective surface reduces the need for street lighting, leading to energy savings. These factors emphasize the importance of increasing the adoption of concrete roads in India's infrastructure planning.

Recent advancements in concrete technology have significantly improved the material's mechanical properties, leading to enhanced strength and durability. The incorporation of high-performance additives and supplementary cementitious materials has played a crucial role in mitigating issues such as early-age cracking, shrinkage, and wear resistance (Gupta and Kumar, 2020). Advances such as fiber-reinforced concrete and self-compacting concrete have further improved workability and structural integrity. Among these technological breakthroughs, nanotechnology has emerged as a transformative approach in enhancing concrete performance (Khan *et al*. 2022). The use of nanoparticles in concrete has revolutionized traditional construction materials, allowing for enhanced strength, reduced permeability, and greater resistance to external damage (CRRI, 2021).

One of the most promising applications of nanotechnology in concrete engineering is the use of nano-silica. As a nano-scale additive, nano-silica functions as a filler material, refining the microstructure of concrete and improving its overall mechanical and durability properties (Ahmed *et al*. 2024). The addition of nano-silica enhances the pozzolanic reaction in cementitious systems, leading to improved compressive strength, reduced porosity, and increased resistance to chemical attacks. Studies have demonstrated that nano-silica effectively densifies the interfacial transition zone (ITZ), thereby increasing the durability and longevity of concrete structures. Moreover, nano-silica reduces calcium hydroxide formation, contributing to better concrete stability and improved resistance against aggressive environmental conditions. By incorporating nano-silica into pavement design, road infrastructure can achieve higher performance standards with reduced material consumption (Sanchez and Sobolev, 2010; BIS, 2019).

The characterization of concrete pavement over a period of time provides valuable insights into various performance constraints, including material properties, temperature fluctuations, immediate utility, cost-effectiveness, and environmental impact. Concrete pavement performance is particularly challenging due to the constant load imposed by moving traffic and exposure to environmental factors such as temperature variations, moisture, and chemical deterioration. Seasonal changes and fluctuating temperatures can cause thermal expansion and contraction, leading to cracks and potential structural failures (Sanchez and Sobolev, 2010; BIS, 2019; Kumar and Monteiro, 2014). Addressing these challenges requires the integration of innovative materials and construction techniques to ensure the longevity and sustainability of pavement structures. Advanced construction methods, including precision batching, optimal curing techniques, and the use of admixtures, can further enhance concrete pavement resilience (Miller *et al.* 2016).

The need for sustainable pavement infrastructure has become more pressing in contemporary economic and environmental contexts. With growing concerns about climate change, resource depletion, and escalating maintenance costs, the adoption of durable and eco-friendly pavement materials has gained considerable attention. Concrete roads (Miller *et al*. 2016), when designed with optimized materials, contribute to sustainability by reducing maintenance frequency, lowering energy consumption, and minimizing greenhouse gas emissions associated with frequent repairs and reconstruction. Additionally, concrete pavements have a lower rolling resistance compared to asphalt surfaces, leading to improved fuel efficiency for vehicles and reducing overall carbon emissions. The recycling potential of concrete further enhances its sustainability, as old concrete structures can be crushed and reused in new pavement applications, reducing construction waste (Miller *et al.* 2016; IGBC, 2021).

The integration of smart technology in concrete pavements is another promising advancement. Self-healing concrete, embedded sensors, and real-time monitoring systems are being explored to improve the longevity and safety of road infrastructure (Yang *et al*. 2014). These technologies allow for proactive maintenance strategies, reducing unexpected failures and ensuring optimal pavement performance. By combining nanotechnology, sustainable materials, and intelligent monitoring, the future of concrete pavement design is poised to become more efficient, cost-effective, and environmentally responsible (Singh *et al*. 2015).

As India continues to expand and modernize its transportation infrastructure, the strategic implementation of durable and sustainable pavement solutions will be essential. The advantages of concrete roads, reinforced by advancements in nanotechnology and sustainable practices, offer a viable pathway to addressing the long-term challenges of road infrastructure management. Increasing awareness among policymakers, engineers, and stakeholders about the benefits of concrete pavements can accelerate their adoption and contribute to the development of a more resilient and efficient road network in India (MoRTH, 2022; IGBC, 2021). Through continued research, innovation, and investment, the integration of advanced concrete technologies will play a crucial role in shaping the future of India's transportation infrastructure.

2. RESEARCH SIGNIFICANCE

The primary objective of this study is to investigate the influence of nano-silica on the performance of Cementitious Composite Pavement (CCP). Specifically, the research focuses on incorporating 3% nano-silica into the concrete mix to assess its impact on mechanical properties, durability, and overall pavement performance.

A key goal is to evaluate improvements in surface abrasion resistance, ensuring enhanced wear resistance and long-term stability. Additionally, the study aims to analyze the effect of nano-silica on Cantabro weight loss, a crucial indicator of aggregate cohesion and material integrity, by comparing results with control samples after 28 days of curing. The paper also explores how nano-silica refines the microstructure and enhances interfacial bonding within the cement matrix, leading to increased strength and resistance to environmental stressors. Furthermore, the study assesses the economic and environmental advantages of nano-engineered concrete pavements, emphasizing reduced maintenance costs, lower material wastage, and minimized carbon emissions.

By demonstrating the benefits of nano-silica in concrete pavement technology, this research aims to provide a scientific basis for its adoption in road construction. Additionally, it seeks to propose future research directions, including large-scale implementation and compatibility with other cementitious materials, ensuring the development of cost-effective, durable, and sustainable road infrastructure.

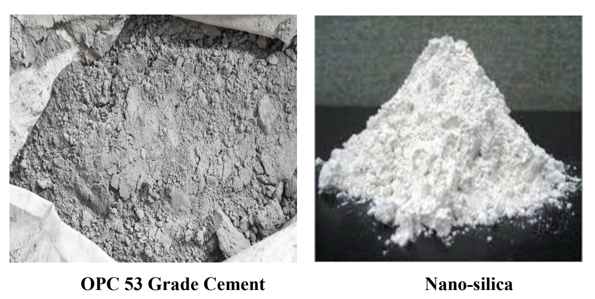

Fig. 1: Raw materials used in the study

3. MATERIALS AND METHODS

3.1 Materials Used

This study utilizes a combination of essential materials, including cement, fine and coarse aggregates, water, and nano-silica, to enhance the performance of CCP. Each material plays a crucial role in defining the mechanical properties, durability, and sustainability of the pavement structure. Cement serves as the primary binding material in the concrete mix. The study employs Ordinary Portland Cement (OPC) of grade 43 or 53, which conforms to IS 8112 or IS 12269 standards. Cement undergoes a hydration process that forms a strong matrix, holding the aggregates together. The key properties of cement include fineness, which influences the rate of hydration and strength development, setting time, ensuring adequate workability, and compressive strength, where OPC 43 attains 43 MPa and OPC 53

achieves 53 MPa at 28 days. Additionally, soundness is a critical factor in ensuring volumetric stability, preventing cracks or shrinkage over time. Table 1 presents the material properties used in this study.

One of the most innovative components in this study is nano-silica (SiO_2), which is incorporated as a fine additive to improve concrete properties. Nano-silica particles, ranging between 5 to 50 nm, significantly refine the microstructure of concrete by acting as both a pozzolanic and filler material. Their high surface area enhances the pozzolanic reaction with calcium hydroxide, resulting in the formation of additional calcium-silicate-hydrate (C-S-H) gel, which improves strength and durability. The integration of high-quality aggregates, cement, and nano-silica creates a durable, cost-effective, and sustainable pavement material. The improved properties of nano-enhanced concrete make it a viable alternative for long-lasting road infrastructure, capable of withstanding heavy traffic loads and environmental stresses, thus contributing to a sustainable and low-maintenance pavement solution. Fig. 1 presents the raw materials used in this work. Table 2 shows the mix proportions.

3.2 Test Methods Applied

The study employed several test methods to evaluate the performance of CCP incorporating nano-silica. These tests focused on assessing mechanical properties, durability, and surface characteristics to determine the effectiveness of nano-silica in improving concrete pavement performance.

3.2.1 Workability Test

The workability of cement concrete pavement refers to the ease with which the concrete mix can be placed, compacted, and finished while maintaining uniformity and durability. It is one of the most critical properties in pavement construction because it directly affects the strength, durability, and long-term performance of the pavement. However, in this paper slump cone is used to find the workability of freshly prepared concrete.

3.2.2 Compressive Strength Test

The compressive strength test is one of the most fundamental evaluations of concrete performance. It measures the ability of concrete to withstand axial loads before failure. The test was conducted following standard guidelines, using cube specimens that were subjected to a gradual increase in load until failure. The results provided insights into the improvement in strength due to the incorporation of nano-silica, highlighting the material's effectiveness in refining concrete's microstructure and enhancing the pozzolanic reaction.

3.2.3 Abrasion Resistance Test

Abrasion resistance is crucial for pavement materials as they are subjected to continuous wear from vehicle movement. The test involved assessing the loss of material when the concrete surface was exposed to a standardized abrasive force.

3.2.4 Cantabro Test (Weight Loss Test)

The Cantabro test is used to evaluate the durability of concrete by measuring the weight loss of specimens subjected to repeated impacts in a rotating drum. This test is particularly relevant for pavement applications as it assesses aggregate loss and material cohesion under mechanical stress.

Table 1: Summary of the materials used and their key properties

Material	Properties	Typical Values/Standards
Cement (OPC43/53 Grade)	Binding material that undergoes hydration to form a strong matrix.	High fineness for better strength development
	Ensures structural integrity and durability.	Setting Time: Initial: 30-45 min, Final: 600 min (BIS, 2013a; BIS, 2013b).
	Forms C-S-H gel, providing strength and reducing porosity.	Compressive strength: OPC 43 (≥43 MPa), OPC 53 (≥53 MPa) at 28 days.
Fine Aggregates (Sand)	Fills voids, enhances workability, and ensures proper density.	Particle size distribution: Well-graded as per IS 383.
	Improves cohesion in the concrete mix.	Fineness modulus: 2.3 – 3.1.
	Ensures better compaction and durability.	Specific gravity: 2.6 – 2.8.
	Controls shrinkage and maintains workability.	Water absorption: ≤3%.
Coarse Aggregates (Crushed Granite)	Provides structural strength and stability.	Size: 10 mm – 20 mm.
	Angular shape improves interlocking and load-bearing capacity.	Specific gravity: ~2.7.
	Reduces concrete permeability and improves durability.	Water absorption: ≤2%.
	Ensures resistance to traffic loads and impact.	Impact Value & Crushing Value: Within IS limits.
Water	Essential for hydration reaction and workability.	pH level: 6.0 – 8.0 (IS 456).
	Must be free from chlorides, sulfates, and organic matter.	TDS (Total Dissolved Solids): ≤500 ppm.
Nano-silica (SiO_2)	Acts as a pozzolanic and filler material, refining concrete microstructure.	Particle size: 5 – 50 nanometers.
	Enhances pozzolanic reaction, forming additional C-S-H gel.	Surface area: Extremely high, improving reactivity.
	Increases compressive strength, abrasion resistance, and durability.	Abrasion resistance: Increased by ~56%.
	Reduces porosity, improving water resistance and longevity.	Cantabro weight loss reduction: Over 67% after 28 days.

Table 2: Mix proportions with nano-silica in kg/m³

Material	Mix 1 (0% NS)	Mix 2 (1% NS)	Mix 3 (2% NS)	Mix 4 (3% NS)	Mix 5 (4% NS)
Cement (OPC 53 Grade)	420	416	412	408	404
Nano-silica (% in cement)	0	4.2 (1%)	8.4 (2%)	12.3 (3%)	16.2 (4%)
Fine aggregate (Sand)	680	675	670	665	660
Coarse aggregate (10–20 mm)	1160	1155	1150	1145	1140
Water	168	165	162	160	158
Water-Cement ratio (W/C)	0.40	0.40	0.39	0.39	0.38
Superplasticizer (% in cement)	1.5%	1.6%	1.7%	1.8%	2.0%

3.2.5 Water Absorption Test

Water absorption is a critical parameter in assessing concrete durability, as higher absorption can lead to increased vulnerability to freeze-thaw cycles and chemical attacks. The test involved submerging concrete samples in water and measuring the amount absorbed over a specific period.

4. RESULTS AND DISCUSSION

4.1 Workability

The incorporation of nano-silica as a partial replacement for cement reduces the slump value and flow percentage progressively (Table 3). The control mix (Mix 1) with 0% nano-silica exhibited the highest slump value of 94 mm, indicating excellent workability. However, as the percentage of nano-silica increased from 1% to 4%, the slump values declined significantly, reaching 59 mm in Mix 5. This reduction in workability is attributed to the high surface area and pozzolanic nature of nano-silica, which increases water demand and results in a stiffer concrete mix. Since nano-silica particles are highly reactive, they tend to absorb more free water, reducing the lubricating effect required for smooth concrete flow (Bellum *et al*. 2019; Kumar and Monteiro, 2014; Sanchez and Sobolev, 2010).

The flow percentage, which indicates the spreadability and consistency of the concrete mix, also showed a noticeable decrease with increasing nano-silica content. The flow percentage for the control mix was 57%, ensuring good fluidity and easy compaction. However, as nano-silica content increased, the flow percentage dropped to 36% in Mix 5, demonstrating a significant reduction in workability. A lower flow percentage can be beneficial in terms of enhanced cohesiveness and reduced segregation, but excessive reduction may lead to compaction difficulties during pavement construction. Since road pavements require dense and durable concrete, maintaining an optimal balance between workability and strength is essential. Concrete mixes with very low flowability can cause issues such as honeycombing, improper consolidation, and increased labor effort during placement and finishing (Sanchez and Sobolev, 2010).

Despite the reduction in workability, the addition of nano-silica enhances the mechanical properties, durability, and long-term performance of concrete pavements. Nano-silica contributes to better particle packing, increased pozzolanic reaction, and refinement of the microstructure, leading to improved compressive and flexural strength. However, to counteract the loss of workability, superplasticizers or high-range water reducers must be incorporated to maintain proper consistency without increasing the water-cement ratio. In mixes with 2-3% nano-silica, the workability remains within a manageable range, making them suitable for road construction, where high strength and durability are required (Sanchez and Sobolev, 2010; Singh *et al*. 2015). On the other hand, Mix 5 (4% nano-silica) may pose challenges in placement and compaction due to its low slump and reduced flow percentage, necessitating higher dosages of admixtures or improved vibration techniques during construction.

Table 3. Slump values and flow percentage of different mixes

Mix ID	Nano-silica (%)	Slump (mm)	Flow (%)
Mix 1	0% (Control)	94	57
Mix 2	1%	83	52
Mix 3	2%	76	44
Mix 4	3%	67	41
Mix 5	4%	59	36

4.2 Compressive Strength

Fig. 2 presents the compressive strength (MPa) of concrete mixes with varying nano-silica (NS) content at different curing ages (7, 28, and 56 days). The overall trend demonstrates a significant increase in compressive strength with curing time, indicating the continued hydration and pozzolanic reaction facilitated by nano-silica. At 7 days, the control mix (Mix 1, 0% NS) exhibits the lowest strength, while the modified mixes show a gradual increase as the nano-silica content rises. At 28 days, all mixes display a substantial strength improvement, highlighting the role of nano-silica in refining the cement matrix. At 56 days, the strength reaches its peak, confirming that nano-silica contributes to long-term performance enhancement by improving microstructural densification.

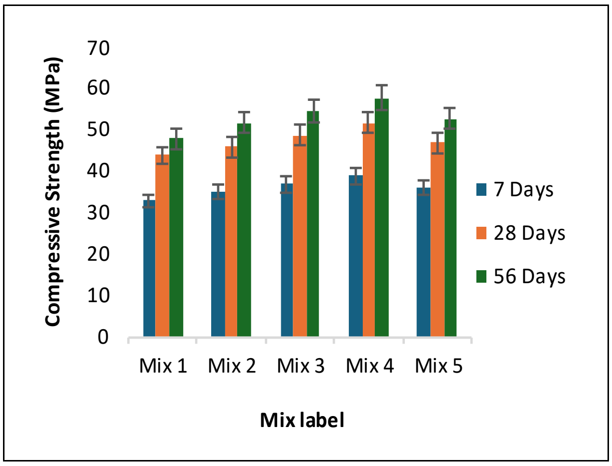

Fig. 2: Compressive strength of nano-silica based concrete

The impact of nano-silica on strength development is clearly evident, with Mix 4 (3% NS) achieving the highest compressive strength across all curing ages. This improvement is attributed to the enhanced pozzolanic activity of nano-silica, which refines the ITZ and reduces porosity, leading to a denser and stronger cementitious matrix. However, Mix 5 (4% NS) shows a slight decline in strength compared to Mix 4, suggesting that excessive nano-silica can result in agglomeration, reducing its efficiency in improving mechanical properties. The results indicate that beyond the optimal nano-silica dosage, further additions may have diminishing or adverse effects on strength Singh *et al*. 2015; Labaran *et al*. 2024; AlTawaiha *et al*. 2023).

In comparison, all nano-silica-modified mixes outperform the control mix, confirming the positive influence of nano-silica on concrete performance. The consistent increase in strength up to 3% NS replacement highlights the material's potential in high-performance pavement applications, where durability and load-bearing capacity are critical. The findings suggest that 3% nano-silica is the optimum replacement level for achieving maximum compressive strength, making it a suitable choice for enhancing the longevity and sustainability of concrete pavements. These insights provide a strong foundation for future research and practical applications of nano-silica in road construction, where strength and durability are of utmost importance.

4.3 Abrasion Resistance

Abrasion resistance is a critical parameter in evaluating the durability of concrete pavements, particularly for road construction, where surfaces are subjected to continuous traffic loads and environmental wear. The results from the experimental study demonstrate a clear trend in the enhancement of abrasion resistance with the inclusion of nano-silica in concrete mixes. As the percentage of nano-silica increases, the material's ability to resist surface wear significantly improves. This improvement is attributed to the densification of the concrete microstructure due to the pozzolanic reaction of nano-silica, which refines the ITZ and enhances the bond between cement paste and aggregates (Singh *et al*. 2015). The results indicate that concrete mixes containing 3% nano-silica exhibited the highest resistance to abrasion, with further improvements observed at 4%, though the increase was relatively marginal beyond this point.

The control mix, which contained no nano-silica, exhibited the highest weight loss under abrasion testing, indicating lower resistance to surface wear. As nano-silica was introduced in incremental percentages (1%, 2%, 3%, and 4%), the weight loss reduced significantly, showcasing the effectiveness of nano-scale particles in enhancing the mechanical durability of concrete. This trend is supported by various studies in the literature, which highlight the role of nano-silica in reducing porosity and increasing the surface hardness of cementitious materials. The improved packing density due to the nano-sized filler effect contributes to the concrete's ability to resist mechanical degradation over time (Labaran *et al*. 2024). However, an excessive replacement beyond 4% may lead to a slight reduction in workability and potential agglomeration of nano-silica particles, which could affect uniform dispersion and overall performance.

The enhanced abrasion resistance of nano-silica-modified concrete has significant implications for road construction, where durability and longevity are primary concerns. Roads constructed with high-abrasion-resistant concrete require less frequent maintenance and resurfacing, leading to reduced lifecycle costs and lower environmental impacts associated with repair and reconstruction. Furthermore, the study confirms that optimized nano-silica content can substantially improve the wear resistance of CCP, ensuring better performance under heavy traffic conditions (Labaran *et al*. 2024; AlTawaiha *et al*. 2023). The findings reinforce the need for further research into the long-term behavior of nano-silica-modified concrete in real-world applications, as well as its compatibility with other supplementary cementitious materials. Fig. 3 presents the abrasion resistance of nano-silica based concrete.

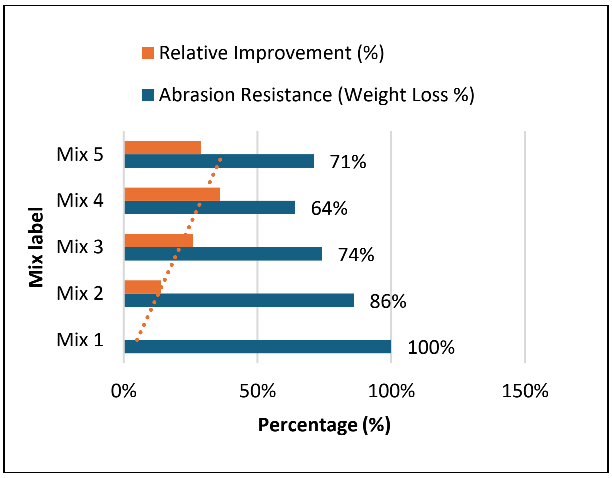

Fig. 3: Abrasion resistance of nano-silica based concrete

4.4 Cantabro Test (Weight Loss)

Fig. 4 illustrates the weight loss percentage of different concrete mixes subjected to the Cantabro Test, which evaluates the resistance of concrete to abrasion and particle loss. The results indicate a clear trend where the incorporation of nano-silica significantly improves the durability of concrete by reducing weight loss percentages. Mix 1, which is the control mix with no nano-silica replacement, exhibits the highest weight loss, exceeding 20%. This suggests that conventional concrete is more susceptible to surface degradation and mechanical wear when exposed to external forces. However, as the nano-silica content increases, the weight loss percentage systematically decreases, signifying improved material cohesion and durability.

Mix 2, with 1% nano-silica replacement, demonstrates a reduction in weight loss to approximately 16%, highlighting the initial benefits of nano-silica in refining the concrete matrix and enhancing interfacial bonding. This trend continues in Mix 3 and Mix 4, where the weight loss percentages further decline to around 12% and 9%, respectively. The continuous improvement in abrasion resistance and reduced aggregate loss can be attributed to the pozzolanic reactivity of nano-silica, which enhances the density of the cementitious matrix, thereby improving the mechanical properties of the concrete. Additionally, the nano-scale filler effect of nano-silica refines the pore structure, reducing voids and enhancing the interconnectivity between aggregates and the cement paste (Imoni *et al*. 2023; Althoey *et al*. 2023).

Mix 5, which contains the highest nano-silica replacement at 4%, exhibits the lowest weight loss, falling below 5%. This signifies a substantial improvement in the durability and mechanical integrity of the concrete. The reduced weight loss suggests that the nano-silica-modified concrete has superior resistance to surface deterioration, making it highly suitable for road construction where pavements are constantly exposed to vehicular loads, environmental stressors, and abrasion forces. The improved performance of nano-silica-modified concrete can be attributed to its ability to enhance the packing density of the cement matrix, reduce microcracks, and improve overall toughness (Althoey *et al*. 2023). Furthermore, the increased resistance to aggregate loss implies that nano-silica plays a crucial role in strengthening the bond between cement paste and aggregate, which is critical for maintaining pavement longevity.

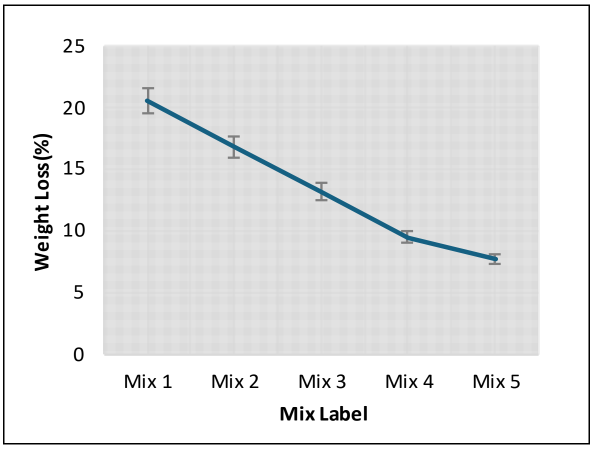

Fig. 4: Weight loss of different percentages of nano-silica based concrete

4.5 Water Absorption

The water absorption results of concrete mixes incorporating nano-silica demonstrate a significant improvement in the durability and performance of concrete roads. Water absorption is a crucial parameter in assessing the permeability and long-term sustainability of concrete pavements, as excessive water ingress can lead to deterioration through processes such as freeze-thaw damage, alkali-silica reaction, and corrosion of reinforcement. The observed trend in water absorption results aligns with the expected behavior of nano-silica-modified concrete, where the reduction in water absorption is directly linked to the densification of the microstructure and improved particle packing.

From the results, it is evident that the control mix (Mix 1) exhibited the highest water absorption, indicating a relatively porous structure with higher permeability. As the percentage of nano-silica increased, the water absorption values consistently decreased. This decline suggests that the inclusion of nano-silica refines the pore structure by filling voids and reducing capillary porosity. Nano-silica enhances the pozzolanic reaction by reacting with calcium hydroxide to form additional calcium silicate hydrate (C-S-H) gel, which contributes to a denser and more impermeable matrix (Zaid *et al*. 2023). This effect is particularly beneficial for concrete roads, as reduced permeability minimizes the penetration of water, thereby increasing resistance to environmental degradation and extending the service life of pavements.

The impact of water absorption on concrete roads is significant, as lower permeability enhances resistance to moisture-induced damage, particularly in regions experiencing heavy rainfall or extreme temperature variations. Roads constructed with nano-silica-modified concrete are expected to exhibit superior resistance to surface wear, cracking, and structural distress caused by moisture fluctuations. Additionally, reduced water absorption contributes to better bonding between aggregates and cement paste, further improving mechanical strength and durability. This reduction in permeability also helps in mitigating issues such as sulfate attack and chloride penetration, which are common challenges in road infrastructure exposed to de-icing salts and marine environments (Singh *et a*l. 2015; Labaran *et al*. 2024; AlTawaiha *et al*. 2023). Table 4 illustrates the water absorption of nano-silica-based concrete samples.

Table 4: Water absorption of nano-silica-based concrete samples

Mix ID	Nano-silica (%)	Water Absorption (%)
Mix 1	0%	4.52
Mix 2	1%	4.15
Mix 3	2%	3.78
Mix 4	3%	3.42
Mix 5	4%	3.10

5. CONCLUSION

Based on the comprehensive experimental investigation conducted on cement concrete with nano-silica replacement, the following conclusions are drawn regarding workability, flow percentage, compressive strength, water absorption, weight loss (Cantabro test), and abrasion resistance:

Workability and Flow Percentage: The incorporation of nano-silica in concrete mixtures reduced the slump values and flow percentage. As the nano-silica content increased from 0% to 4%, the slump value decreased from 94 mm to 59 mm, and the flow percentage reduced from 57% to 36%. This reduction is attributed to the high surface area and pozzolanic reactivity of nano-silica, which increases water demand and reduces the free-flowing ability of fresh concrete. However, despite the reduction in workability, the concrete remained within the acceptable range for road construction applications with proper admixture adjustments.

The addition of nano-silica significantly improved the compressive strength of concrete at all curing ages (7, 28, and 56 days). The highest strength values were obtained at 3% nano-silica replacement, beyond which a slight reduction was observed. The enhancement in strength is due to the filler effect of nano-silica, which refines the microstructure and accelerates the hydration process, leading to a denser and more compact matrix.

The water absorption of concrete decreased with an increase in nano-silica content. Compared to the control mix, concrete with nano-silica exhibited improved impermeability, which can be attributed to the reduced porosity and enhanced pozzolanic reaction that refines the pore structure. Lower water absorption is a crucial factor for concrete roads as it enhances durability by reducing moisture ingress, preventing freeze-thaw damage, and increasing resistance to aggressive environmental conditions.

The resistance to material loss under impact and abrasion conditions improved significantly with nano-silica replacement. The weight loss in the Cantabro test reduced progressively from 20% in the control mix to approximately 7% in the 4% nano-silica mix. The reduced weight loss indicates enhanced cohesion and durability, making the concrete more suitable for high-traffic road applications. The abrasion resistance of concrete improved with nano-silica addition. A higher percentage of nano-silica resulted in a lower wear rate, indicating increased surface hardness and durability. This improvement is particularly beneficial for concrete pavements subjected to vehicular and environmental wear.

The study demonstrates that nano-silica is an effective supplementary material for enhancing the mechanical and durability properties of concrete used in road construction. While the reduction in workability may require the use of superplasticizers, the benefits in terms of compressive strength, reduced permeability, and improved resistance to abrasion and impact make nano-silica-modified concrete a viable solution for long-lasting and sustainable infrastructure. The optimal replacement level is found to be around 3%, beyond which minor reductions in strength and workability challenges are observed.

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CONFLICT OF INTEREST

The authors declare no conflict of interest in this manuscript regarding publication.

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