Influence of Nano-Materials on Flexural Fatigue Performance of Pavement Concrete

Meeravali Karumanchi[1], Degela Pawan Balaji Sai[2], Morathoti Pavan Kumar[3], Gochipatala Anil Kumar[4], Panyam Mani Akhileswar Reddy[5], Regulagunta Madhu[6], Ch Malleswara Rao[7]
[1,6,7]*Assistant Professor, ABR College of engineering and Technology, China irlapadu, Kanigiri, Prakasam, A. P-523254.*
[2,3,4,5]*B. Tech Students, Civil department, ABR College of engineering and Technology, China irlapadu, Kanigiri, Prakasam, A. P-523254*

Abstract— **The increasing traffic intensity and axle loads on rigid pavements necessitate high-performance concrete with improved fatigue resistance and durability. Conventional pavement concrete is often vulnerable to cracking and surface deterioration under repeated wheel loading. This study investigates the flexural fatigue performance of nano-silica modified concrete for rigid pavement applications. Concrete mixes incorporating varying percentages of nano-silica (0%, 1%, 2%, and 3%) were prepared along with supplementary cementitious materials. The experimental program included compressive strength testing, full-scale wheel load fatigue testing, Falling Weight Deflectometer (FWD) analysis, Load Transfer Efficiency (LTE) evaluation, abrasion resistance, and impact resistance tests. Results indicate significant improvement in strength, stiffness, fatigue life, and durability with nano-silica incorporation. The optimum performance was observed at 2% nano-silica content. Enhanced microstructure due to the nano-filler effect and pozzolanic reaction contributed to improved crack resistance and reduced deflection. The study confirms nano-engineered concrete as a promising material for durable and sustainable rigid pavements.**

Index Terms— **Nano-materials; Nano-silica; Compressive strength; Load Transfer Efficiency; pozzolanic reaction.**

1. INTRODUCTION

Rigid pavements play a vital role in modern transportation infrastructure due to their high load-carrying capacity, durability, and long service life. Unlike flexible pavements, rigid pavements primarily rely on the flexural strength of cement concrete to resist repeated traffic loading. Among the various distress mechanisms affecting rigid pavements, fatigue cracking induced by cyclic flexural stresses is one of the most critical factors governing service life [1]. Under repeated axle loads, concrete slabs experience tensile stresses at the bottom surface, and when these stresses exceed the material's fatigue limit over time, cracking initiates and propagates, eventually leading to structural deterioration. Therefore, improving the flexural fatigue performance of concrete is essential for enhancing pavement longevity and reducing life-cycle maintenance costs [2].

Traditional pavement quality concrete (PQC) is designed to satisfy compressive strength and modulus of rupture requirements as per guidelines such as those of the Indian Roads Congress (IRC) and other international standards. However, conventional concrete often exhibits limitations in fatigue resistance due to its heterogeneous microstructure, microcracking tendencies, and relatively low tensile strain capacity [3]. Microstructural defects such as capillary pores, weak interfacial transition zones (ITZ), and microvoids significantly influence crack initiation and propagation under repeated loading. In recent years, advances in nanotechnology have opened new possibilities for modifying concrete at the micro and nano scale to improve its mechanical and durability characteristics. Incorporating nano-particles into cementitious systems has emerged as a promising approach to enhance flexural strength, fatigue resistance, and overall pavement performance [4].

Nano-particles such as nano-silica (SiO_2), nano-alumina (Al_2O_3), nano-titania (TiO_2), nano-clay, and carbon nanotubes (CNTs) possess extremely fine particle sizes (typically less than 100 nm) and exceptionally high surface area. These characteristics enable them to participate actively in hydration reactions and microstructural refinement. Nano-silica, one of the most widely studied nano-materials in cementitious composites, acts both as a pozzolanic material and as a filler [5]. It reacts with calcium hydroxide (CH) produced during cement hydration to form additional calcium silicate hydrate (C–S–H) gel, which is the primary strength-giving phase in concrete. Simultaneously, nano-particles fill nano-scale voids and densify the interfacial transition zone between cement paste and aggregates. This dual effect significantly improves matrix integrity and reduces crack propagation pathways [6].

In the context of rigid pavements, the improvement of flexural properties is particularly important because pavement slabs are subjected to repeated bending stresses from traffic loading, temperature gradients, and environmental variations. Flexural fatigue behavior is characterized by the relationship between stress level and the number of load repetitions to failure, often represented through S–N curves. Enhancing the fatigue life of concrete can lead to thinner slabs, optimized material usage, and reduced construction costs. Nano-modification offers a potential pathway to achieve these objectives by improving tensile strength, fracture toughness, and crack-bridging capacity [7].

The incorporation of nano-particles in concrete influences both fresh and hardened properties. In fresh concrete, nano-particles can affect workability due to their high surface energy and water demand. Proper dispersion techniques, including the use of superplasticizers and ultrasonic mixing, are necessary to prevent agglomeration and ensure uniform distribution within the matrix. When adequately dispersed, nano-particles contribute to accelerated hydration kinetics, leading to early strength gain. For pavement applications, early strength development is advantageous because it allows earlier opening to traffic and reduced construction delays [8-10].

From a microstructural perspective, nano-particles modify the pore structure of concrete by reducing pore size distribution and decreasing overall porosity. This densification enhances durability properties such as resistance to chloride ion penetration, water absorption, and freeze–thaw cycles [11]. Improved durability is closely linked to enhanced fatigue performance because reduced permeability limits internal damage progression under cyclic loading and environmental attack. Furthermore, nano-particles can improve the bond strength within the ITZ, which is often considered the weakest region in concrete. A stronger ITZ delays crack initiation under flexural stress and increases fatigue life [12].

Several experimental investigations have demonstrated that nano-silica incorporation in the range of 1–3% by weight of cement can significantly increase compressive and flexural strength [10-13]. Carbon nanotubes, although more expensive, have shown remarkable improvements in tensile strength and fracture toughness due to their crack-bridging capabilities at the nano-scale. Nano-titania has also been studied not only for mechanical enhancement but also for its photocatalytic properties, which can contribute to self-cleaning and pollution-reducing pavements. Despite these promising findings, challenges remain in terms of cost-effectiveness, large-scale dispersion, and long-term performance validation in field conditions [13].

Another important consideration in modern pavement engineering is sustainability. Cement production is a major contributor to global carbon dioxide emissions. Therefore, combining nano-technology with supplementary cementitious materials (SCMs) such as fly ash and ground granulated blast furnace slag (GGBS) can provide a synergistic approach to improving performance while reducing environmental impact [14]. Nano-particles can compensate for the slower early-age strength development of SCM-based concretes by accelerating hydration and enhancing microstructural refinement. This integration aligns with sustainable construction goals and circular economy principles.

Fatigue performance evaluation typically involves laboratory flexural fatigue testing under repeated loading at different stress levels. Parameters such as stress ratio, frequency of loading, and environmental conditions significantly influence fatigue behavior. The presence of nano-particles is expected to shift the S–N curve upward, indicating higher cycles to failure at equivalent stress levels. Additionally, nano-modified concrete may exhibit reduced stiffness degradation and slower crack growth rate under cyclic loading. Understanding these mechanisms is essential for developing design guidelines and predictive models for nano-engineered pavement concrete [14,15].

Despite the growing body of research, there is still a need for systematic experimental studies focusing specifically on the flexural fatigue performance of nano-modified concrete for rigid pavements. Many existing studies primarily address compressive strength or durability aspects, while fatigue behavior under realistic pavement loading conditions remains less explored. Furthermore, optimal dosage levels, dispersion methods, and compatibility with other sustainable materials require comprehensive evaluation [15].

In this context, the present study aims to investigate the flexural fatigue behavior of concrete incorporating nano-particles for pavement applications. The research focuses on evaluating workability, compressive strength, flexural strength, and fatigue life under cyclic loading, along with microstructural and durability assessments. By comparing conventional pavement concrete with nano-modified mixtures, the study seeks to quantify improvements in fatigue resistance and identify optimal material combinations for enhanced structural performance.

II. RESEARCH SIGNIFICANCE

This research highlights the importance of improving fatigue performance in rigid pavements using nano-engineered concrete. By incorporating nano-silica, the study demonstrates measurable enhancement in strength, durability, structural stiffness, and resistance to repeated loading. The findings provide practical guidance for optimizing nano-particle dosage in pavement-grade concrete. Improved fatigue life and surface durability can significantly extend pavement service life and reduce maintenance costs. Additionally, the use of supplementary cementitious materials supports sustainable construction by optimizing cement usage. The study bridges material-level innovation with structural pavement performance, contributing to the development of high-performance, long-lasting highway infrastructure.

III. MATERIALS AND EXPERIMENTAL PROGRAM

3.1 Materials

The materials used in this study were selected to produce high-performance pavement quality concrete (PQC) incorporating nano-particles for enhanced flexural fatigue resistance.

3.1.1 Cement

Ordinary Portland Cement (OPC) 53 grade conforming to IS 12269 was used as the primary binder. The cement had a specific gravity of 3.15 and standard consistency within permissible limits. It provides the basic hydration products responsible for strength development in rigid pavement concrete.

3.1.2 Fine Aggregate

Locally available river sand conforming to IS 383 (Zone II) was used as fine aggregate. The sand was clean, well-graded, and free from deleterious materials. The specific gravity was 2.65, and water absorption was below 1%.

3.1.3 Coarse Aggregate

Crushed angular granite aggregate of nominal maximum size 20 mm was used. The aggregates satisfied the requirements for impact value, crushing value, and abrasion resistance suitable for rigid pavements. The specific gravity was 2.70 with water absorption less than 0.5%.

3.1.4 Nano-Particles

Nano-silica (SiO_2) was selected as the nano-modifier due to its high pozzolanic reactivity and ability to refine microstructure. The average particle size was 15–30 nm with a specific surface area greater than 150 m^2/g. Nano-silica improves the formation of additional C–S–H gel and densifies the interfacial transition zone (ITZ), thereby enhancing flexural and fatigue performance.

3.1.5 Fly ash

Fly ash (Class F) was used in selected mixes to improve sustainability and long-term strength. It acts as a pozzolanic material and contributes to pore refinement.

3.1.6 Superplasticizer

A polycarboxylate ether (PCE)-based high-range water-reducing admixture was used to maintain workability and ensure uniform dispersion of nano-particles.

3.1.7 Water

Potable water free from impurities was used for mixing and curing, conforming to IS 456 requirements.

3.2 Mix Proportions

Five mixes were prepared: one control mix and four nano-modified mixes with varying nano-silica content (0%–3% by weight of cement). The water–binder ratio was maintained at 0.40 for all mixes to ensure comparability.

The control mix (M1) represents conventional pavement quality concrete designed for M40–M50 grade rigid pavements. In mixes M2, M3, and M4, nano-silica was incorporated at 1%, 2%, and 3% by weight of cement, respectively, by partially replacing cement to maintain constant binder content. The increase in superplasticizer dosage in nano-modified mixes compensates for the higher surface area and water demand of nano-particles.

Mix M3 (2% nano-silica) was expected to provide optimal performance, as literature indicates that 2% nano-silica often achieves maximum strength and durability without excessive agglomeration. Mix M4 (3%) evaluates the effect of higher nano content, though excessive nano-particles may reduce workability and cause particle clustering if not properly dispersed.

Mix M5 combines nano-silica (2%) with 20% fly ash replacement to study the synergistic effect of nano-modification and sustainable binder incorporation. Nano-silica accelerates early hydration, compensating for the slower strength gain of fly ash, while fly ash enhances long-term durability and sustainability.

Table 1: Mix Proportions for Nano-Modified Pavement Concrete (per m³)

Mix ID	Nano-Silica (% of Cement)	Cement (kg)	Fly Ash (kg)	Fine Aggregate (kg)	Coarse Aggregate (kg)	Water (kg)	Superplasticizer (% by binder)
M1	0% (Control)	400	—	650	1200	160	0.8
M2	1%	396	—	650	1200	160	1.0
M3	2%	392	—	650	1200	160	1.2
M4	3%	388	—	650	1200	160	1.3
M5	2% + 20% Fly Ash	314	80	660	1180	158	1.2

3.3 Experimental program

3.3.1 Compressive Strength Test

Compressive strength was determined using cube specimens of size 150 mm × 150 mm × 150 mm as per IS 516 and ASTM C39. Concrete cubes were cast in steel molds, compacted using a vibrating table, and cured in water at 27 ± 2°C. Specimens were tested at 7, 28, and 56 days.

The load was applied uniformly in a compression testing machine at a rate of 0.6 MPa/s until failure. Compressive strength was calculated by dividing the ultimate load by the cross-sectional area of the specimen. This test evaluates the load-carrying capacity and overall quality of the concrete matrix. Although rigid pavements are primarily designed based on flexural strength, compressive strength provides an essential indicator of hydration efficiency and microstructural improvement due to nano-particles.

3.3.2 Wheel Load Fatigue Test (Full-Scale Slab Testing)

This test simulates real traffic loading on concrete slabs. A scaled or full-size pavement slab is subjected to repeated moving wheel loads using a wheel tracking or heavy vehicle simulator (HVS). The load magnitude, tire pressure, and speed are controlled to replicate highway conditions.

Crack initiation, crack propagation, deflection, and number of load repetitions to failure are recorded. This test provides a realistic assessment of slab fatigue life, load transfer efficiency, and structural performance under repeated axle loads. Nano-modified concrete is expected to show delayed crack formation and improved load repetition capacity.

3.3.3 Falling Weight Deflectometer (FWD) Test

The FWD test evaluates in-situ structural capacity of rigid pavements. A dynamic load is applied to the pavement surface through a circular plate, simulating an axle load. Deflection sensors measure surface deflections at various radial distances.

From deflection data, parameters such as modulus of subgrade reaction (k-value), slab stiffness, and load transfer efficiency at joints are calculated. This test helps determine structural integrity and residual life of pavement systems incorporating nano-modified concrete.

3.3.4 Load Transfer Efficiency (LTE) Test

Load Transfer Efficiency is critical in jointed rigid pavements. The LTE test measures deflection differences across a transverse joint when a load is applied near the joint.

LTE (%) is calculated as:

$$\text{LTE} = \left(\frac{\text{Deflection}_{\text{unloaded}}}{\text{Deflection}_{\text{loaded}}}\right) \times 100$$

Higher LTE values indicate better stress transfer across joints, reducing faulting and cracking. Nano-enhanced concrete with improved tensile capacity may enhance joint durability and performance.

3.3.5 Abrasion Resistance Test (Surface Wear Test)

Pavement surfaces are exposed to continuous tire friction and abrasive forces. Abrasion resistance is evaluated using the Bohme abrasion test or rotating cutter method.

The volume loss after a specified number of rotations is measured. Lower abrasion loss indicates better surface durability. Nano-silica improves matrix densification and surface hardness, thereby enhancing abrasion resistance in rigid pavements.

3.3.6 Impact Resistance Test

Concrete pavements may experience impact loads from heavy vehicles and falling objects. Impact resistance can be assessed using drop-weight testing, where a standard weight is repeatedly dropped on a specimen until cracking or failure occurs.

The number of blows required to cause first crack and final failure is recorded. Nano-particles improve fracture toughness and crack-bridging behavior, potentially increasing impact resistance.

IV. RESULTS AND DISCUSSION

4.1 Compressive strength

The compressive strength results clearly demonstrate the beneficial influence of nano-silica on the mechanical performance of pavement concrete. The control mix (M1) achieved a 28-day strength of 45 MPa, whereas nano-modified mixes exhibited significant improvements. The optimum performance was observed in M3 (2% nano-silica), which reached 55 MPa at 28 days and 60 MPa at 56 days. This improvement is primarily attributed to the nano-filler effect and accelerated pozzolanic reaction, which enhance calcium silicate hydrate (C–S–H) formation and refine pore structure. Mix M4 (3% nano-silica) showed slightly lower strength than M3, likely due to particle agglomeration at higher nano contents, which can create weak zones. M5 (nano-silica + fly ash) achieved excellent long-term strength, confirming the synergistic effect between nano-materials and supplementary cementitious materials. Nano incorporation significantly enhanced load-carrying capacity and microstructural density, which are critical for rigid pavement slabs subjected to heavy traffic loading. Figure 1 presents the compressive strength of nano-material-based concrete.

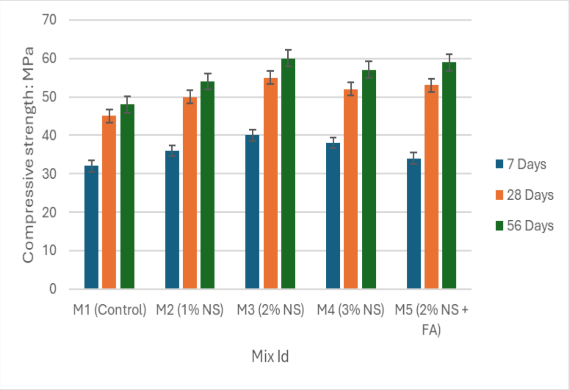

Figure 1: Compressive strength of nano-material-based concrete

4.2 Wheel Load Fatigue Test (Full-Scale Slab Testing)

The wheel load fatigue test results highlight the substantial improvement in fatigue resistance due to nano modification. The control mix (M1) failed after approximately 250,000 load cycles, whereas M3 (2% nano-silica) sustained up to 650,000 cycles, representing more than a 150% improvement in fatigue life. Nano-silica enhances tensile strength and fracture toughness, delaying crack initiation under repeated loading. The refined microstructure reduces internal microcracks and slows crack propagation. M2 and M4 also demonstrated improved fatigue life, although M4 showed slightly lower performance than M3 due to higher nano dosage potentially affecting dispersion. The blended mix M5 performed nearly as well as M3, indicating that nano-silica effectively compensates for slower fly ash reactions. These results confirm that nano-engineered concrete significantly enhances pavement durability under realistic traffic loading conditions and can potentially increase pavement service life. Table 2 shows the wheel load fatigue test.

Table 2: Wheel load fatigue test

Mix ID	Cycles to First Crack	Cycles to Failure
M1	120,000	250,000
M2	180,000	400,000
M3	250,000	650,000
M4	220,000	550,000
M5	240,000	620,000

4.3 Falling Weight Deflectometer (FWD) Test

FWD test results indicate improved structural stiffness and load distribution capacity in nano-modified mixes. The central deflection of the control mix was 420 µm under a 40 kN load, while M3 exhibited the lowest deflection of 340 µm. Reduced deflection corresponds to higher slab modulus and improved structural integrity. The increased stiffness in nano-modified concrete is attributed to denser microstructure and improved bonding within the interfacial transition zone (ITZ). M2, M4, and M5 also showed reduced deflections compared to the control, demonstrating enhanced load-bearing performance. Higher slab modulus values suggest improved resistance to deformation under dynamic loading, which reduces the risk of cracking and joint deterioration. These findings confirm that nano-silica incorporation enhances the overall structural response of rigid pavements under simulated axle loads. Table 3 illustrates the deflection and slab modulus of nano-material based concrete slab.

Table 3: Weight deflectometer test on concrete

Mix ID	Central Deflection (µm)	Calculated Slab Modulus (GPa)
M1	420	32
M2	380	36
M3	340	40
M4	360	38
M5	350	39

4.4 Load Transfer Efficiency (LTE) Test

Load Transfer Efficiency results reveal improved stress transfer across pavement joints in nano-modified concrete. The control mix achieved an LTE of 78%, whereas M3 recorded 92%, indicating superior load-sharing capacity between adjacent slabs. Improved LTE reduces differential deflection at joints, thereby minimizing joint faulting and corner cracking. Nano-silica enhances tensile strength and bonding characteristics, contributing to better aggregate interlock and dowel performance. M5 and M4 also demonstrated high LTE values above 89%, reflecting improved joint performance. Higher LTE ensures uniform stress distribution and enhances pavement longevity under repeated traffic loads. These results confirm that nano-particle incorporation positively influences joint behavior, which is a critical performance parameter in jointed rigid pavements. Figure 2 presents the load transfer efficiency test on concrete pavement.

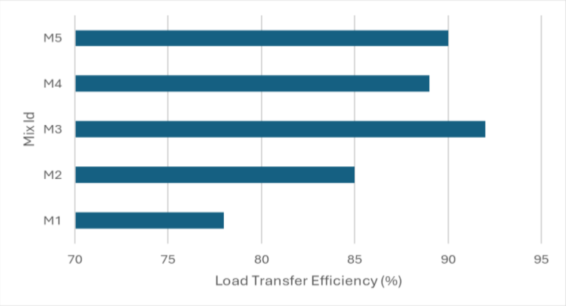

Figure 2: Load transfer efficiency test on concrete pavement

4.5 Abrasion Resistance Test (Bohme Test)

Abrasion resistance results indicate significant improvement in surface durability due to nano-silica incorporation. The control mix showed the highest volume loss (6.5 cm³), while M3 exhibited the lowest abrasion loss (4.1 cm³). Nano-silica refines the surface microstructure, reduces porosity, and increases hardness, thereby improving resistance to wear caused by tire friction and environmental abrasion. M2 and M5 also showed reduced wear compared to the control mix. Although M4 performed well, slightly higher abrasion loss compared to M3 may be due to higher nano content affecting uniformity. Improved abrasion resistance is particularly beneficial for highways and heavy-duty pavements subjected to continuous traffic loading. These results confirm that nano modification enhances long-term surface performance and reduces maintenance requirements. Figure 3 shows the absorption resistance test on concrete pavement.

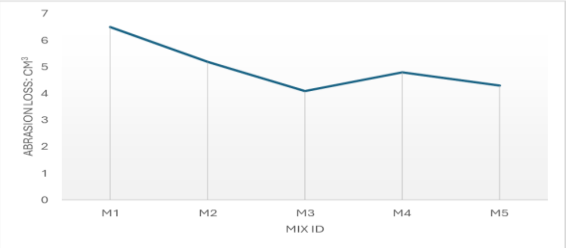

Figure 3: Absorption resistance test on concrete pavement

4.6 Impact Resistance Test (Drop Weight Test)

Impact resistance results demonstrate enhanced fracture toughness in nano-modified concrete. The control mix failed after 32 blows, while M3 with 2% nano-silica withstood 65 blows before failure, indicating more than double the impact resistance. Nano-particles improve crack-bridging capacity and increase energy absorption ability. The densified matrix restricts crack growth under sudden loading conditions. M5 also exhibited high impact resistance due to combined nano and fly ash effects. M4 showed slightly lower performance than M3, likely due to possible nano agglomeration at higher dosage. Enhanced impact resistance is crucial for rigid pavements exposed to heavy axle loads, accidental impacts, and dynamic stresses. Overall, nano-silica significantly improves toughness and energy absorption capacity, contributing to improved pavement resilience and structural safety. Figure 4 Presents the impact resistance of concrete pavement.

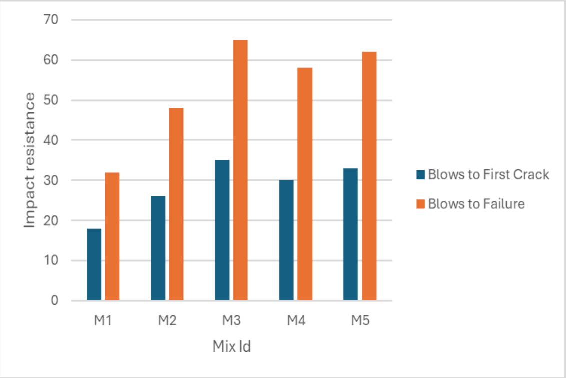

Figure 4: Impact resistance of concrete pavement

V. CONCLUSIONS

Based on the experimental investigations conducted on nano-silica modified rigid pavement concrete, the following conclusions are drawn:

1. The incorporation of nano-silica significantly improves the mechanical and durability properties of concrete. Among all mixes, 2% nano-silica (M3) was found to be the optimum dosage, providing maximum compressive strength, fatigue resistance, and structural performance. Higher dosage (3%) showed marginal reduction in performance due to possible particle agglomeration.
2. Nano-modified mixes exhibited considerable enhancement in compressive strength compared to conventional concrete. The improvement is attributed to the nano-filler effect and accelerated pozzolanic reaction, which promote additional C–S–H gel formation and refine pore structure.
3. Wheel load fatigue testing confirmed a substantial increase in load cycle capacity for nano-modified slabs. The fatigue life improvement indicates better crack resistance and delayed crack propagation under repeated traffic loading.
4. Falling Weight Deflectometer (FWD) results showed reduced deflections and increased slab modulus in nano-modified concrete, confirming improved load distribution and structural rigidity.
5. Load Transfer Efficiency (LTE) values were significantly higher in nano-modified mixes, demonstrating better stress transfer across joints and reduced potential for joint distress.
6. Abrasion resistance improved noticeably with nano incorporation, reducing surface wear and enhancing long-term serviceability of pavements.
7. Nano-silica enhanced fracture toughness and energy absorption capacity, leading to higher impact resistance and improved resilience against dynamic loads.
8. The combination of nano-silica and fly ash demonstrated promising long-term performance, indicating that nano-materials can complement supplementary cementitious materials effectively.

ACKNOWLEDGEMENTS

The authors are thankful to the ABR College of engineering and Technology for infrastructure, lab facilities, and constant support for this Research work.

Declarations

The authors declared that there is no conflict-of-interest statement to publish this paper.

Conflicts Of Interest

The authors declare that there is no conflict of interest.

REFERENCES

[1] V. M. Malhotra and P. K. Mehta, *High-Performance, High-Volume Fly Ash Concrete*. Ottawa, Canada: Supplementary Cementing Materials for Sustainable Development, 2002.

[2] Neville, "Properties of Concrete Incorporating Fly Ash, Slag, and Silica Fume," *ACI Materials Journal*, vol. 99, no. 5, pp. 535–542, Sep.–Oct. 2002.

[3] S. Mindess, J. F. Young, and D. Darwin, *Concrete*, 2nd ed. Upper Saddle River, NJ, USA: Prentice Hall, 2003.

[4] S. H. Kosmatka, B. Kerkhoff, and W. C. Panarese, *Design and Control of Concrete Mixtures*, 14th ed. Skokie, IL, USA: Portland Cement Association, 2002.

[5] Ghosh and G. Ransinchung, "Performance evaluation of fly ash and red mud geopolymers for pavement applications," *International Journal of Pavement Research and Technology*, vol. 17, pp. 680–692, 2024.

[6] J. Migunthanna, P. Rajeev, and J. Sanjayan, "Waste clay brick as a binder for pavement grade geopolymer concrete," *International Journal of Pavement Research and Technology*, vol. 17, pp. 1450–1467, 2024.

[7] K. H. Khayat *et al.*, "High-volume recycled materials for sustainable pavement construction," *Transportation Research Record*, vol. 2608, pp. 1–12, 2017.

[8] Sahu *et al.*, "Thermal and mechanical performance of geopolymer concrete with recycled aggregate and copper slag," *Scientific Reports*, vol. 15, Art. no. 28968, 2025.

[9] J. T. Smith and S. L. Tighe, "Environmentally sustainable concrete pavements using recycled concrete aggregate," in *Proc. International Conference on Concrete Pavements*, 2025.

[10] M. Thomas and P. R. Daniels, "Nano-silica modification in cementitious composites: Mechanical and durability effects," *Construction and Building Materials*, vol. 278, Art. no. 122347, 2021.

[11] K. Singh and S. Kumar, "Effects of nano-silica on flexural fatigue behavior of concrete," *Journal of Materials in Civil Engineering*, vol. 32, no. 8, Art. no. 04020120, 2020.

[12] H. Li, X. Zhao, and J. Wu, "Nano-particle effects on microstructure and fatigue resistance of cement concrete," *Cement and Concrete Composites*, vol. 112, pp. 103–118, 2020.

[13] R. Siddique, "Utilization of silica fume in concrete: A review," *Journal of Advanced Concrete Technology*, vol. 1, no. 3, pp. 241–254, 2013.

[14] S. Thomas and R. Patel, "Life-cycle assessment of pavement concrete with supplementary cementitious materials," *Journal of Cleaner Production*, vol. 256, Art. no. 120467, 2020.

[15] N. M. Neithalath, "Performance characteristics of ultra-high-performance concrete for pavement applications: An overview," *Journal of Materials in Civil Engineering*, vol. 28, no. 4, 2016.

[16] Bureau of Indian Standards, *IS 456:2000 – Plain and Reinforced Concrete – Code of Practice*. New Delhi, India: BIS, 2000.

[17] Bureau of Indian Standards, *IS 10262:2019 – Concrete Mix Proportioning – Guidelines*. New Delhi, India: BIS, 2019.

[18] Bureau of Indian Standards, *IS 1199:1959 – Methods of Sampling and Analysis of Concrete*. New Delhi, India: BIS, 1959.

[19] Bureau of Indian Standards, *IS 516:1959 – Methods of Tests for Strength of Concrete*. New Delhi, India: BIS, 1959.

[20] Bureau of Indian Standards, *IS 9103:1999 – Specification for Concrete Admixtures*. New Delhi, India: BIS, 1999.

[21] Bureau of Indian Standards, *IS 383:2016 – Specification for Coarse and Fine Aggregates*. New Delhi, India: BIS, 2016.

[22] Bureau of Indian Standards, *IS 2386 (Parts I–VIII):1963 – Methods of Test for Aggregates for Concrete*. New Delhi, India: BIS, 1963.

[23] Bureau of Indian Standards, *IS 8112:2013 – Specification for 43 Grade Ordinary Portland Cement*. New Delhi, India: BIS, 2013.

[24] Indian Roads Congress, *IRC:44-2017 – Code of Practice for Concrete Mix Design*. New Delhi, India: IRC, 2017.

[25] Indian Roads Congress, *IRC:58-2015 – Guidelines for the Design of Plain Jointed Rigid Pavements for Highways*. New Delhi, India: IRC, 2015.