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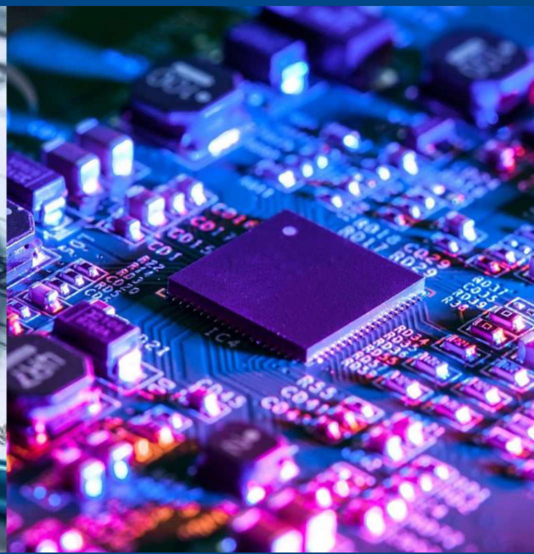

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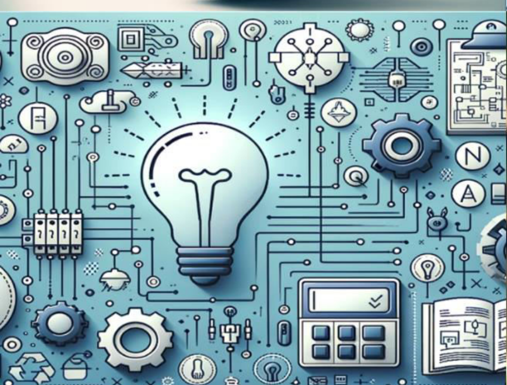

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Influence of Nano Silica and Flyash on High Volume Blended Concrete

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ABSTRACT: This project investigates the influence of nano silica and fly ash on the mechanical and durability properties of high-volume blended concrete by partially replacing cement with these materials. Three concrete samples were prepared: Sample 1 with 5% nano silica, Sample 2 with 10% nano silica, and Sample 3 with a combination of 10% nano silica and 15% fly ash. To evaluate the performance, tests such as split tensile strength, flexural strength, acid attack resistance, and water absorption were conducted. The results showed that increasing nano silica content improved both tensile and flexural strengths, with Sample 2 performing better than Sample 1. Sample 3, which included both nano silica and fly ash, demonstrated enhanced durability, particularly in acid resistance and lower water absorption, due to the synergistic effect of pozzolanic reaction and densification of the concrete matrix. Overall, the combination of nano silica and fly ash proved effective in producing sustainable, high-performance concrete suitable for modern construction needs.

I. INTRODUCTION

Concrete is the most widely used construction material, but the production of cement, its key ingredient, contributes significantly to environmental pollution due to high energy consumption and CO_2 emissions. To address these concerns and enhance concrete performance, this project investigates the influence of nano silica and fly ash as partial cement replacements in high-volume blended concrete. Nano silica, known for its fine particle size and high pozzolanic reactivity, improves the microstructure and early strength of concrete, while fly ash, an industrial by-product, contributes to long-term strength and sustainability. In this study, three concrete samples were prepared: Sample 1 with 5% nano silica, Sample 2 with 10% nano silica, and Sample 3 with a combination of 10% nano silica and 15% fly ash by weight of cement. The mechanical and durability performance of these mixes was evaluated using split tensile strength, flexural strength, acid attack resistance, and water absorption tests. The objective is to assess how these materials influence the strength and durability characteristics of blended concrete and to promote the use of sustainable alternatives in modern construction practices.

II. LITERATURE REVIEW

According to Zeyad Najeeb et al. (2023) the cement industry contributes around 7% of global CO_2 emissions, prompting the need for sustainable alternatives in construction. Recent studies have explored the use of Supplementary Cementitious Materials (SCMs) such as fly ash, nano silica (NS), and cenospheres (CS) to reduce cement consumption and enhance concrete performance. Cenospheres, lightweight hollow spheres rich in silica and alumina, offer benefits like reduced density, improved workability, and thermal insulation, while nano silica, due to its ultra-fine particle size and high pozzolanic activity, enhances strength and microstructure. Research shows that incorporating 1–2% NS improves compressive and flexural strength by up to 13% and 26% respectively, while 10% CS enhances flexural strength and provides better resistance to acid and high temperatures, despite a slight reduction in compressive strength. The optimal combination of 10% CS and 1% NS resulted in improved mechanical properties, lower water absorption, reduced drying shrinkage, and a denser microstructure, making it a promising solution for producing sustainable, high-performance cement mortar.

Mahdi Mahdikhani et al. (2018) states that Concrete structures are highly vulnerable to acid rain, which deteriorates their mechanical strength and durability, leading to cracking, weight loss, and eventual failure. As acid rain is an unavoidable environmental issue, recent research has explored advanced materials like nano silica to enhance concrete's resistance to acidic conditions. Nano silica, due to its ultra-fine particle size and high pozzolanic activity, improves the microstructure, reduces porosity, and enhances bonding within the cement matrix. Studies involving concrete mixtures with up to 6% nano silica replacement showed significant improvements in compressive strength, electrical resistance, water absorption, and weight retention under acid rain exposure with varying pH levels. The inclusion of nano silica not only increased the mechanical performance but also improved durability, particularly at lower pH levels where acid attack is more aggressive. The research confirms that nano silica is effective in mitigating acid rain damage by strengthening the cementitious matrix and reducing permeability, making it a promising additive for producing durable, acid-resistant concrete.

A study by V. Sairam et al. (2020) examined the durability of Composite Fiber Reinforced High-Performance Concrete (CFRHPC) incorporating ultra-fine fly ash (UFFA) and nanosilica as partial cement replacements. In this research, 15% of the cement was replaced with UFFA, and nanosilica was added in varying proportions of 0%, 1.5%, 3.0%, and 4.5%, along with the inclusion of steel (1%) and polypropylene (0.25%) fibers by volume. Durability was assessed through tests such as sorptivity, rapid chloride permeability (RCPT), and exposure to aggressive environments including HCl, H_2SO_4, and $MgSO_4$. The results showed a significant reduction in chloride ion permeability, with improvements ranging from 53.83% to 71.45% at 28 days and 55.88% to 74.27% at 56 days. The mixture with 15% UFFA and 3% nanosilica offered the best performance in terms of resistance to chloride and sulfate attacks, while the fibers contributed to improved durability by enhancing crack resistance and reducing permeability. Overall, the study concluded that combining UFFA, nanosilica, and fibers refines the concrete's microstructure by reducing porosity and permeability, thus extending its service life and offering valuable insights for future concrete mix design in aggressive environments.

R. Abdulwahab et al. (2021) examined the limitations of relying heavily on Ordinary Portland Cement (OPC), particularly in countries like Nigeria, where both the cost and environmental toll of cement production are major concerns. Since OPC manufacturing is a major source of CO_2 emissions and ecological damage, the study emphasized the importance of adopting Supplementary Cementitious Materials (SCMs) such as fly ash, silica fume, rice husk ash, and metakaolin as partial substitutes for cement. These materials not only help reduce construction expenses and environmental impact but also contribute to improved concrete performance in terms of strength and durability. The study also explored the application of nanomaterials in concrete, noting their ability to enhance mechanical properties by refining the microstructure, accelerating hydration, and increasing strength due to their fine particle size and high surface area. Although nanomaterials offer advantages in sustainability and performance, challenges such as uniform dispersion in the mix and potential issues with brittleness still need to be addressed. Overall, the integration of SCMs and nanotechnology presents a promising path toward more efficient and environmentally responsible concrete production.

Yunchao Tang et al. (2022) research presents a comprehensive study on enhancing the performance of recycled aggregate concrete (RAC) using a combination of nano-silica (NS) and fly ash (FA), forming what the authors call NFRAC. The study addresses the inherent weaknesses of RAC, particularly reduced mechanical strength and poor interfacial transition zones (ITZ), by incorporating these supplementary cementitious materials (SCMs). Through an orthogonal experimental design varying RCA replacement rates (0%, 50%, 100%), NS (0–3%), and FA (0–20%) contents, the study evaluates workability, strength, and microstructural improvements across different curing ages (3, 7, 28 days). Findings reveal that NS improves early-age strength and densifies the ITZ due to its high pozzolanic reactivity, while FA enhances workability and long-term durability through particle packing and slow pozzolanic action. The optimal mix was identified as 10% FA with 2–3% NS. Additionally, a constitutive stress–strain model was developed based on Guo's equation, integrating NS and FA content to predict mechanical behavior. Scanning electron microscopy (SEM) confirmed microstructural densification with reduced microcracks and enhanced bonding in ITZs. Overall, the research offers valuable insights into sustainable concrete design by improving RAC properties through SCM synergy, though further studies on long-term durability and field applications are suggested.

Musa Adamu et al. (2018) explores the development of an environmentally sustainable roller-compacted concrete (RCC) by integrating high-volume fly ash (HVFA), crumb rubber, and nano-silica. HVFA serves as a partial cement replacement, reducing CO_2 emissions associated with cement production. Crumb rubber, derived from waste tires, partially replaces fine aggregates, enhancing toughness and energy absorption but potentially compromising mechanical properties due to increased porosity. Nano-silica is incorporated to mitigate these adverse effects by refining the pore structure and densifying the interfacial transition zone between the cement matrix and aggregates. Using Response Surface Methodology (RSM), the study identifies an optimized mix: 53.72% cement replaced with fly ash, 10% fine aggregate replaced with crumb rubber, and 1.22% nano-silica by weight of cementitious materials. Experimental results indicate that while HVFA RCC exhibits lower early-age strengths compared to conventional RCC, the inclusion of nano-silica enhances early strength development by accelerating the pozzolanic reaction of fly ash. Additionally, the optimized mix demonstrates improved impact resistance and skid resistance, making it suitable for pavement applications. Overall, the synergistic use of HVFA, crumb rubber, and nano-silica in RCC presents a viable approach to producing sustainable and durable concrete pavements.

Osama Zaid et al. (2023) investigated how nano-silica (NS) influences the strength, durability, and internal structure of concrete. Their study found that due to the high surface area of nano-materials, concrete mixes incorporating NS often require more water or chemical admixtures to maintain proper workability. The effectiveness of NS is closely linked to characteristics like its surface area, particle size, the water-to-cement ratio, and the quantity used. An optimal NS content of 3–4% was identified as most beneficial for improving both the mechanical properties and durability of concrete, primarily because of its ability to fill voids, refine pore structure, and engage in pozzolanic reactions. However, using more than 4% may negatively impact strength. NS also accelerates cement hydration, particularly in the early stages, thereby increasing early compressive strength; this advantage diminishes at higher dosages. Furthermore, NS contributes to a denser microstructure by minimizing detrimental pores and reducing permeability. It enhances the strength and structure of the calcium-silicate-hydrate (C-S-H) gel and improves the bond between aggregates and the cement matrix, leading to better long-term durability. The combined use of NS with supplementary pozzolanic materials results in improved mechanical performance, refined pore structure, and more effective hydration. Overall, NS plays a key role in enhancing concrete performance by improving hydration processes, refining pores, and strengthening the interfacial zones.

According to Ruijun Wang et al. (2022), the characteristics of high-volume fly ash concrete (HVFAC)—where more than 40% of Portland cement is replaced with fly ash—are thoroughly analyzed. Drawing insights from around 180 studies, the paper explores HVFAC's microstructural behavior, fresh properties, mechanical performance, and durability, comparing it with low-volume fly ash concrete (LVFAC) and traditional 100% Portland cement concrete. While HVFAC tends to exhibit reduced mechanical strength at early ages, it gains superior strength over time. It also offers better workability, lower drying shrinkage, and increased resistance to both sulfate attacks and chloride ingress. The review outlines three main strategies to enhance early strength development: accelerating the pozzolanic activity of fly ash, incorporating additives with high pozzolanic reactivity, and applying alkali activation techniques. Additionally, the study highlights HVFAC's potential to lower carbon emissions and reduce construction costs, contributing to its sustainability benefits. However, the review emphasizes the need for more research on its long-term durability under various environmental conditions. It recommends that future work focus on improving HVFAC's resilience and promoting its practical implementation in the construction industry for more sustainable concrete solutions.

Abdulkadir Çevik et al. (2018) study explores the role of nano-silica in enhancing the short-term durability and mechanical properties of low-calcium fly ash-based geopolymer concrete (GPC) when exposed to aggressive chemical environments. Four types of GPC were developed using two classes of low-calcium fly ash (FAI and FAII), with and without nano-silica, alongside a reference mix of ordinary Portland cement (OPC) concrete. The alkaline activator used for geopolymerization was a blend of sodium silicate and sodium hydroxide in a 2.5:1 ratio. The concrete specimens were exposed to 5% sulfuric acid, 5% magnesium sulfate, and 3.5% seawater to assess their resistance through surface observations, weight changes, and mechanical strength testing. Results indicated that GPC mixtures, particularly those incorporating FAII and nano-silica, exhibited greater resistance to chemical attack and maintained higher strength levels compared to OPC concrete. Nano-silica significantly improved the microstructure by refining pores and increasing matrix density, which enhanced the concrete's resistance to deterioration. Sulfuric acid was the most damaging chemical, yet the GPC mixes, due to their lower calcium content, were more resilient than OPC. The findings suggest that nano-silica-enriched fly ash-based GPC offers a promising, eco-friendly alternative to OPC concrete, especially in environments with severe chemical exposure, while also highlighting the need for further research to support its wider structural application.

Junliang Zhao et al. (2023) Stated that the combined influence of nano-silica (NS) and steel fibers (SF) on the strength and durability of high-volume fly ash (HVFA) cement mortar, where fly ash replaces half of the Portland cement to promote sustainability by reducing CO_2 emissions. While high fly ash content typically lowers early strength and toughness, adding NS and SF significantly improves performance. The incorporation of 1.0 vol% steel fibers and 2.0 wt% nano-silica increased the 28-day flexural and compressive strengths by over 70% and 50%, respectively, and reduced water absorption substantially. Steel fibers enhance crack resistance by bridging microcracks, while nano-silica boosts the pozzolanic reaction and refines the pore structure, contributing to improved durability. The mortar also showed better resistance to sulfate attack, with lower mass loss and higher residual strength after prolonged exposure. Microstructural analyses confirmed that these additives effectively densify the mortar matrix, leading to improved mechanical properties and sulfate resistance. This combined use of NS and SF presents a promising approach to producing eco-friendly cementitious materials with enhanced early strength, toughness, and long-term durability.

Mavoori Hitesh Kumar et al. (2022) highlights the effectiveness of incorporating a triple blend of fly ash (FA), silica fume (SF), and steel fibers in enhancing the mechanical and workability properties of concrete. Various mix combinations using FA (0%, 15%, 30%), SF (0%, 6%, 12%, 18%), and steel fibers (0%, 0.5%, 1%) were evaluated, with results showing that the optimal mix of 15% FA, 12% SF, and 1% steel fibers led to notable improvements in compressive strength (5.89%), flexural strength (20.4%), and split tensile strength (28.02%) compared to control specimens. The study found that incorporating these materials not only improved strength but also positively influenced porosity, workability, and durability. A detailed literature review supports these findings, referencing prior research on the impact of industrial by-products and fibers in concrete, including the use of recycled aggregates, metakaolin, waste glass powder, and natural fibers. Although none of the experimental mixes achieved the target mean strength, those containing FA, SF, and steel fibers consistently outperformed the conventional mix, proving beneficial for structural applications. Overall, the work confirms that the combined use of FA, SF, and steel fibers can significantly enhance the performance of concrete, making it a viable option for sustainable and high-strength construction.

Mohammed Abd El-Salam Arab et al. (2025) Study investigates the enhancement of high-strength geopolymer concrete (GPC) through the integration of nano-silica fume (NSF) and nano-alumina (NA), with a focus on their impact on mechanical performance and durability. Motivated by the environmental concerns of cement production, geopolymer concrete presents a sustainable alternative due to its low carbon footprint and use of industrial by-products like fly ash. The study compares the effects of NSF and NA, both in physically mixed and calcinated forms (at 600°C, 800°C, and 1000°C), on concrete properties. Experimental results show that incorporating these nanomaterials leads to significant improvements in compressive, tensile, and flexural strength. Notably, calcination at 800°C provided optimal performance enhancements. In terms of durability, the refined microstructure achieved with nanomaterial additives, particularly NSF, led to lower water sorptivity and better acid resistance. Nano-silica accelerated hydration and matrix densification due to its high surface area and pozzolanic activity, while nano-alumina enhanced early strength gain and sulfate resistance. The combined use of both materials showed synergistic effects, contributing to a durable and high-performance concrete matrix. This review underscores the potential of NSF and NA in producing eco-efficient, high-strength geopolymer concretes suitable for sustainable infrastructure applications.

Grzegorz Ludwik Golewski (2024) study explores the combined effects of nano-silica (NS) and fly ash (FA) on the mechanical and fracture properties of concrete, focusing on ordinary concrete mixes modified with 5% NS and varying FA contents (0%, 15%, and 25%). Results from fracture tests using three-point bending and digital image correlation indicate that the addition of NS and FA significantly enhances compressive and tensile strength, along with fracture toughness, as measured by critical stress intensity factor and crack tip opening displacement. NS alone leads to straight, wider cracks, while the inclusion of FA results in more complex crack paths with branching and microcracking, reflecting improved energy dissipation and resistance to fracture. The study highlights the environmental and technical benefits of partially replacing ordinary Portland cement with FA and NS, noting improvements in strength, durability, pore structure, and early-age performance. While FA alone may delay strength gain at early stages, the reactive nature of NS helps offset this limitation. The research fills a gap by focusing on fracture behavior in conventional concretes, showing that NS and FA together can produce durable, crack-resistant materials suitable for structures subjected to dynamic and fatigue loading.

Ghasan Fahim Huseien et al. (2024) study evaluates the development of sustainable and durable cement mortars by incorporating high volumes of fly ash (FA) and bottle glass waste nanoparticles (BGWNPs) as partial replacements for ordinary Portland cement (OPC). Aiming to reduce the environmental footprint of cement production, the researchers

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replaced 60% of OPC with FA and added BGWNPs in varying proportions (2–10%) to improve the mechanical and durability characteristics of the mortar. The inclusion of up to 6% BGWNPs significantly enhanced bond strength, reduced drying shrinkage, and increased resistance to acid attack and abrasion. These improvements are attributed to the pozzolanic activity and filler effect of the nanoparticles, which densify the microstructure and accelerate hydration. Additionally, the use of these industrial waste materials led to notable reductions in carbon dioxide emissions, energy use, and overall material costs, supporting environmental sustainability. The findings suggest that using FA and BGWNPs together offers a practical solution for producing eco-friendly, high-performance repair mortars, while also addressing challenges associated with glass waste disposal and the high carbon footprint of conventional cement.

Mayank Nigam et al. (2023) study highlights that nanotechnology has emerged as a promising approach in enhancing concrete properties through the incorporation of nano-materials, particularly nano-silica, due to its extremely fine particle size which improves packing density and reduces permeability. This study investigates the influence of nano-silica, incorporated in varying proportions from 0.0% to 3.0% at 0.5% intervals, on the fresh and mechanical properties of conventional concrete. The results indicate that while the addition of nano-silica significantly improves compressive, flexural, and splitting tensile strengths due to increased packing density and pozzolanic activity, it concurrently reduces workability, as shown by decreased slump and compaction factors. The setting time also shortens with increased nano-silica content. A strong correlation ($R^2 = 0.82$) was established between compressive and flexural strength, allowing for predictive modeling. These findings support the potential of nano-silica as a viable additive for improving the performance of cementitious materials, especially in high-performance concrete applications.

Pushpalatha R.Gadag et al. (2022) study investigates the combined effects of ultra-fine fly ash (UFA) and nanosilica on the mechanical properties of High-Performance Concrete (HPC). Cement was partially replaced with UFA at 0%, 10%, 20%, and 30%, and nanosilica was added at 0%, 1.5%, 3.0%, and 4.5% by weight of binder. Concrete mixes were designed using varying water-to-binder (W/B) ratios ranging from 0.30 to 0.425. Experimental evaluations included compressive strength (7, 28, and 90 days), and split tensile and flexural strength (7 and 28 days). The optimal mix containing 10% UFA, 3.0% nanosilica, and 0.30 W/B ratio yielded significant strength improvements, with compressive strength increases of 28.24%, 28.11%, and 31.89% at 7, 28, and 90 days, respectively. Enhancements in tensile and flexural strength were also observed. Nanosilica contributed to improved microstructure by refining the interfacial transition zone and accelerating cement hydration. Regression models were developed to correlate compressive strength with both tensile and flexural strength. The study concludes that small dosages of nanosilica and limited UFA replacement can significantly enhance the mechanical performance of HPC, particularly at lower W/B ratios, providing a cost-effective and sustainable alternative to conventional high cement content mixes.

Chamila Gunasekara et al. (2020) study explores the use of high-volume fly ash (HVFA) concrete with 65% and 80% cement replacement levels, incorporating fly ash, hydrated lime, and nano-silica to improve sustainability and performance. The addition of 3% nano-silica significantly enhanced early-age compressive strength due to its role in accelerating hydration and promoting the formation of C-S-H gel. The HVFA–65 and HVFA–80 mixes showed notable strength improvements at 28 days, especially with nano-silica, achieving 47.1 MPa and 40.1 MPa respectively. Environmentally, these mixes demonstrated a reduction in carbon emissions by 51–60%, along with slight improvements in acidification and photochemical impacts. Economically, a life cycle cost assessment indicated up to 10% cost savings compared to traditional Portland cement concrete. The findings emphasize that combining nano-silica with fly ash and hydrated lime not only addresses the early-age strength limitations of HVFA concrete but also provides clear environmental and economic benefits, supporting its potential as a sustainable construction material.

III. METHODOLOGY

1. Materials Used

- Cement: Ordinary Portland Cement (OPC) 53 grade was used in accordance with IS: 12269-1987.
- Nano-Silica: Commercially available nano-silica with an average particle size <100 nm was used to enhance microstructure and reactivity.
- Fly Ash: Class F fly ash obtained from a thermal power plant, confirming to IS: 3812 (Part 1) – 2003.
- Fine Aggregate: Locally sourced river sand conforming to Zone II grading as per IS: 383-2016.
- Coarse Aggregate: Angular crushed granite stones with a nominal maximum size of 20 mm.
- Water: Clean potable water free from impurities was used for both mixing and curing.

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2. Mix Proportioning
Concrete was proportioned for M20 grade as per IS: 10262–2019. A constant water–binder ratio of 0.50 was maintained for all mixes.

Four concrete mixes were prepared:
- Mix 1 (CM): Control Mix with 100% cement
- Mix 2 (NS5): 5% Nano-silica + 95% Cement
- Mix 3 (NS10): 10% Nano-silica + 90% Cement
- Mix 4 (NS10FA15): 10% Nano-silica + 15% Fly ash + 75% Cement

Superplasticizer (if required) was used to maintain workability across all mixes.

3. Specimen Casting and Curing
Concrete was mixed using a mechanical mixer and poured into standard moulds:

- Split Tensile Strength: Cylinders (150 mm diameter × 300 mm height)
- Flexural Strength: Beams (100 × 100 × 500 mm)
- Water Absorption & Acid Attack: Cubes (150 mm × 150 mm × 150 mm)

Specimens were demoulded after 24 hours and cured in water at 27 ± 2°C for 7, 28, and 56 days based on test requirements.

4. Testing Procedures
4.1 Split Tensile Strength
Performed as per IS: 5816-1999. Cylinders were placed horizontally in the testing machine, and load was applied diametrically until failure. The maximum load was used to calculate split tensile strength.

4.2 Flexural Strength
Tested according to IS: 516-1959 using a two-point loading method. The maximum load at failure was recorded and used to calculate the modulus of rupture.

4.3 Water Absorption Test
Conducted in line with ASTM C642:
1. Specimens were oven-dried at 105°C until constant weight (W1) was obtained.
2. Specimens were submerged in water for 24 hours and reweighed (W2).
3. Water Absorption (%) = [(W2 − W1) / W1] × 100

4.4 Acid Attack Test
After 28 days of curing, specimens were immersed in a 5% sulfuric acid (H_2SO_4) solution for 28 days. After immersion:
- Surface deterioration and color changes were visually observed.
- Weight before (Wb) and after (Wa) exposure was recorded.
- Weight Loss (%) = [(Wb − Wa) / Wb] × 100
- Compressive strength was also tested to assess deterioration.

IV. RESULTS

Test	**Days**	**CM(100% Cement)**	**NS5(5% Nano-Silica)**	**NS10(10% Nano-Silica)**	**NS10FA15(10% NS + 15% FA)**
Split Tensile Strength (MPa)	7	2.1	2.5	2.8	2.6
	28	2.9	3.4	3.7	3.5
	90	3.2	3.8	4.1	4.0
Flexural Strength (MPa)	7	2.7	3.0	3.3	3.1

Test	Days	CM(100% Cement)	NS5(5% Nano-Silica)	NS10(10% Nano-Silica)	NS10FA15(10% NS + 15% FA)
	28	3.5	4.0	4.3	4.1
	90	3.8	4.4	4.7	4.5
Water Absorption (%)	28	5.2	4.6	4.2	4.0
	90	5.0	4.3	3.9	3.7
Acid Attack: Weight Loss (%)	56	7.5	6.0	5.2	5.0
Acid Attack: Compressive Strength Loss (%)	56	12.0	9.0	7.5	7.2

The inclusion of nano-silica (NS) and fly ash (FA) in cement mixtures significantly enhances the mechanical properties and durability of the concrete compared to the conventional 100% cement mix (CM). Improvements were observed in split tensile and flexural strengths over 7, 28, and 90 days, with the 10% nano-silica mix (NS10) consistently outperforming other variations. Water absorption rates decreased notably with the addition of NS and FA, indicating reduced porosity and better resistance to moisture ingress. Furthermore, samples containing NS and FA exhibited lower weight and compressive strength losses when exposed to acidic environments, demonstrating enhanced chemical resistance. Among the different combinations, the mix with 10% nano-silica and 15% fly ash (NS10FA15) also showed substantial improvements, closely following the performance of NS10. These results highlight the potential of nano-silica and fly ash as effective partial cement replacements in producing more durable and higher-strength concrete.

V. CONCLUSION

This literature review underscores a critical shift in concrete technology, driven by the need for more sustainable construction practices and enhanced material performance. The extensive body of research confirms that Supplementary Cementitious Materials (SCMs) like fly ash and nanomaterials, particularly nano-silica, are highly effective in partially replacing Ordinary Portland Cement (OPC). Fly ash contributes to long-term strength and workability, while nano-silica dramatically improves early-age strength, refines the microstructure, and densifies the concrete matrix due to its high reactivity and fine particle size. The synergistic combination of these materials not only bolsters mechanical properties such as compressive, tensile, and flexural strengths but also significantly enhances durability, providing superior resistance to acid attack, reduced water absorption, and improved chloride penetration. While further optimization of mix designs and long-term performance assessments are ongoing, the evidence consistently supports the use of high-volume fly ash and nano-silica blended concrete as a viable, eco-friendly, and high-performance alternative for modern construction needs.

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