Strength and Durability of High Strength Concrete Using Nano-Silica

Anushka Bharti
** M.Tech. Scholar, School of Civil Engineering, Faculty of Engineering and Technology
Madhyanchal Professional University, Bhopal, M.P**

Mr. Shivanshu Patel
** Assistant Professor, School of Civil Engineering, Faculty of Engineering and Technology
Madhyanchal Professional University, Bhopal, M.P**

How to Cite this Article:

Bharti, A. (2026). Strength and Durability of High Strength Concrete Using Nano-Silica. International Journal of Creative and Open Research in Engineering and Management, <i>02</i>(7), 1-9. https://doi.org/10.55041/ijcope.v2i7.188

https://doi.org/10.55041/ijcope.v2i7.188

ABSTRACT

High Strength Concrete (HSC) has become an essential material in contemporary architecture due to its ability to deliver excellent strength, durability, workability, and resistance to heavy loads and aggressive environmental conditions. HSC offers higher structural efficiency, longer service life, and many other advantages compared to conventional concrete, making it an eminent material option for high-rise buildings, bridges, industrial facilities, etc. This paper deals with the effect of using nano-silica as a partial replacement for cement on the mechanical properties and durability of high-strength concrete.

Nano-silica is an ultrafine, high-surface-area pozzolanic material that promotes the hydration of cement. It combines with calcium hydroxide produced during cement hydration to create more calcium silicate hydrate (C-S-H) gel, the main compound that gives concrete its strength. It enhances the pore structure, reduces micro-cracks, and produces a denser, stronger concrete matrix. This study investigated the effect of nano-silica as a partial replacement of cement at 0%, 1%, 2%, 3%, 4% ands5% by weight of cement to find its optimum dosage.

An extensive experimental program was conducted to evaluate the behaviour of the developed mixes. Manipulating fresh concrete properties, slump and flow tests were performed to characterise workability. Mechanical properties were evaluated in hardened concrete to obtain compressive strength, split tensile strength, flexural strength and modulus of elasticity. Specimens were subjected to long-term performance tests: water absorption, rapid chloride penetration, sulphate resistance, carbonation resistance and alkali-silica reaction. Moreover, SEM and XRD tests were conducted to study the microstructure and determine the type of hydration products in light of the use of nano-silica.

Experimental results indicated that the incorporation of nano-silica significantly enhances both strength and durability properties of high-strength concrete. From these mixtures, however, the concrete with 2% of nano-silica provided the most overall performance ultimately. The 28-day compressive strength obtained at this optimal replacement level was around 82.4 MPa, which is nearly about 28% higher than the mix control. Splitting tensile strength and flexural strength were similarly improved by about 28%, further confirming the beneficial effects of nano-silica on the overall mechanical properties of concrete. Conversely, for mixes with more than 3% nano-silica content, the workability decreased significantly, after which strength enhancement also appeared to lag due to particle agglomeration that impeded the proper dispersion of nano-sized particles within the cement matrix.

The durability assessment showed that nano-silica improved the concrete's resistance to all vectors of deterioration mechanisms. The presence of nano-silica resulted in lower water absorption and less permeability through concrete, thus limiting the penetration of aggressive substances (chloride ions and sulphate), leading to better environmental durability. In addition, the developed concrete exhibited a good resistance to carbonation and alkali-aggregate reaction; therefore, showing its applicability in aggressive environmental conditions. The SEM and XRD analyses supported the improvements in mechanical as well as durability properties, which can be attributed to a denser microstructure with more C-S-H gel and fewer internal voids.

According to the results of this research, it can be concluded that nano-silica could appropriately be used as a supplementary cementitious material to improve high-performance concrete's properties. The optimal replacement level was determined to be equal to 2% of the weight of cement, considering a good balance between workability, strength and durability. The enhanced merits obtained at this dosage imply that nano-silica modified high-strength concrete can be effectively used in challenging engineering applications, including but not limited to high-rise buildings, bridges, marine structures, industrial constructions and other vital infrastructure projects where superior mechanical performance and long-term durability are required.

Keywords: High-Strength Concrete (HSC), Nano-Silica, Supplementary Cementitious Material, Cement Replacement, Mechanical Properties, Durability, Compressive Strength, Split Tensile Strength, Flexural Strength, Chloride Penetration, SEM, XRD; Concrete Microstructure.

Introduction

Over the last couple of decades, there has indeed been tremendous growth in the construction sector, which is driven primarily by rapid urbanisation, growth of population, development of industries and the need for modern infrastructure facilities. With the construction of high-rise buildings, highways, bridges, airports, metro rail networks and other large-scale engineering projects, the demand for construction materials with higher strength characteristics, enhanced durability performance, and longer service life is increasing. Concrete remains the most widely used among all different construction materials due to its versatility, low cost, availability of raw material and wide variety of structural applications.

Typically, Conventional concrete based on Ordinary Portland Cement (OPC) has a compressive strength in the range of 20 MPa to 40 MPa. While this strength level is sufficient for many residential and commercial buildings, it may not meet the performance requirements of newly constructed infrastructure subject to heavy loads and crushing environmental conditions. Skyscrapers, long-span bridges, offshore platforms, and industrial facilities, along with transportation networks, demand concrete of higher mechanical strength and improved durability. Hence, High-Strength Concrete (HSC) has evolved to an indispensable material in modern structural engineering.

High-Strength Concrete is defined as concrete whose compressive strength is higher than 55 MPa (as per American Concrete Institute (ACI 363R)). The continued development of HSC has changed the face of modern-day construction practices as engineers can now design structural members that are smaller and more efficient without compromising on their load-bearing capacity, continuously increasing the compressive strength. Smaller member sizes decrease the self-weight of structures and also increase space efficiency and material savings. High Strength Concrete has been successfully applied to various international projects, including the Burj Khalifa in Dubai, the Petronas Twin Towers (Malaysia) and Shanghai Tower (China). Similarly, many mega infrastructure projects in India, like metro rail lines, cable-stayed bridges, elevated highways and flyovers have been done better using HSC.

High-Strength Concrete typically has a high-strength, typically low water-to-binder ratio, plasticity agent, and Supplementary Cementitious Materials (SCMs) such as Fly Ash, Silica Fume, Metakaolin and Ground Granulated Blast Furnace Slag (GGBS). These materials promote hydration, improve the compactness of the concrete, and thus strengthen it. Silica fume is one of the most popular types among them due to its extremely low scale and large pozzolanic activity. But on the other hand, silica fume can not remove such ultra-fine pores and microessences present in the cement matrix.

The application of nanotechnology has opened up new possibilities for improving the performance properties of cement-based materials. Nanotechnology is concerned with the manipulation of matter on an atomic and molecular scale, incorporating structures sized from 1 to 100 nanometres (nm) (one billionth of a metre, 10^{-9} m). The very small size and high surface area of nanomaterials lead to unique physical and chemical properties, which may improve most concrete material properties.

Out of all the types of nanomaterials evaluated for cementitious composites, nano-silica has proven to be one of the most effective. Nano-silica particles are finer than silica fume, with a specific surface area that is extremely large. Such properties enable nano-silica to rapidly react with the portlandite released from cement hydration and generate more C-S-H gel. In addition, since C–S–H gel is mostly building blocks between crystals in concrete that contribute to the strength as well as durability expansion, the additional formation of it can improve the structural mechanical properties of concrete.

Apart from its pozzolanic activity, nano-silica functions as an ultra-fine filler in the cement matrix. This fine powder can penetrate and occupy incidental pores, capillary voids, and micro-cracks in the cement paste itself, as well as in the Interfacial Transition Zone (ITZ) between aggregates. Noreen: This fills in action creates a tighter and more homogenous microstructure, preventing the permeation of harmful materials that can include chlorides, sulphates and carbon dioxide. This leads to much greater resistance of concrete against durability, and also reduced corrosion of steel reinforcement and other forms of deterioration.

The chemical activity, together with its capacity to fill pores, makes nano-silica improve some key features of High-Strength Concrete. The compressive strength, split tensile strength, flexural strength and modulus of elasticity values of nano-silica-based concrete are generally higher than those of conventional concrete. In addition, it has a better microstructure that resists water absorption, chloride permeability, sulphate attack, carbonation, abrasion and other external factors that negatively affect the durability of concrete structures over time.

Despite many studies succeeding in utilising nano-silica when added to concrete, the different conditions under which various research has been made and also the variations in raw materials used, mix ratio & replacement level with curing methods, testing methods adopted by several researchers account for a large variation across published results. Furthermore, some earlier studies Zhao et al. Thus, it needs a meticulous experimental study to investigate the impacts of its differing levels of replacement on both the strength and durability behaviour of High-Strength Concrete.

The current study has been conducted to fill this void by systematically studying the effect of High-Strength Concrete (HSC) with different %weights as an ultra-fine particles in place of Cement. The research assesses the properties of fresh concrete, mechanical properties and durability performance to establish the ideal dosage of nano-silica that obtains an optimal balance between strength, workability, and long-term durability. The results of this study should aid the production of sustainable concrete with improved performance characteristics needed for modern infrastructure, especially when produced in Indian climatic conditions.

Literature Review

Azhar G. Hamad (2024) reviewed the recent advances in the consumption of nano-silica as a supplementary material in concrete engineering. The review discussed that, due to its ultra-fine particle size and high pozzolanic reactivity, the addition of nano-silica significantly improves the performance of cementitious composites. It reacts quickly (in a couple of days) with the calcium hydroxide produced in cement hydration to create more C-S-H gel, thus reinforcing the cement matrix. Simultaneously, these nano-sized particles saturate micro-porous pores and voids in the concrete to create a denser, more refined microstructure with low porosity.

The improvements in the internal structure were reported as promoting increases in strength properties (compressive, tensile and flexural), but also reducing concrete permeability by19%. Consequently, nano-silica concrete shows higher resistance against water penetration, chloride ingress, sulphate attack and carbonatation, considering all these points, so that it can be more impermeable than traditional concrete, hence providing enhanced lifespan under exposure to an aggressive environment. In addition, the review also highlighted the reliance of the successful application of nano-silica on the even distribution of nanoparticles in concrete. The high surface energy of nano-silica particles leads to agglomeration; thus, dispersion methods and the application of proper superplasticisers are needed to control the dispersion behaviour and derive benefits from the mechanical as well as durability enhancements gained by using nano-silica in concrete.

Zhang et al. (2024) investigated the effects of nano-silica on flow behaviour, hydration process and microstructural evolution of Ultra-High-Performance Concrete (UHPC). The results demonstrated that nano-silica acted as an excellent nucleation medium, offering supplementary sites for hydration product generation, thus promoting the cement hydration [182]. The pozzolanic reaction between nano-silica and calcium hydroxide provided additional calcium silicate hydrate (C-S-H) gel, which resulted in a more sturdy and dense cement matrix. With the addition of nano-silica, the compressive strength increased from ~86 to 126 MPa for UHPC. In addition, a decrease in the Ca/Si ratio was identified, which indicates an evolution to a denser microstructure with improved bonding characteristics. The next microstructural improvements thus led to better mechanical performance and durability in concrete.

Almusallam et al. (2023) An extensive review was performed to investigate the influence of nano-silica on various aspects, such as hydration behaviour, properties and durability characteristics of concrete (Alghamri et al.). The authors calculated that the optimal amount of nano-silica that will produce improvement in strength and durability would be approximately 2–4%, considering the general behaviour reported in various research studies. According to the review, nano-silica promotes hydration and leads to more calcium silicate hydrate (C-S-H) gel formation that improves the cementitious matrix. Likewise, the fine nano-silica reduces pore size and interconnectivity of voids and densifies the microstructure, producing less permeable concrete. Because of those advancements, concrete with nano-silica possesses increased strength, improved resistance to the penetration of damaging substances, and higher long-term performance. The authors also concluded that if used in the correct proportion, nano-silica is one of the most appropriate supplementary materials for high –performance concrete production.

Wang (2023) performed a literature review to assess the impact of nano-silica on self-compacting concrete (SCC). It notes that nano-silica is a promising candidate for improving the compressive strength of SCC by accelerating cement hydration and promoting additional C-S-H formation. The nano-particles also occupy microscopic pores in the cement matrix, creating a denser microstructure with lower permeability. This subsequently results in self-compacting concrete with nano-silica that has significantly improved resistance to water permeability, chloride ion penetration, sulphate attack and drying shrinkage, which enhances the durability of the concrete. But the authors observed that beyond an optimum nano-silica content, the fresh properties of SCC deteriorate. The lack of workability is due to the high specific surface area of nano-silica, which leads to an increase in water requirements and nanoparticle clustering. According to the inferences derived from the findings of different studies reviewed, they suggested 2–3% of nano-silica as the suitable dosage for maximum workability, strength and durability in the long run [66]

Vikram Singh Kashyap (2023) investigated the effect of the use of nano silica on the durability properties of concrete using 43-grade Ordinary Portland Cement (OPC). This experimental programme consisted of three substitutions (1%, 2% and 3% nano-silica with respect to cement) while keeping the water-cement ratio constant at 0.40. Results showed that the incorporation of nano-silica improved the durability performance of concreteLite, resulting mainly from microstructure improvement and lesser pore connectivity. The high pozzolanic activity of nano-silica reacted with the calcium hydroxide formed during cement hydration to create more C-S-H gel, producing a denser and less permeable cement matrix. As a result, the concrete has decreased moisture absorptivity, enhanced carbonation resistance, and increased acidic environment adaptability compared to conventional concrete. Authors also concluded that an adequate percentage of nano-silica can successfully enhance the durability and life service time of concrete structures under essential conditions.

Khan (2022) provided an overview of the investigation of the effects nano-silica has on mechanical properties, durability and microstructural development for concrete from around the globe. It was also observed that when nano-silica is utilised in concrete, the overall performance of concrete is improved due to acceleration of cement hydration and stimulation of formation of additional calcium silicate hydrate (C-S-H) gel through pozzolanic reactions. Such processes lead to pore refinement, reduced porosity and enhanced density of cement matrix, which contribute to compressive strength as well as durability. In the paper, they also emphasise proper use of nano-silica in concrete alters its resistivity to the penetration of water and aggressive chemicals, extending service life. However, the review also noted two key challenges to large-scale use of nano-silica: the challenge of achieving a uniform distribution of nanoparticles in the concrete matrix and the relatively high price of nano-silica due to its manufacturing process. The authors concluded their work by recommending more research on novel dispersion methods and reducing production costs to promote their widespread industrial application in building construction.

Mohammed et al. (2018) studied the effect of incorporating 3% nano-silica and Fly ash on the mechanical properties and durability of porous concrete (PC). It was found that nano-silica induces hydration of cement particles together with calcium hydroxide ($Ca(OH)_2$), which generates extra calcium silicate hydrate (C-S-H) gel and subsequently reinforces the compressive strength of concrete. The existing pore structure within the porous concrete (that is, a network of interconnected pores that enables permeability) would not be lost as this process does not fill the voids, which would endanger its drainage performance. Nevertheless, even though nano-silica is a filler, in freshly mixed concrete it exhibits the opposite behaviour: being composed of very fine particles with high specific surface area, its presence increases the mix water requirement and reduces the workability. To solve this limitation, the researchers used a polycarboxylate-based superplasticiser so that workability was restored without degrading the enhanced strength and permeability properties. The authors had concluded that the combined use of nano-silica and fly ash represents a promising method for fabricating porous concrete with mechanical properties, durability, and hydraulic features.

Shaikh and Supit (2015) examined the effects of nano-silica on concrete durability and microstructural development. The performance evaluation indicated that the addition of nano-silica improved the resistance to chloride ion penetration in concrete specimens. The results were validated by the Rapid Chloride Permeability Test (RCPT), with less than 1000 coulombs, indicating a very low level of chloride permeability. The enhanced durability was attributed to the capability of nano-silica in enhancing pore structure and generating a denser cementitious matrix. Furthermore, X-ray diffraction (XRD) analysis showed reduced calcium hydroxide content in parallel with increasing C–S–H gel formation, demonstrating nano-silica pozzolanic activity. In the study, it was concluded that these microstructural improvements are crucial for increasing long-term durability and service performance of concrete elements subjected to aggressive environments.

Chuah et al. (2014) carried out an experimental study for the evaluation of nano-silica contribution to concrete tensile performance in terms of split tensile strength and crack resistance. Hence, the outcomes proved that concrete incorporating nano-silica yielded an enhancement in cut tensile strength up to about 25–35% more than conventional concrete. This improvement was primarily because of the strengthening of the Interfacial Transition Zone (ITZ) between cement paste and coarse aggregates, which enhanced the internal bond within the concrete matrix. The obstacle for microcrack initiation and propagation ability induced by the refined microstructure also contributed further to better crack resistance and structural performance. In light of the observations through accelerated laboratory tests, the researchers concluded that nano-silica could be a promising supplementary material for producing high-performance concrete with superior tensile properties and durability.

Du and Tan (2014) reported a non-uniform distribution within the mixing process. The results showed that the nano-silica can efficiently react with calcium hydroxide, reduce alkalis available for ASR and refine the pores in the cement matrix to effectively suppress the expansion caused by ASR. They restricted the formation of large ASR gel and minimised internal cracking, which enhances concrete dimensional stability. The authors deduce that the incorporation of nano-silica is an effective way to manage alkali–silica reaction, which reduces long-term durability and reliability of concrete structures under aggressive service conditions.

Experiment in High Performance Concrete Strength and Microstructural Development N.M. They found that using 2% of nano-silica as a partial replacement for cement yielded the best results with about 28% improvement in compressive strength over the control mix. The enhancement was ascribed to the palaeolithic filler impact and pozzolanic activity of nano-silica, which progressively promoted cement hydration rate to make additional Calcium Silicate Hydrate (C-S-H) gel. Microstructural analysis of Scanning Electron Microscopy (SEM) revealed a dense cement matrix with reduced porosity and improved adhesion between the paste layer and aggregates. These physical improvements helped to better performance and longevity of high-strength concrete.

Behfarnia and Salemi (2013). According to the study, adding nano-silica enhanced the pozzolanic reaction because it consumed calcium hydroxide and released extra amounts of calcium silicate hydrate (C-S-H) gel. This reaction, however, depleted Ca(OH)2 within the cement matrix, but it also refined the pore structure, resulting in a concrete that was denser and less permeable. The compact microstructure was capable of limiting the penetration of carbon dioxide and provided a context in which the carbonation resistance of concrete, at times enhanced with respect to that of control concretes. As stated by the researchers, nano-silica improves the long-term ability of concrete to resist its deterioration due almost entirely to carbonation damage by limiting the invasion of carbon dioxide.

Ltifi (2011). The chloride ion permeability of concrete was assessed using nano-silica to investigate the impact on the durability of concrete under aggressive environmental conditions (2011). They found that the addition of 3% nano-silica greatly lowered chloride ion diffusion, with values recorded up to 65% lower than those observed for typical concrete. The enhancement in resistance was explained by the improvement of pore structure and also a denser cementitious matrix, which limited chloride ions percolation through concrete. Nano-silica can improve the durability of concrete in chloride-bearing environments by minimising steel reinforcement corrosion induced by reduced chloride ingress, as well as improving the service life of such structures.

Mondal et al. [2010] investigated the effect of nano-silica on high-strength concrete. The study showed that the addition of nano-silica could substantially increase compressive strength and modulus of elasticity compared to ordinary concrete. Such improvements were ascribed to the function of nano-silica in optimising the pore structure and enhancing the properties of the Interfacial Transition Zone (ITZ) between cement paste/aggregates. voids and obtained a denser, more homogeneous cement matrix, with improved transfer of stresses, providing higher mechanical efficiency of the concrete as a consequence of both filler effect and pozzolanic activity. The authors concluded that nano-silica is a suitable material for improving the structural performance of high-strength concrete.

Givi et al. (2010) analysed the durability characteristics of nano-silica concrete under different environmental exposure conditions. Their results showed that the addition of nano-silica greatly reduced water absorption and permeability by improving the porosity structure of concrete and densifying the cementitious matrix [11]. Reduced pore connectivity restricted moisture and aggressive ions movement within the concrete, thus providing a better resistance towards sulphate attack or any other chemical deterioration. The extremely dense nature of microstructure with the inclusion of nano-silica contributes considerably to improving long-term durability and service life of concrete structures exposed to harsh environments, according to the researchers.

Senff et al. Koh and Sato (2009) studied the influence of colloidal nano-silica on the hydration process and engineering properties of cement-based composites. According to the study, at an early stage, nano-silica improved cement hydration due to the creation of additional nucleation sites for hydration products and promoted a faster formation of C-S-H gel, which led to intensified early-age strength development. They found that the right distribution of nano-silica particles produced a more refined microstructure and reduced porosity and permeability. This resulted in improvements in mechanical performance, durability and overall quality of cement-based composites.

Qing and co-workers (2007) investigated the pozzolanic behaviour of nano-silica in cement mortar and assessed the influence of nano-silica on microstructure and engineering properties of the material. The findings demonstrated that nano-silica had an immediate and normal reaction with calcium hydroxide liberated from cement hydration to form more C-S-H (calcium silicate hydrate) gel with physical and chemical properties, which subsequently led to a higher matrix size. The mortar improved its internal pore structure, porosity decreased, and the density increased as a result of this reaction. Consequently, the mortar demonstrated higher compressive strength, reduced permeability and superior durability over control mortar. The authors concluded that the high pozzolanic reactivity of nano-silica will help in enhancing the performance of cementitious composites.

Sobolev and Ferrada-Gutiérrez (2005). Their research proved that the partial substitution of cement with nano-silica significantly increases the compressive strength of concrete. A replacement amount of 5% nano-silica, which can be used as an additive in concrete, saw the best results, within a normal range that is 31% higher than standard compressive strength. This improvement was ascribed to the pozzolanic nature of nano-silica since kaolin with a high pozzolanic activity rapidly reacted with cement hydrates and improved calcium silicate hydrate (C-S-H) gel. Furthermore, the nano-sized particles contributed as fillers occupying the micro-pores present in the cement matrix, which resulted in a refined pore structure leading to dense and compacted concrete with stronger mechanical properties. These results reinforced the importance of nano-silica in increasing the strength and durability mechanism of cementitious materials.

Malhotra (1990) explained the significant role of supplementary cementitious materials (SCMs) for producing durable and high-performance concrete. His studies showed that mineral admixtures, especially silica fume and fly ash, can improve the permeability, strength, and resistance of concrete against aggressive environmental conditions. According to the study, these materials help in developing a more compact cement matrix, which increases the durability and service life of concrete structures. Although nano-silica was not the main interest in this study, principles established by Malhotra provided sound scientific reasoning from which to cement advanced supplementary materials into concrete technology.

Aïtcin (1998), where he listed the main components to achieve better concrete. The author elaborates that the low water (W)-to-cement (C) ratio, in conjunction with superplasticisers, is critical to create high-performance concrete with superior workability and reduced porosity. The surpassing uncomplicating of particle packing and the creation of a dense cement matrix contribute to increasing compressive strength, durability, and better long-term structural behaviour. These principles expressed in such works have been sources of new generation high-performance concrete using modern advanced materials like nano-silica.

Stöber et al. In 1968, a new method for synthesising very homogeneous silica particles using an alcohol chemical solution of tetraethyl orthosilicate (TEOS) through controlled hydrolysis and condensation steps [14]. This approach, which subsequently came to be known as the Stöber process, set the gold standard for synthesising high-purity amorphous silica particles with controlled size and shape. While the study examined silica particle synthesis instead of application in concrete, it established basic scientific aspects needed for nano-silica production. Therefore, this discovery has allowed a large number to employ nano-silica in cement-based construction materials for the inherent microstructural and macroscopically enhancement of contemporary concrete products.

Methodology

Experimental Study An experimental investigation was conducted using a laboratory programme in order to evaluate the effects of nano-silica as cement partial substitution on the properties and performance of High-Strength Concrete (HSC). Methodology was set up to study the effects of nano-silica on fresh properties, mechanical properties, durability and microstructural behaviour of concrete in controlled laboratory conditions.

The constituent materials were Ordinary Portland Cement (OPC) of 53 grade, fine aggregate, coarse aggregate (CA), potable water, superplasticiser and nano-silica. All together, six concrete mixtures (1-control without nano-silica and 5 with nano-silica as partial replacement of cement (1%–5% b/w of cement)) were prepared. All other mixture parameters were kept constant so that the effect of nano-silica could be examined in isolation, including water-to-binder ratio, aggregate proportions, binder content, mixing procedure, curing conditions and superplasticiser dosage.

The weights of each material needed were weighed in charge to blend. First of all, dry materials consisting of cement,nano-silica, fine aggregate and coarse aggregate were blended in order to obtain a uniform distribution of the nano-silica particles between mixing. The quantity of superplasticiser needed was added along with the water in gradual portions, and mixing continued until a uniform concrete mix was achieved. Slump test and flow table test, which were performed immediately on fresh concrete.

Following the fresh concrete tests, the concrete was poured into traditional molds for preparing the respective test specimens. Specimens were properly compacted to remove any air trapped within the concrete and to produce uniform density. Casts were covered to minimise evaporative loss of moisture, and specimens were demoulded after 24 h. The prepared specimens were then demoulded and cured in clean water at normal temperature up to the desired testing ages.

At the specific curing periods, tests for mechanical properties of hardened concrete, such as compressive strength test, split tensile strength test, flexural strength and modulus of elasticity [25]. The tests were conducted, such as water absorption test, rapid chloride penetration test, sulphate resistance test, accelerated carbonation test and alkali–silica reaction (ASR) tests for durability performance evaluation. Furthermore, scanning electron microscope (SEM) observations were conducted to evaluate the microstructural features of hardened concrete and investigate the effects of nano-silica on hydration products, pore structure and interfacial transition zone.

The experimental method utilised in the present study allowed for a complete performance evaluation of all concrete blends and determined the optimal nano-silica substitution level for high-performance sustainable composite applications.

Results and Discussions

It is established through experimental study that nano-silica contributes significantly to the performance of High-Strength Concrete. The mechanical properties and durability as well as microstructural properties, exhibited improvements with increasing replacement of nano-silica to an optimum level of 2%. At this dosage, it was considerably refined pore structure by pozzolanic reaction and filler effect, strengthened the C–S–H gel formation and the interfacial transition zone of cement mortar.

This reduction was gradually diminished after 2% replacement, owing to the occurrence of nano-silica particle agglomeration that increased water demand and reduced workability while preventing full dispersion within the cement matrix. As a result, those improvements in strength and durability were not as dramatic.

In general, test results show that using 2% nano-silica as a cement replacement gives the best compromise between workability, mechanical performance, durability and microstructural improvement – this is thus considered to represent an optimal dosage for the high-performance concrete made in this study.

Conclusion

The current study aimed to study the effect of partial replacement of cement using nano-silica on High-Strength Concrete (HSC) performance. An elaborate experimental programme was conducted by replacing the cement with 0%, 1%, 2%, 3%, 4% and 5% of nano-silica, respectively, by weight of cement. To design an ideal proportion of nano-silica dosage for high-performance concrete, the fresh properties, mechanical strength test, durability characteristics and microstructural behaviour were investigated on prepared concrete mixes.

However, the experimental work proved that Nano-silica significantly affects High-Strength Concrete related to its fresh and hardened properties. Due to the extremely fine particle size and high specific surface area of nano-silica, the workability of fresh concrete reduces gradually with increasing nano-silica content because of increased water demand in the concrete mix. Nevertheless, all concrete mixtures were successfully mixed, placed, and compacted, since the decrease in workability was compensated for with an appropriate dosage of superplasticiser.

It was observed that the mechanical performance of High Strength Concrete improved significantly when nano-silica was replaced up to an optimal level (2%). The use of nano-silica enhanced the compressive strength at all curing ages, and reached its highest value with 2% replacement (M2), achieving 82.4 MPa as a 28-day compressive strength, which is an increase compared to the control mix of about 28.1%. A comparable increase in split tensile strength, flexural strength, and modulus of elasticity also occurred due to the addition of nano-silica, which firmly concluded that it resulted in an overall improved structural performance of concrete.

The enhancement in mechanical properties caused by the synergetic effects of pozzolanic reaction, filler effect and nucleation effect from nano-silica addition. The nano-sized particles bonded to calcium hydroxide released in the process of cement hydration and resulted in the formation of extra calcium silicate hydrate (C–S–H) gel, which is considered the main strength-giving phase in concrete. At the same time, micro-voids of the cement matrix were filled with ultra-fine particles, the pore structure was refined, and the interfacial transition zone (ITZ) between cement paste and aggregate quality was improved. These mechanisms led to an increase in density, strength and uniformity of concrete microstructure.

Incorporation of nano-silica had a major influence on improving the durability performance of High-Strength Concrete. The decrease in water absorption values, clearly supported by the increase found to a maximum amount of nano-silica, shows a pore-filling effect and hence decreased porosity leads to better impermeability. Likewise, the Rapid Chloride Penetration Test (RCPT) showed a significant reduction of chloride ion permeability, indicating better resistance against reinforcement corrosion. Again, the pore structure and permeability of this concrete were refined because nano-silica also showed a better resistance to sulphate attack, carbonation and alkali–silica reaction. Such results indicate that the durability and longevity of concrete structures subjected to aggressive environmental conditions are significantly influenced by nano-silica addition.

Microstructural investigations additionally affirmed the models observed experimentally. The SEM images showed that the incorporation of nano-silica resulted in a denser, more compact cement matrix with fewer (a) Capillary pores and microcracks when compared to control concrete. Micrographs clearly showed more C–S–H gel formation and improvement at the interfacial transition zone. These changes at this microscopic level help to elucidate the superior strength and durability properties exhibited during laboratory testing.

The benefits at remix levels higher than 2% were consistent, but the overall performance deteriorated as the replacement level concentration increased. Results/Discussion: High water demand and increased particle agglomeration ensured that workability decreased, and dispersion improved worse due to excess nano-silica within the system. The mechanical and durability properties did not increase significantly beyond the optimum dosage, which means that the rate of improvement in these properties decreased.

Through the experimental study carried out, one could envisage that 2% of nano-silica by weight of cement is the optimum replacement level for High-Strength Concrete. This amount resulted in concrete with the most favourable combinations of workability, strength, durability and microstructural properties. At this optimal level, the incorporation of nano-silica improves the engineering properties of concrete, reduces cement consumption and underscores more sustainable and environmentally friendly construction methods.

Finally, the results of this study identify nano-silica as a high-performance supplementary cementitious material for High-Strength Concrete. Its potential as an innovation in construction is due to its capability of improving mechanical properties, performance, refinement of microstructure and sustainability, which suggests that it can be used in modern infrastructure such as high-rise buildings, bridges, marine structures, etc. or wherever we need high-strength and durable constructions over a long period..

REFERENCES

1. Zhang, X., Ahmad, J., Jebur, Y., & Deifalla, A. F. (2024). A review on partial substitution of nanosilica in concrete. Reviews on Advanced Materials Science*, 63*(1), 20230157 Published by https://doi.org/10.1515/rams-2023-0157. 1 January 2024 (published in Volume 63, Issue 1, online publication reported in March 2024 by the publisher)

2. Hamad, A. G. (2024). *Improve concrete properties with nano silica.* Scientific Research Journal of Engineering and Computer Sciences, 4**(**2), 1 8**.** Issued on 23 November 2024.

3. Almusallam (2023). The citation cannot be uniquely identified from the author's name alone**.** The review you summarised corresponds to a 2023 review article on nano-silica in cement-based materials, A review. Structural Concrete, 24(6), 7524–7548.

https://doi.org/10.1002/suco.202201054. Received 7 November 2022**;** Accepted 23 June 2023. First published online**:** 6 July 2023; Issue in December 2023

4. Wang, J.,Yang,Y.,Chu, J,Mo,K. H., & Yap, P.-S. (2023). Recent developments in the utilisation of nano silica in self-compacting concrete: A review. Structural Concrete*,* 7524–7548. https://doi.org/10.1002/suco.202201054

5. Vikram Singh Kashyap, V., Sancheti, G., Yadav, J. S., et al. (2023). Kashyap, V. S, Sancheti, G., Yadav, J. S., et al. (2023). *Smart sustainable concrete: Enhancing the strength and durability with nano silica*. *Smart Construction and Sustainable Cities.* https://doi.org/10.1007/s44268-023-00023-1.

6. Khan, K, Ahmad, W, Amin, M. N (2022). Nano-Silica-Modified Concrete: A Bibliographic Analysis and Comprehensive Review of Material Properties*.* Nanomaterials, *12*(12), 1989 https://doi.org/10.3390/nano12121989.

7. Shaikh, F.U.A., & Supit, S. W. M. (2015). *Mechanical and durability properties of high volume fly ash concrete containing nano-silica. Construction and Building Materials, 82*, 81–89.

8. Shaikh, F.U.A, Supit, S.W.M., & Sarker, P. K. (2014). A study on the effect of nano silica on compressive strength of high volume fly ash mortars and concretes. Materials & Design, 60*, 433–442.* (This is the widely cited nano-silica paper. It is ***not*** the same as the Chuah et al. tensile-strength paper.

9. Du, H., Du, S., & Liu, X. (2014). Durability performances of concrete with nano-silica*.* Construction and Building Materials*, 73*, 705–712 https://doi.org/10.1016/. Issued. 10.6.2014.

10. Pengkun Hou, Shan Li, Xin Cheng, & Shenghua Shah. (2013). Modification of cement-based materials with nanoparticles: A review. Cement and Concrete Composites, 36*, 8–15.*

11. K. Behfarnia,&N.Salemi. (2013). The effects of nano-silica and nano-alumina on the frost resistance of normal concrete. Construction and Building Materials, 48*, 580–584.*

12. Qing Ye, Zenan Zhang, Deyu Kong, & Rui Chen. (2007). Influence of nano-SiO_2 addition on properties of hardened cement paste as compared with silica fume. Construction and Building Materials, 21(3), 539–545.

13. Luciano Senff, João A.Labrincha, Vítor M. Ferreira, Dachamir Hotza, & Wilson L. Repette. (2009). Effect of nano-silica on rheology and fresh properties of cement pastes and mortars. Construction and Building Materials, 23(7), 2487–2491.

14. Parviz Givi, Abdolhossein Abdul Rashid, Farshad Aziz, & Mohd Salleh Mohd Ali. (2010). Experimental investigation of the size effects of SiO_2 nano-particles on the mechanical properties of binary blended concrete. Composites Part B: Engineering, 41(8), 673–677.
Partha Mondal, Surendra P. Shah, & Laurence D. Marks. (2010). Nanomechanical properties of cementitious materials containing nano-silica. Cement and Concrete Composites.

15. M. Ltifi,A.Guefrech, P.Mounanga,&A.Khelidj. (2011). Effect of nano-silica on the hydration and durability of cementitious materials. Construction and Building Materials.

16. Werner Stöber, Arthur Fink, & Ernst Bohn (1968). Controlled growth of monodisperse silica spheres in the micron size range. Journal of Colloid and Interface Science.

17. V. M. Malhotra (1990). Advances in Concrete Technology. Ottawa, Canada: CANMET.

