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Experimental Investigation of the Effects of Nano-Silica on the Mechanical and Durability Properties of Concrete

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Abstract

Nanotechnology is one of the rapidly developing fields in engineering and construction materials, with increasing applications in cement-based materials and concrete. In recent years, considerable attention has been directed toward the use of nanoparticles, particularly nano-silica, due to their high surface area, pozzolanic activity, and ability to modify the microstructure of cementitious materials. Nano-silica can participate in hydration reactions and fill fine pores within the cement matrix, potentially improving the mechanical properties, permeability, and durability of concrete. Despite the increasing application of nanomaterials in concrete, studies concerning their influence on the strength and durability characteristics of concrete at different ages remain necessary. In this study, the effects of nano-silica on the mechanical and durability properties of concrete were experimentally investigated. Five different mix designs were prepared, including mix A as the control mixture without nano-silica and mixes B1, B2, B3, and B4 containing different proportions of nano-silica. The specimens were tested at the ages of 7, 28, 90, and 180 days. Compressive strength, tensile strength, water penetration, and electrical resistivity tests were performed to evaluate the effects of nano-silica on the performance of the concrete. The results demonstrated that the incorporation of nano-silica generally improved the compressive and tensile strengths compared with the control mixture. The rate of strength development was particularly significant at early ages, while the improvement continued at later ages. The results of the water penetration test also showed that increasing the nano-silica content reduced water penetration, which can be attributed to the pore-filling effect and high pozzolanic activity of nano-silica, resulting in a denser cementitious matrix. Furthermore, the electrical resistivity of concrete increased significantly with the addition of nano-silica, particularly at later ages. The increase in electrical resistivity indicates a reduction in ionic transport and electrical conductivity, which can contribute to reducing the risk of reinforcement corrosion. Overall, the findings indicate that the appropriate incorporation of nano-silica can improve the mechanical performance and durability of concrete.

Keywords: Concrete, Compressive strength, Tensile strength, Water absorption, Electrical resistivity, Nanotechnology, Nano-Silica.

1 | Introduction

Concrete is one of the most widely used construction materials in the world because of its availability, relatively low cost, versatility, and favorable mechanical properties. Consequently, improving the performance, durability, workability, and sustainability of concrete has remained an important research topic

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in civil engineering. The long-term performance of concrete structures is strongly dependent on their microstructure, permeability, degree of compaction, and resistance to environmental actions. Defects such as capillary pores, entrapped air, microcracks, and weak zones at the aggregate–cement paste interface can significantly affect the mechanical and durability performance of concrete. These defects can provide pathways for water and aggressive ions to penetrate into the cementitious matrix, thereby accelerating deterioration and reducing the service life of concrete structures.

One of the important developments in concrete technology has been the introduction of Self-Compacting Concrete (SCC). Unlike conventional concrete, SCC is designed to flow under its own weight, fill complex formworks, pass through congested reinforcement, and achieve adequate consolidation without the need for external mechanical vibration. The development of SCC has therefore provided an effective solution for structures in which conventional compaction is difficult or where high construction quality and surface finish are required. The use of SCC can also reduce construction noise, facilitate placement in heavily reinforced members, and decrease the dependence on mechanical vibration during construction [1].

Despite its advantages, the performance of SCC is closely related to its mixture composition and the characteristics of its cementitious matrix. The relatively high powder content required to obtain sufficient flowability and stability can influence shrinkage, permeability, hydration, and mechanical properties. Therefore, the incorporation of supplementary cementitious materials and ultrafine particles has received considerable attention as a means of controlling the fresh and hardened properties of SCC.

In recent years, nanotechnology has emerged as a promising approach for modifying cement-based materials. Nanomaterials possess extremely small particle sizes and very high specific surface areas, which can significantly influence cement hydration, particle packing, pore structure, and the development of the interfacial transition zone. Among different nanoparticles investigated for cement-based materials, nano-silica has received particular attention because of its high pozzolanic activity and filler effect. Nano-silica can react with calcium hydroxide and contribute to the formation of additional calcium silicate hydrate (C–S–H), while its very fine particles can fill nanoscale voids within the cementitious matrix [1].

The interaction between nanotechnology and concrete technology can therefore provide an opportunity to develop cement-based materials with improved mechanical and durability characteristics. The refinement of the pore structure is particularly important because concrete durability is strongly related to its permeability and transport properties. A denser cementitious matrix can reduce the penetration of water and aggressive substances, including chloride ions, and consequently improve resistance to environmental deterioration [1–3].

The incorporation of nano-silica into SCC, however, is not without challenges. Because nano-silica has a very high specific surface area, even relatively small amounts can substantially increase the water demand of the mixture. Consequently, the workability and flowability of SCC may decrease unless the mixture is properly adjusted using an appropriate water-to-binder ratio and chemical admixtures. Hani et al. [4] investigated the effects of water-to-binder ratio and nano-silica dosage on SCC and demonstrated that nano-silica dosage is an important parameter governing both fresh and hardened properties. Similarly, Bernal et al. [5] reported that the incorporation of nano-silica can reduce workability because of its high water demand, while its combination with silica fume can improve the compressive strength of SCC.

The simultaneous use of micro-silica and nano-silica has also attracted significant interest because these two materials can act at different scales. Micro-silica can improve particle packing and contribute to pozzolanic reactions, whereas nano-silica can provide additional nucleation sites and fill very fine pores. Experimental investigations have indicated that ternary mixtures containing both materials can provide favorable mechanical and durability performance. In particular, mixtures containing 2.5% nano-silica and 2.5% micro-silica showed high compressive strength in comparison with the corresponding binary mixtures [5]. Similar observations were reported for high-performance SCC, where combinations of nano- and micro-silica improved resistance to carbonation and freeze–thaw cycles [6].

Therefore, the optimization of SCC containing nano-silica and silica-based supplementary materials requires simultaneous consideration of fresh properties, mechanical performance, microstructure, and durability. The objective should not simply be to maximize compressive strength, but also to obtain an appropriate balance between flowability, passing ability, segregation resistance, pore refinement, shrinkage, and long-term durability.

2 | Literature Review

The development of SCC represents an important advancement in concrete technology. The fundamental concept of SCC is based on producing a concrete mixture with sufficient deformability and stability so that it can flow and consolidate under its own weight without mechanical vibration. Early investigations by Zhang et al. [7] established important principles for SCC mixture design and emphasized the need to control the volume and rheological characteristics of the cement paste.

The development of SCC was motivated partly by the need to improve the reliability of concrete placement and reduce the problems associated with inadequate compaction. In conventional reinforced concrete, insufficient vibration can lead to entrapped air, honeycombing, poor surface quality, and weak zones around reinforcement. SCC addresses these problems by providing high filling ability and passing ability while maintaining resistance to segregation.

Subsequent research has focused on optimizing the proportions of powder, aggregate, water, and chemical admixtures to obtain the required rheological properties. Modern SCC mixture design approaches consider parameters such as water-to-binder ratio, paste volume, aggregate packing, viscosity, and the characteristics of supplementary cementitious materials [1], [7].

Nanotechnology involves the control and modification of materials at extremely small length scales, where changes in particle size can lead to significant changes in physical and chemical behavior. In cement-based materials, nanotechnology has attracted attention because nanoscale particles can influence hydration reactions, pore structure, particle packing, and the formation of hydration products.

Among the different nanomaterials investigated in concrete, nano-silica has been one of the most extensively studied. Its high specific surface area allows it to act as a highly reactive pozzolanic material as well as a filler for very small pores. According to the comprehensive review of Faraj et al. [1], nano-silica has been the most frequently investigated nanoparticle for SCC among the various types of nanoparticles reported in the literature. Their review of 76 studies showed that nanoparticles can affect the fresh, mechanical, durability, and microstructural characteristics of SCC.

Nano-silica can contribute to the refinement of the cementitious matrix through two principal mechanisms. First, its ultrafine particles can physically fill spaces between larger cement particles. Second, its reactive silica can participate in pozzolanic reactions with calcium hydroxide, producing additional C–S–H gel. These mechanisms can result in a denser microstructure and reduced pore connectivity [1].

Although nano-silica can improve several hardened properties of SCC, its incorporation may negatively affect fresh-state workability. The high specific surface area of nano-silica increases the amount of water required to wet the particles. As a result, increasing nano-silica content can reduce slump flow and increase the demand for superplasticizer.

Hani et al. [4] investigated SCC mixtures with different water-to-binder ratios and nano-silica dosages. Their results demonstrated that the influence of nano-silica on SCC depends on both the nano-silica content and the water-to-binder ratio. This finding highlights the importance of optimizing nano-silica dosage rather than assuming that increasing its content will always improve concrete performance.

Bernal et al. [5] similarly found that the addition of nano-silica reduced SCC workability and increased the demand for superplasticizer. Nevertheless, the incorporation of nano-silica and micro-silica resulted in improved compressive strength, and the ternary mixture containing both materials exhibited particularly favorable performance.

Afzali Naniz and Mazloom [2] also investigated colloidal nano-silica in self-compacting lightweight concrete. Their results indicated that the incorporation of colloidal nano-silica significantly affected workability, while combinations of micro-silica and nano-silica improved mechanical performance and electrical resistivity.

These findings indicate that the use of nano-silica in SCC requires careful control of the fresh-state rheology. The beneficial effects of nano-silica can only be fully exploited if adequate filling ability, passing ability, and segregation resistance are maintained.

The mechanical performance of SCC depends strongly on the quality and density of its cementitious matrix. Nano-silica can contribute to strength development by accelerating hydration and providing additional sites for C–S–H formation. Its filler effect can also reduce the size and connectivity of pores within the cement paste.

Bernal et al. [5] investigated SCC mixtures incorporating nano-silica, silica fume, and ternary combinations. Their results showed that both nano-silica and micro-silica increased compressive strength, while the ternary mixture containing 2.5% micro-silica and 2.5% nano-silica produced particularly high strength.

Almohammad-albakkar and Behfarnia [8] investigated the combined use of micro-silica and nano-silica in SCC. Their study considered different water-to-binder ratios and replacement levels of the two silica-based materials. The results demonstrated that the combined use of micro- and nano-silica could provide a synergistic effect. In particular, the mixture containing 9% micro-silica and 1% nano-silica showed a reduction in long-term drying shrinkage and a considerable increase in compressive strength compared with the reference mixture.

The results obtained from these studies suggest that the simultaneous use of silica-based materials at different particle scales can improve the packing density of the cementitious system. Micro-silica can fill relatively larger voids, while nano-silica can contribute to filling and reacting within smaller pores. Consequently, a more compact matrix with improved mechanical properties can be developed.

Durability is one of the most important performance characteristics of concrete because the ingress of water and aggressive ions is closely associated with deterioration mechanisms. A reduction in pore size and pore connectivity can therefore contribute to improved durability.

The incorporation of nano- and micro-silica has been reported to improve the durability characteristics of high-performance SCC. An investigation of binary and ternary mixtures containing nano- and micro-silica showed that ternary mixtures generally provided greater resistance to carbonation and freeze–thaw cycles [6]. The observed improvements were associated with the refinement of the cementitious matrix and reduction in the pathways available for the transport of aggressive agents.

The role of nano-silica in modifying the microstructure of SCC has also been examined through studies involving water absorption, permeability, and electrical resistivity. Afzali Naniz and Mazloom [2] reported that mixtures containing micro-silica and colloidal nano-silica exhibited substantially increased electrical resistivity, indicating a reduction in the connectivity of conductive pore networks.

The improvement in durability is particularly relevant to chloride penetration. Chloride ions can migrate through the pore system of concrete and reach embedded steel reinforcement, where they can initiate corrosion. Consequently, reducing permeability and refining the pore structure can be an important approach for extending the service life of reinforced concrete structures.

Recent studies have also investigated the combined use of nano-silica with other supplementary cementitious materials. Hakeem et al. [9] investigated SCC incorporating nano-silica, fly ash, silica fume, and limestone powder. Their experimental program included fresh, mechanical, permeability, and high-temperature properties. The authors reported that the combination of 3% nano-silica, 10% silica fume, and 15% limestone powder produced favorable mechanical performance, demonstrating the potential of combining nano-silica with conventional supplementary cementitious materials.

Research during the last decade has gradually shifted from studying the isolated influence of nano-silica toward investigating optimized combinations of nanoparticles and supplementary cementitious materials. This transition is important because the performance of SCC is governed by interactions among multiple mixture components rather than by a single material.

A comprehensive review by Faraj et al. [1] examined 76 studies concerning nanoparticles in SCC and concluded that nanoparticles can significantly influence fresh properties, mechanical performance, durability, and microstructure. The authors also identified nano-silica as the most widely investigated nanoparticle and emphasized its potential to improve strength and durability through pore refinement and additional C–S–H formation.

The systematic review of self-compacting mortars modified with nanoparticles similarly indicated that nanoparticles can influence slump flow, V-funnel flow time, compressive and flexural strength, water absorption, chloride penetration, and electrical resistivity [1]. These findings demonstrate that the effect of nanoparticles should be evaluated from a multi-performance perspective rather than solely through compressive strength.

More recent experimental work has further investigated combinations of nano-silica with fly ash, silica fume, and limestone powder. Hakeem et al. [9] showed that nano-silica can be effectively incorporated into SCC containing supplementary cementitious materials while maintaining the required fresh properties and improving several mechanical and durability characteristics.

Overall, the available literature indicates that nano-silica has considerable potential for improving SCC, but its effectiveness depends strongly on dosage, water-to-binder ratio, type of silica source, dispersion method, and the presence of other supplementary cementitious materials. Excessive nano-silica may negatively affect workability and increase the demand for chemical admixtures, whereas an optimized dosage can contribute to strength development, pore refinement, and improved durability [1], [4-6], [8], [9].

Although numerous studies have investigated the use of nano-silica in SCC, several aspects still require further investigation. First, the optimum nano-silica content is not universal and depends on the water-to-binder ratio, cement type, supplementary cementitious materials, and dispersion conditions. Second, increasing nano-silica content can improve the hardened microstructure while simultaneously reducing fresh-state workability. Therefore, identifying an appropriate balance between fresh and hardened properties remains an important research challenge.

Furthermore, although the individual effects of nano-silica and micro-silica have been extensively investigated, the synergistic interaction between these materials and its influence on long-term durability requires additional experimental investigation. In particular, further research is needed to establish relationships between nano-silica content, pore structure, permeability, chloride penetration, mechanical strength, and shrinkage.

Accordingly, the development of optimized SCC mixtures containing nano-silica and silica-based supplementary cementitious materials can contribute to the production of concrete with improved mechanical performance, reduced permeability, enhanced durability, and potentially longer service life. Such optimization should simultaneously consider the fresh properties of SCC, including filling ability and passing ability, and the hardened properties, including compressive strength, microstructure, permeability, shrinkage, and resistance to aggressive environmental conditions.

3 | Research Methodology

Concrete is currently recognized as one of the most widely used construction materials in the world and is often regarded as a major construction material of the twenty-first century. Lightweight construction is one of the emerging topics in modern building science and has been continuously developing in recent years. This technology involves reducing the final weight of a building through the application of advanced construction techniques, innovative materials, and optimization of construction methods. Reducing the weight of a structure can not only lead to savings in cost, construction time, and energy consumption, but can also reduce the adverse effects of natural hazards such as earthquakes and minimize damage resulting from excessive structural weight.

Despite its considerable compressive strength, concrete has relatively low tensile strength and is inherently brittle. These characteristics limit its application in structural members subjected predominantly to tensile stresses. This fundamental limitation is generally addressed by reinforcing concrete with steel reinforcement positioned in the direction of the tensile forces. Since steel reinforcement constitutes only a relatively small portion of the total cross-sectional area, it is not appropriate to consider a reinforced concrete section as a completely homogeneous and isotropic material.

In order to improve the isotropic behavior of concrete and reduce its brittleness and susceptibility to cracking, the use of thin and relatively long nano-scale fibers dispersed throughout the concrete matrix has become increasingly common in recent decades. Compared with conventional concrete, nanomaterial-containing concrete can exhibit significantly different behavior due to the chemical interactions between nanomaterials and cement particles, as well as their interactions with calcium hydroxide crystals formed during cement hydration.

In the present study, the effects of nano-silica and fibers on the properties and performance of concrete are investigated. Particular attention is given to their influence on the mechanical and physical characteristics of the concrete matrix.

3.1 | Materials and Constituents

3.1.1 | Cement

Cement is a hydraulic binding material produced primarily from finely ground clinker containing calcium silicates and calcium aluminates, together with certain calcium sulfates that are added during the manufacturing process. Cement is one of the most widely available construction materials and is used extensively in concrete production. Calcareous materials, such as limestone and shale, and argillaceous materials, such as clay and blast-furnace slag, constitute the principal raw materials used in the production of Portland cement.

When cement is mixed with water, a cementitious paste with plastic properties is initially formed. During this stage, the mixture can be mixed, placed, and remixed without significant damage to its structure. However, as the hydration reaction between cement and water progresses, the mixture gradually loses its plasticity. This initial stage of hardening is referred to as the initial setting period.

In the present study, Portland pozzolanic cement produced by Mazandaran Cement Factory was used. The specific gravity of the cement was 3130 kg/m^3, according to the manufacturer's catalog. The chemical composition of the cement used in this study is presented in *Table 1*.

Table 1. Chemical composition of the cement used.

Cement Compounds	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O
Content (%)	21.32	3.83	2.98	62.02	3.44	2.09	0.12	0.73

3.1.2 | Sand and aggregate

The aggregates used in this study were natural, normal-weight aggregates obtained from a sand and gravel production plant. In terms of particle shape, the coarse aggregate was angular and crushed, while the fine aggregate consisted of natural crushed sand. The particle-size distribution of the aggregates was determined according to the procedure specified in ASTM C136 (ASTM, 2014). The particle-size distribution curve and the physical properties of the aggregates used in this study are presented in *Fig. 1* and *Table 2*, respectively.

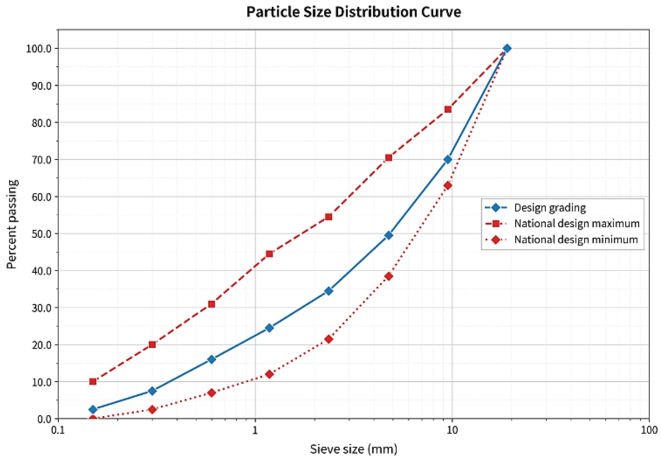


Fig. 1. Gradation curve of the aggregates used.

Table 2. Physical properties of the aggregates used.

Aggregate	Water Absorption (%)	Density (g/cm³)	Fineness Modulus	Maximum Aggregate Size (mm)
Gravel	1.74	2.57	6.6	19
Sand	2.3	2.56	3.3	19

3.1.3 | Silica fume

Silica fume is a by-product of electric arc furnaces generated during the production of silicon metal or ferrosilicon alloys. During the development and widespread application of SCC over the past decades, silica fume was among the first materials to be used as a filler in concrete mixtures and as an effective cementitious material. Filling the voids between cement particles with the fine particles of silica fume reduces the porosity of concrete.

3.1.4 | Nano-Silica

Nanotechnology deals with various material structures with dimensions on the order of one-billionth of a meter. A nanostructured material is generally defined as a solid material whose constituent crystals or structural components are within the nanometer scale. The prefix “nano” denotes one-billionth. Due to the extremely small size of their constituent particles and their high surface-area-to-volume ratio, nanomaterials have attracted considerable attention.

Nano-silica products are manufactured over a wide range of specific surface areas, typically from 50 to 1000 m^2/g. In addition, various production methods are used to manufacture nano-silica. In general, nano-silica can be classified into colloidal nano-silica, pyrogenic nano-silica, precipitated nano-silica, and nano-silica gels. Obviously, nano-silica with a specific surface area of 50 m^2/g cannot be expected to have the same effect on the properties of concrete as nano-silica with a specific surface area of 1000 m^2/g.

Furthermore, the properties of nano-silica produced by different methods can vary considerably and may consequently affect its behavior in cement-based materials. For example, some types of nano-silica exist in agglomerated form, whereas others are present as individual particles dispersed separately from one another.

In this study, colloidal silica solution was used as the nano-silica material. The physical properties of the nano-silica solution used are presented in *Table 3*.

Table 3. Physical properties of the Nano-Silica solution used.

Property	Solid Particles (%)	Viscosity (cP)	Specific Gravity (g/cm³)	pH	Color	Physical State
Value	30	<10	1.05–1.4	13	Transparent	Liquid

3.1.5 | Polypropylene fibers

The polypropylene fibers used in this study were 18 mm long and had a diameter of 0.02 micron. The fibers were manufactured by Pars Beton Company. The properties of the polypropylene fibers are presented in *Table 4*.

Table 4. Properties of the polypropylene fibers.

Property	Specific Gravity (g/cm³)	Reaction with Water	Tensile Strength	Melting Point (°C)	Length (mm)
Value	0.9	Hydrophobic	3000–4000	175	18

3.1.6 | Superplasticizer admixture

A superplasticizer, namely Superplasticizer 260, manufactured by Namikaran Company, was used in this study. This admixture is an effective water-reducing and high-range water-reducing agent used for producing high-quality concrete. It complies with ASTM C494 Type [G] and Iranian Standard No. 2930, Type G.

Table 5. Properties of the superplasticizer.

Property	Color	pH	Specific Gravity (g/cm³)
Value	Brown	7	1.12

3.1.7 | Water

Potable municipal water was used for preparing the concrete mixtures.

3.1.8 | Leca

The lightweight aggregate used in this study was domestically produced Leca, with a particle-size range of 0.5 mm, a specific gravity of 1225 kg/m³, and a 24-h water absorption of 32%. The Leca aggregate was used as a replacement for sand in the lightweight concrete mixtures.

3.1.9 | Specimen molds

For the compressive strength, ultrasonic pulse velocity, and electrical resistivity tests, cubic steel molds with dimensions of 10 × 10 × 10 cm were used. For the indirect tensile strength test, cylindrical steel molds with dimensions of 10 × 20 cm were employed. Before casting the concrete, the inner surfaces of the steel molds were coated with form-release oil to prevent adhesion between the concrete and the molds.

3.2 | Conventional Concrete Containing Nano-Silica and Polypropylene Fibers

Based on the tests performed on the aggregates and cement, the cement content of the conventional concrete mixture was determined to be 436.2 kg/m³ under the selected optimum conditions. The water-to-cement ratio (W/C) obtained from the concrete mix design based on the ACI method was 0.47. After accounting for the moisture content of the aggregates, this ratio was adjusted to 0.38. The quantities of materials required to produce one cubic meter of conventional concrete are presented in *Table 6*.

Table 6. Quantities of materials used in the conventional concrete mix design.

Gravel (kg/m³)	Sand (kg/m³)	Cement (kg/m³)	W/C
1025	660	436.2	0.38

3.3 | Lightweight Concrete Containing Nano-Silica and Polypropylene Fibers

Based on the tests conducted on the aggregates and cement, the cement content was set at 500 kg/m³. Since the Leca aggregate used in this study has a high water absorption capacity and dry Leca was used in the experiments, the water-to-cement ratio was increased to 0.50, taking the aggregate moisture conditions into account, in order to avoid a significant reduction in slump.

The proportions of the constituent materials in the concrete mixtures were determined using the absolute-volume method in accordance with ACI 211, based on the properties of the constituent materials and the target properties of the concrete. The quantities of materials required to produce one cubic meter of lightweight concrete are presented in *Table 7*.

Table 7. Quantities of materials used in the SCC mix design.

Gravel (kg/m³)	Sand (kg/m³)	Cement (kg/m³)	W/C
455	500	500	0.50

Fig. 2. Polypropylene fibers used in the experiments.

3.4 | Mix Design Specifications

In this study, five concrete mix designs were considered to investigate the mechanical properties and durability of the concrete specimens. Mix A represented the conventional concrete, while the other mixtures contained different percentages of nano-silica replacement. The experimental program included testing at the ages of 7, 28, 90, and 180 days. All mixtures were designed with a water-to-cement ratio (W/C) of 0.45 and a total cementitious material content of 400 kg/m³. The specifications of the concrete mix designs are presented in *Table 8*.

Table 8. Specifications of the concrete mix designs.

Mix ID	Water (kg/m³)	Cement (kg/m³)	Nano-Silica (%)	Nano-Silica Content (kg/m³)	Superplasticizer-to-Cement Ratio (%)	Flowability (cm)
A	180	400	—	—	0	8.6
B1	180	390	2.5	10	0.62	9.4
B2	180	382	4.5	18	0.83	8.3
B3	180	374	6.5	26	1.21	8.1
B4	180	366	8.5	34	1.84	7.8

The use of concrete structures under different climatic conditions makes the deterioration of these structures and, consequently, their repair and maintenance, one of the major concerns of engineers and researchers. At the nanoscale, particles exhibit unique physical and chemical properties compared with conventional materials. SCC is an innovative technology in the construction industry that can fill formwork under its own weight without requiring external or internal vibration while maintaining its homogeneity.

Similarly, the development of nanotechnology has introduced significant advances in the concrete industry. The incorporation of nanomaterials into cement-based materials has resulted in considerable improvements in the strength and durability of concrete. Therefore, this study aimed not only to develop an appropriate mix design for producing SCC, but also to investigate the effects of incorporating different forms of domestically produced nano-silica, including nano-silica powder, gel, and colloidal nano-silica solutions manufactured by knowledge-based companies.

Furthermore, Lightweight Expanded Clay Aggregate (LECA) was used as a lightweight aggregate to replace a portion of the conventional cement and aggregate materials in the concrete mixtures. The objective was to achieve desirable mechanical properties and evaluate selected mechanical and durability characteristics of the resulting concrete. In this study, the effect of nano-silica on both normal-weight and lightweight concrete containing nano-silica solution was investigated at different curing ages. The results were also compared with those obtained from reference specimens without nano-silica.

4 | Results and Discussion

In this section, following the presentation of the quantities of materials used and the proportions of nano-silica and fibers incorporated into each concrete mix design, the results of the experimental tests are presented and analyzed. The tests included compressive strength, tensile strength, water penetration, and electrical resistivity. It should be noted that all tests were performed on the prepared specimens at the ages of 7, 28, 90, and 180 days. The results of these experiments are subsequently presented, analyzed, and interpreted.

After completion of the curing period, the following tests were performed on the concrete specimens.

4.1 | Compressive Strength Test

Based on the proportions specified in the mix designs, the required quantities of gravel, sand, cement, and water were accurately weighed. The gravel, sand, and cement were first placed into a concrete mixer and thoroughly mixed. Water was then added, and the mixture was continuously mixed until the fine and coarse particles were uniformly distributed throughout the concrete mixture. After preparation, the concrete mixture was tested as described below.

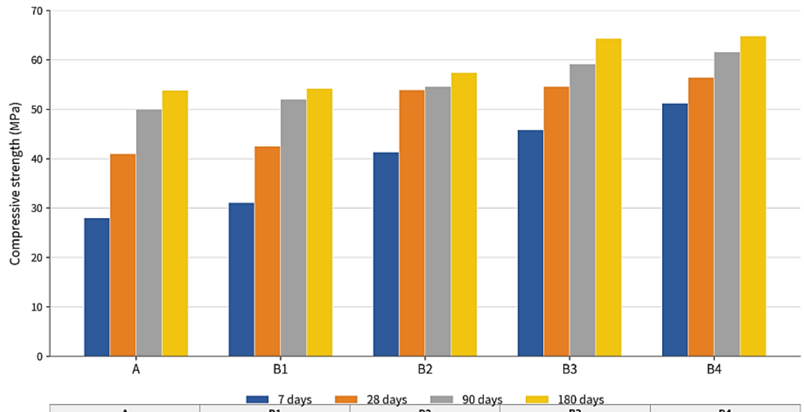
Initially, to prevent adhesion of the concrete to the mold surfaces, the internal surfaces of the molds were coated with a thin layer of mineral oil.

The compressive strength test of concrete is required to determine the load-bearing capacity of structural members. The prepared concrete specimens were subjected to compressive loading to determine their compressive strength. Compressive strength is generally calculated by dividing the failure load by the loaded cross-sectional area and is commonly determined at different ages during the curing period.

The strength of concrete is influenced by the proportions of cement, fine and coarse aggregates, water, and various chemical or mineral admixtures. In general, a lower water-to-cement ratio results in higher compressive strength, provided that adequate workability and compaction are maintained.

Concrete compressive strength is commonly reported in pounds per square inch (psi) in the United States customary system and in megapascals (MPa) in the SI system. For conventional applications, concrete compressive strength generally ranges from approximately 10 to 60 MPa. For specialized applications, concretes with compressive strengths exceeding 500 MPa can be produced; such materials are generally classified as ultra-high-strength concrete or reactive powder concrete.

The compressive strength test of hardened concrete was performed on 100-mm cubic specimens at the ages of 7, 28, 90, and 180 days. Three specimens from each mix design were tested at each age. The tests were conducted using a compression testing machine with a capacity of 2000 kN and a loading rate of 2.5 kN/s, in accordance with ACI C330. The standard procedure for determining the compressive strength of concrete is specified in ASTM C39.



	A	B1	B2	B3	B4
7 days	28	31.1	41.3	45.79	51.2
28 days	41	42.5	53.9	54.59	56.4
90 days	50	52	54.6	59.15	61.6
180 days	53.8	54.2	57.4	64.3	64.8

Fig. 3. Results of the compressive strength test.

4.2 | Indirect Tensile Strength Test

The splitting tensile strength test is used to determine the tensile strength of molded or cored cylindrical concrete specimens. In general, the indirect tensile strength of concrete, determined by the splitting method, is higher than its direct tensile strength and lower than its flexural tensile strength (modulus of rupture).

The splitting tensile strength test is particularly applicable to the design of lightweight concrete structural members, as it can be used to evaluate the shear strength and determine the development length of reinforcing bars embedded in concrete.

In general, concrete exhibits considerably lower tensile strength than compressive strength. Therefore, reinforcing bars play an important role in resisting tensile forces in structural concrete members.

Fig. 4. Concrete Specimen in the testing machine.

In this method, a diametrical compressive load is applied at a specified rate along the longitudinal axis of the cylindrical concrete specimen until failure occurs. This loading induces tensile stresses along the plane subjected to the applied load, while relatively high compressive stresses develop in the surrounding areas.

Tensile failure occurs earlier than compressive failure because the areas under the applied load are subjected to a triaxial compression state. Consequently, these areas can withstand much higher compressive stresses than those developed during a uniaxial compressive strength test. Thin plywood bearing strips are used for loading to distribute the applied load along the length of the cylinder.

4.2.1|Procedure for the Splitting Tensile Strength Test of Concrete (Brazilian Test)

Using a suitable device, draw diametrical lines on both ends of the specimen so that the lines lie in the plane passing through the longitudinal axis of the specimen.

Measure the diameter of the specimen to an accuracy of 0.25 mm by calculating the average of three diameter measurements taken at the two ends and the middle of the cylinder.

Determine the length of the specimen to an accuracy of 2 mm by calculating the average of at least two length measurements taken along the marked plane at both ends of the specimen.

Align the center of one of the plywood bearing strips with the center of the lower bearing support.

Place the specimen on the wooden strip so that the marked lines at both ends of the cylinder are perpendicular to the axis of the wooden strip and coincide with its centerline.

After positioning the specimen, the following conditions should be satisfied:

The plane passing through the two marked lines at the ends of the specimen should pass through the center of the upper bearing support.

When auxiliary bearing plates are used, the center of the specimen should be positioned directly beneath the center of the spherical loading head.

Apply the load continuously and at a uniform rate of approximately 0.7–1.4 MPa/min until the tensile stress causes failure of the specimen.

Record the maximum applied load measured by the testing machine and note the type of failure.

The maximum tensile strength of the specimen can be determined using the following equation:

$$T = \frac{2P}{\pi LD},$$

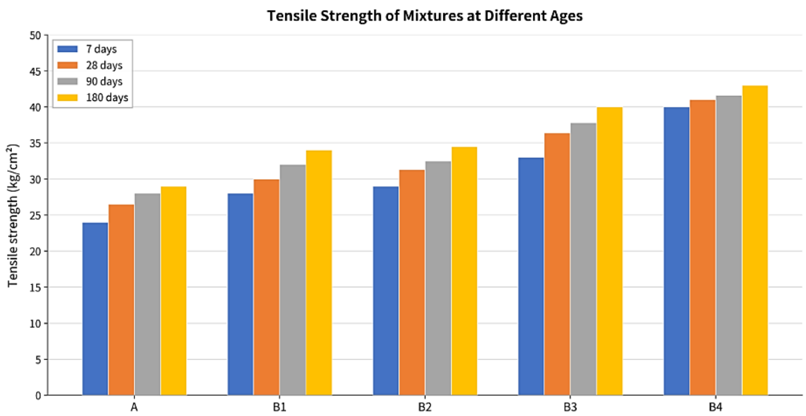
T: Splitting tensile strength, in MPa

P: Maximum load applied by the testing machine, in newtons (N)

L: Length of the specimen, in mm

d: Diameter of the specimen, in mm

The indirect tensile strength, or splitting tensile strength, of cylindrical concrete specimens was determined using 10 × 20 cm specimens with the same compression testing machine, at a loading rate of 80 kN/min, in accordance with ACI.



	A	B1	B2	B3	B4
7 days	24	28	29	33	40
28 days	26.5	30	31.3	36.4	41
90 days	28	32	32.5	37.8	41.6
180 days	29	34	34.5	40	43

Fig. 5. Results of the tensile strength test.

a.

b.

Fig. 6. Tensile strength test of the Specimens: a. Specimen placement under the jack, and b. Crack development in the Specimens after the test.

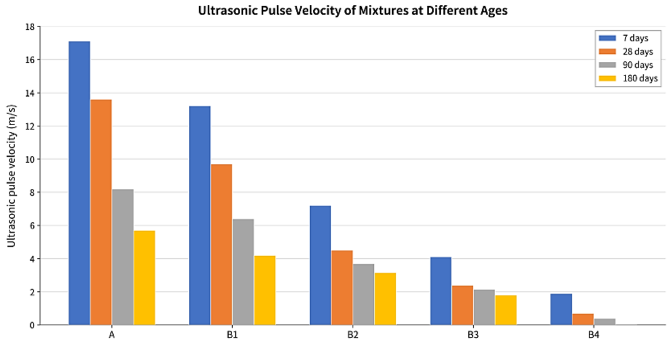
4.3 | Water Penetration Test

This test is intended to determine the amount of water absorbed when water is poured onto the horizontal surface of a concrete specimen or a portion of a precast concrete element, while the water head available to exert pressure is limited to 200 mm. In this test, the amount of water absorbed at different time intervals is reported in grams or milliliters per unit surface area (m^2).

The permeability of concrete and the rate of transport of materials through concrete depend on its internal structure. To determine the permeability of a concrete structure, its permeability coefficient must be determined. The permeability coefficient of concrete is defined as the amount of liquid or gas flow passing through a unit cross-sectional area per unit time, usually expressed in liters, under a unit hydraulic gradient (the ratio of the hydraulic head, equivalent to one meter of water, to the flow path, i.e., the concrete thickness in meters). In general, the permeability of concrete is quantitatively characterized by the fluid leakage coefficient, which is determined and calculated using a conventional index based on the penetration of gas or water.

Concrete permeability is one of the important properties affecting concrete durability. This property facilitates the penetration of water or other fluids through the concrete, allowing harmful and damaging substances to be transported into the concrete.

This test was conducted in accordance with BS EN 12390-8:2000 at the ages of 7, 28, 90, and 180 days on cubic specimens with dimensions of 15 cm. After the specimens were subjected to a water pressure of 105 × 5 Pa, they were split, and the depth of water penetration was measured. The value reported for the water penetration of the specimens was calculated as the average of the different penetration depths measured along the 15-cm length of the specimens.



	A	B1	B2	B3	B4
7 days	17.1	13.2	7.2	4.1	1.9
28 days	13.6	9.7	4.5	2.4	0.7
90 days	8.2	6.4	3.7	2.15	0.4
180 days	5.7	4.2	3.15	1.8	0

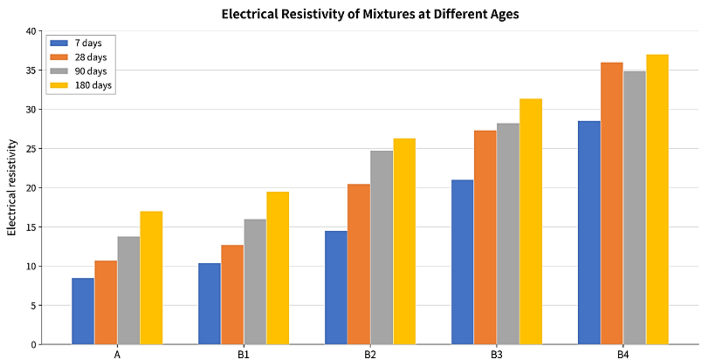
Fig. 7. Results of the water penetration test.

4.4 | Electrical Resistivity

Corrosion is an electrochemical phenomenon in which the reinforcing bars act as the anode and the concrete acts as the cathode, resulting in an electric current between the reinforcement and the concrete surface. This process is inevitably accompanied by the movement of ions. The easier and more readily this movement occurs, the lower the resistance to ionic transport and the higher the electrical conductivity of the concrete. As electrical resistivity increases, ionic movement decreases, thereby reducing the likelihood of corrosion of the reinforcing bars embedded in the concrete.

The surface electrical resistivity of the concrete was measured using a four-electrode Wenner device with equal electrode spacings of 40 mm. Saturated cylindrical specimens measuring 100 × 200 mm were used at each testing age. Four measurements were taken around the circumference of each specimen, and their average value was considered.

Fig. 8. Electrical resistivity measurement device.



	A	B1	B2	B3	B4
7 days	8.5	10.4	14.5	21.02	28.55
28 days	10.7	12.7	20.47	27.33	36
90 days	13.8	16	24.75	28.23	34.87
180 days	17	19.5	26.3	31.35	37

Fig. 9. Results of the electrical resistivity test.

4.5 | Inferential Analysis of the Experimental Results

4.5.1 | Analysis of the compressive strength test results

As shown in *Fig. 3*, the compressive strength of the specimens containing nano-silica is higher than that of specimen A, which contains no nano-silica, at all testing ages. As the particle size decreases and the material is refined to the nanoscale, a high degree of atomic surface irregularity is generated, intensifying chemical reactions. Therefore, nano-silica has high surface energy, and the atoms at its surface exhibit high activity. This enables the atoms to react with surrounding atoms, resulting in a very high pozzolanic activity of nano-silica at early ages.

Fig. 3 shows that the rate of strength development of the specimens containing nano-silica is highest up to the age of 7 days and decreases as the age of the specimens increases. Accordingly, the improvement in compressive strength of the specimen containing 8.5% nano-silica compared with specimen A is 18% and 83% at the ages of 7 and 180 days, respectively. In addition, at the ages of 90 and 180 days, only a small difference is observed between the results of the specimens containing 4.5%, 6.5%, and 8.5% nano-silica.

4.5.2 | Analysis of the tensile strength test results

In conventional concrete, it is expected that increasing the nano-silica ratio beyond 0.06 will increase tensile strength; however, at higher nano-silica ratios, the rate of increase becomes slower. This can be attributed to the pozzolanic activity of nano-silica. As the amount of nano-silica increases, a portion of the nano-silica behaves similarly to cement, causing the mixture to require more water. Therefore, this drawback must be addressed appropriately in the mixture.

4.5.3 | Analysis of the water penetration test results

As observed in *Fig. 7*, as the age of the specimens increases, the amount of water penetration decreases, indicating the more complete progress of hydration reactions and a reduction in porosity, capillary pores, and their interconnectivity. It is also observed that the addition of nano-silica is effective in reducing permeability, and increasing its amount in the mix design results in a greater reduction in permeability. This improvement can be attributed to the ability of nano-silica to fill the voids and pores within the concrete. In the mixtures containing 8.5% nano-silica, no water penetration was observed at the age of 180 days. When more than 4.5% nano-silica was incorporated into the mixtures, the penetration depth showed little change from 28 to 180 days, indicating that most of the hydration process in these specimens had been completed by the age of 28 days.

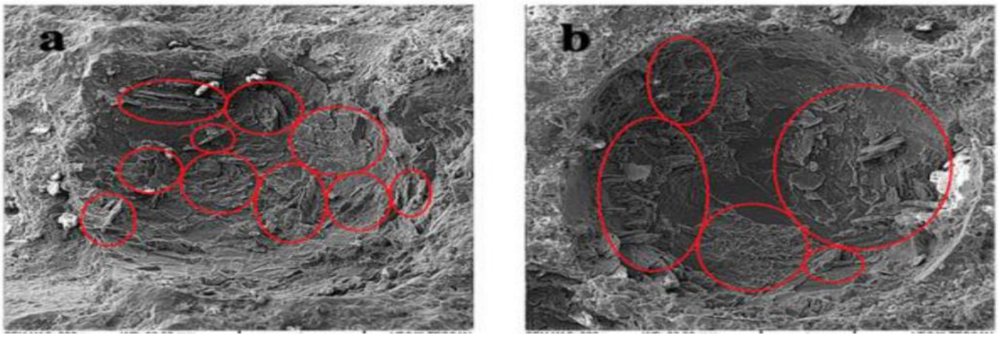


Fig. 10. Pore-filling effect when using 1% by weight of nano-clay.

4.5.4 | Analysis of the electrical resistivity results

According to *Fig. 10*, it is evident that the addition of nano-silica increases electrical resistivity, and that electrical resistivity further increases with increasing amounts of this material. As shown by the results, the addition of nano-silica increased the 180-day electrical resistivity by 120% in specimens containing nano-silica when 8.5% of the cement was replaced with this material. This increase in electrical resistivity helps prevent corrosion of the reinforcing bars in concrete.

Due to the use of concrete structures under different climatic conditions, the deterioration of these structures and, consequently, their repair and maintenance constitute one of the major concerns of experts. At the nanoscale, particles exhibit unique physical and chemical properties compared with other materials. SCC is a new technology in the construction industry that fills the formwork under its own weight, without the need for any external or internal vibrator, while maintaining its uniformity. Furthermore, nanotechnology has brought significant changes to the advanced concrete industry, and the production of nanomaterials has led to considerable improvements in the strength and durability of concrete. Therefore, this study attempted, in addition to developing a specific mix design for producing SCC, to achieve desirable mechanical properties by varying and incorporating domestically produced nano-silica powder, gel, and colloidal solution manufactured by knowledge-based companies, as well as using LECA as a replacement for a percentage of the cement and aggregate materials used in the concrete, and to investigate some of its mechanical properties. In this study, the effect of nano-silica on normal-weight and lightweight concrete containing nano-silica solution at different ages was investigated and compared with the strength properties of specimens without nano-silica.

The addition of nano-silica materials plays a significant role in increasing compressive and tensile strength. These materials also reduce the permeability of concrete, which in turn lowers moisture absorption by the concrete and enables it to act as a suitable thermal insulator against cold and heat under different climatic conditions. The addition of nanomaterials reduces ionic activity in concrete and consequently helps prevent corrosion and deterioration of the reinforcing bars.

5 | Conclusion

Based on the concrete tests, it was observed that the use of various nanomaterials in concrete has positive effects on its rheological properties. However, care should be taken because excessive use of nano-silica and nanofibers, due to their high reactivity, can reduce workability and increase the consistency and viscosity of concrete.

One of the objectives of this research was to investigate the feasibility and economic justification of using concrete containing nano-silica materials in domestic projects. As previously mentioned, the quality-related benefits of this concrete compared with conventional concrete are clearly evident. However, consideration of time and, particularly, production and implementation costs requires further investigation, control, and precision. The approach is to first make the necessary comparisons in terms of the execution of conventional concrete in order to evaluate changes in construction costs and, consequently, the overall project cost, taking into account influential factors such as labor. In the next stage, the cost of the materials required for mixing conventional concrete and nano-material-containing concrete with similar mechanical properties should be estimated.

In this research, the effect of nanomaterials on the concrete under study was investigated, and the results obtained are as follows:

I. The mechanical properties of concrete, including the compressive and tensile strengths of the produced concrete, increase with an increase in the nano-silica content up to 6%. It should be noted that excessive use of nano-silica materials can have the opposite effect.

II. To add nano-silica to the mixture of materials, it should be thoroughly mixed with water to prevent agglomeration and thereby facilitate its relatively uniform distribution throughout the concrete.

III. To add nano-calcium to the mixture of materials, it should be thoroughly mixed with cement so that it can be uniformly distributed throughout the concrete mixture.

IV. The addition of nano-silica is effective in reducing permeability and capillary water absorption, which can be attributed to the high pozzolanic activity of nano-silica, its pore-filling effect in concrete, and the elimination of fine voids within the silicate gel structure.

V. The results of the water absorption and accelerated chloride-ion penetration tests indicate that replacing part of the cement with nano-silica can improve conventional concrete from a condition of moderate or high permeability to low or very low permeability.

VI. The use of nano-silica particles in concrete should comply with existing standards, because excessive addition of nano-silica materials may have an adverse effect or produce no significant effect, resulting in additional costs.

VII. Most engineering structures, particularly underground structures, require early-age concrete strength. In the tests conducted, the increase in compressive strength during the early curing period reached approximately 70% compared with conventional concrete at 7 days, while at 28 days it reached approximately 30%.

VIII. Uniform distribution of nanoparticles in concrete is one of the challenges associated with the use of these particles. These particles commonly form agglomerated masses during their addition to concrete and are not adequately distributed throughout the mixture.

IX. The addition of silica nanoparticles reduced the cumulative amount of produced cement compared with conventional concrete over the two time periods. In fact, the role of silica nanoparticles in reducing defects present in the concrete paste demonstrates their beneficial effect in improving the concrete matrix

References

[1] Faraj, R. H., Mohammed, A. A., & Omer, K. M. (2022). Self-compacting concrete composites modified with nanoparticles: A comprehensive review, analysis and modeling. *Journal of building engineering*, *50*, 104170. https://doi.org/10.1016/j.jobe.2022.104170

[2] Afzali Naniz, O., & Mazloom, M. (2018). Effects of colloidal nano-silica on fresh and hardened properties of self-compacting lightweight concrete. *Journal of building engineering*, *20*, 400–410. https://doi.org/10.1016/j.jobe.2018.08.014

[3] Nasr, D., Behforouz, B., Borujeni, P. R., Borujeni, S. A., & Zehtab, B. (2019). Effect of nano-silica on mechanical properties and durability of self-compacting mortar containing natural zeolite: Experimental investigations and artificial neural network modeling. *Construction and building materials*, *229*, 116888. https://doi.org/10.1016/j.conbuildmat.2019.116888

[4] Hani, N., Nawawy, O., Ragab, K. S., & Kohail, M. (2018). The effect of different water/binder ratio and nano-silica dosage on the fresh and hardened properties of self-compacting concrete. *Construction and building materials*, *165*, 504–513. https://doi.org/10.1016/j.conbuildmat.2018.01.045

[5] Bernal, J., Reyes, E., Massana, J., León, N., & Sánchez, E. (2018). Fresh and mechanical behavior of a self-compacting concrete with additions of nano-silica, silica fume and ternary mixtures. *Construction and building materials*, *160*, 196–210. https://doi.org/10.1016/j.conbuildmat.2017.11.048

[6] Massana, J., Reyes, E., Bernal, J., León, N., & Sánchez-Espinosa, E. (2018). Influence of nano- and micro-silica additions on the durability of a high-performance self-compacting concrete. *Construction and building materials*, *165*, 93–103. https://doi.org/10.1016/j.conbuildmat.2017.12.100

[7] Zhang, J., An, X., & Li, P. (2020). Research on a mix design method of self-compacting concrete based on a paste rheological threshold theory and a powder equivalence model. *Construction and building materials*, *233*, 117292. https://doi.org/10.1016/j.conbuildmat.2019.117292

[8] Almohammad-albakkar, M., & Behfarnia, K. (2021). Effects of the combined usage of micro and nano-silica on the drying shrinkage and compressive strength of the self-compacting concrete. *Journal of sustainable cement-based materials*, *10*(2), 92–110. https://doi.org/10.1080/21650373.2020.1755382

[9] Hakeem, I. Y., Amin, M., Zeyad, A. M., Tayeh, B. A., Agwa, I. S., & Abu el-hassan, K. (2023). Properties and durability of self-compacting concrete incorporated with nanosilica, fly ash, and limestone powder. *Structural concrete*, *24*(5), 6738–6760. https://doi.org/10.1002/suco.202300121