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Management and Optimization of Concrete Production Using Nanostructured Materials

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Abstract

Nanotechnology is one of most active research field which has several fields in civil engineering and construction materials. However, the trends are more active in electronics, biomechanics, etc. Interest about study of nanotechnology and compound Portland cement increase so that, most research which has done these days, are about how hydration of cement in and concrete occur or the use of nano particles such as alumina and carbon nano tube and etc. Over the course of time into the 21th century, concrete has been known as one of the highest usage materials in the construction industry. As a consequence, trying to produce light concrete is an active and developing area within the new field of construction science. In spite of considerable amount of compressive strength, low tensile strength and relatively high fragility of the concrete, are limitations in using it in some parts of structures which are partially or fully faced with tensile forces. This fundamental defect of concrete in practice can be eliminated by reinforcing it using steel bars in the direction of traction forces. Having in mind that the steel bar just constitutes a small part of the whole cross section of the structure, it will not be correct to conceive of the cross section of concrete as an isotropic and homogeneous surface. In recent decades, in order to come up with the isotropic condition and decrease the fragility, weakness and retrogression of concrete, new techniques and trends of applying slender fibers running through the internal section of the bulk of concrete has become prevalent and common practice. Nano materials - compared to the normal concrete affected by Nano chemical materials with cement particles and calcium hydroxide crystals which exist in cement - have a severe effect on the performance of concrete composites.

Keywords: Concrete, Compressive strength, Tensile strength, Water absorption, Electrical resistance.

1 | Introduction

Concrete is one of the most widely used construction materials because of its versatility, availability, relatively low cost, and desirable mechanical performance. However, conventional concrete is associated with several limitations, including high cement consumption, environmental impacts, permeability, cracking, and

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deterioration under aggressive service conditions. Therefore, improving the mechanical properties, durability, sustainability, and overall performance of concrete has become an important research objective in civil and construction engineering. In particular, the growing demand for infrastructure, together with increasing environmental concerns associated with cement production and the depletion of natural resources, has encouraged researchers to develop innovative and more sustainable concrete materials [1], [2].

The performance of concrete is strongly influenced by its microstructure, including the distribution of pores, the characteristics of hydration products, and the interfacial transition zone between the cement paste and aggregates. Modification of these microstructural characteristics can improve the mechanical and durability-related properties of cement-based materials. In this context, nanotechnology has emerged as a promising approach for controlling and modifying cementitious materials at the nanoscale. Nanomaterials can act as ultrafine fillers, accelerate cement hydration, refine the pore structure, and modify the interfacial transition zone, thereby contributing to improvements in strength and durability [3], [4]. The effectiveness of nanomaterials, however, depends strongly on their type, particle size, dispersion, dosage, and interaction with other constituents of the concrete mixture [1], [3].

Among the various nanomaterials investigated for cement-based materials, nano-silica (nano-SiO₂) has received considerable attention because of its high specific surface area, filler effect, and pozzolanic activity. The incorporation of nano-silica can promote hydration reactions, fill micro- and nano-scale voids, refine the pore structure, and improve the mechanical and durability performance of concrete. Previous research has also demonstrated that nano-SiO₂ can improve the microstructure and performance of high-performance concrete, although excessive amounts may adversely affect workability and lead to difficulties in dispersion [3]. A comprehensive review of nano-SiO₂ in high-performance concrete has similarly highlighted its effects on fresh properties, mechanical performance, durability, and microstructural characteristics [5].

Other nanomaterials, including nano-TiO₂, nano-CaCO₃, graphene oxide, nano-metakaolin, and nano-based industrial or agricultural wastes, have also been investigated as potential modifiers of cementitious materials. The simultaneous use of different nanomaterials can provide synergistic effects because each material may influence hydration, particle packing, pore refinement, and mechanical performance through different mechanisms. Nevertheless, the optimum dosage of nanomaterials is a critical factor. Increasing the number of nanoparticles does not necessarily result in continuous improvement in concrete performance, since excessive nanoparticle contents may increase water demand, reduce workability, promote agglomeration, and negatively affect the uniformity of the cementitious matrix [3], [5].

Sustainability is another important aspect of contemporary concrete research. The production of Portland cement is associated with substantial energy consumption and greenhouse-gas emissions. Consequently, reducing cement consumption and incorporating industrial, agricultural, and recycled materials into concrete have become important strategies for developing environmentally friendly construction materials [2], [4]. The incorporation of waste-derived materials together with nanotechnology provides an opportunity to simultaneously address environmental concerns and improve concrete performance. For example, agricultural by-products such as Palm Oil Fuel Ash (POFA) can be processed at the nanoscale and used as a partial cement replacement, while Palm Oil Clinker (POC) can be utilized as a lightweight aggregate [6], [7]. Such approaches can reduce the consumption of conventional raw materials while enhancing selected mechanical and durability properties.

In addition to the environmental benefits, the optimization of concrete mixtures has become increasingly important because concrete performance is governed by the complex interaction of numerous mixture parameters. Traditional trial-and-error approaches can require a large number of experiments and may not efficiently identify the optimum combination of variables. Response Surface Methodology (RSM) provides a statistical and mathematical framework for evaluating the individual and interactive effects of mixture parameters and identifying optimum combinations based on multiple response variables. Its application in cement-based materials has demonstrated its capability for optimizing nanomaterial contents and achieving a balance between mechanical performance and other important properties [5], [7]. Statistical mixture design

has also been successfully applied to the development of eco-efficient Ultra-High-Performance Concrete (UHPC), demonstrating the potential of optimization techniques for reducing experimental effort while improving overall mixture efficiency [1].

Therefore, the combination of nanotechnology, sustainable materials, and statistical optimization represents a promising approach for the development of next-generation concrete. Recent studies have increasingly focused not only on achieving higher strength but also on simultaneously considering durability, workability, environmental impacts, economic efficiency, and resource utilization [6], [8], [9]. This integrated approach is particularly relevant to the development of sustainable high-performance and self-compacting concrete, where the optimum balance between fresh properties, mechanical performance, durability, and environmental considerations is essential.

2 | Literature Review

Research on nanomaterial-modified concrete has developed considerably over the past two decades, with studies focusing on the mechanisms of nanomaterials, their influence on fresh and hardened concrete properties, sustainability, and optimization of mixture proportions. Early reviews emphasized that nanotechnology can provide a new approach to modifying cement-based materials by controlling their properties at the nano- and micro-scales. Nanoparticles can improve particle packing, accelerate hydration, and refine the pore structure, resulting in enhanced mechanical and durability characteristics. However, the effectiveness of nanomaterials depends on their dosage, dispersion, particle characteristics, and compatibility with the cementitious system [3], [4].

A comprehensive review of the application of nanomaterials in concrete reported that nano-silica, nano-alumina, nano-titania, and other nanoparticles can improve the strength and durability of cement-based materials through filler, nucleation, and microstructural refinement mechanisms. The ultrafine size of nanoparticles enables them to fill voids between larger cement particles and reduce the formation and development of micro-pores. Nevertheless, the same study highlighted some limitations, particularly increased water demand, potential agglomeration, cost, and limited availability of certain nanomaterials [3].

The environmental implications of nanomaterial-modified concrete have also received increasing attention. Sustainable concrete development requires consideration of not only mechanical properties but also cement consumption, resource utilization, energy requirements, and environmental impacts. Studies concerning sustainable concrete have demonstrated that the use of alternative aggregates and supplementary cementitious materials can reduce dependence on conventional raw materials. The integration of nanomaterials with these sustainable constituents can further improve the performance of concrete while contributing to resource efficiency [2], [4].

The application of nanomaterials in UHPC has been particularly investigated because UHPC generally requires high quantities of cement and silica fume. This high binder content can increase both the cost and environmental footprint of the material. A critical review indicated that nanomaterials could contribute to the development of more eco-efficient UHPC by improving the microstructure and mechanical performance and potentially allowing optimization of the binder system [1]. Therefore, the appropriate incorporation of nanomaterials may provide a means of maintaining or improving UHPC performance while reducing its environmental burden.

The influence of different nanoparticles on cement hydration and mechanical performance was systematically investigated using RSM. In one study, nano-SiO₂, nano-TiO₂, and nano-CaCO₃ were simultaneously incorporated into Portland cement paste and their contents were optimized using RSM. The results demonstrated that the combined use of the three nanoparticles could accelerate hydration, increase early-age compressive strength, improve the pore structure, and reduce total porosity. The study also demonstrated that there was an optimum combination of nanoparticle contents rather than a simple relationship between

increasing nanoparticle dosage and performance improvement [5]. These findings highlight the importance of optimization when multiple nanomaterials are incorporated into cementitious systems.

The potential of agricultural waste-derived nanomaterials has also attracted significant attention. POFA, an agricultural by-product, can be processed into nanoparticles and used as a supplementary cementitious material. Research on lightweight concrete containing nano-POFA and POC showed that nano-POFA could improve several mechanical and durability-related indicators, while the use of POC provided a pathway for incorporating agricultural waste into lightweight concrete. RSM and Central Composite Design were employed to optimize the mixture proportions. The results demonstrated that the interaction between POC and nano-POFA significantly influenced ultrasonic pulse velocity, flexural strength, and splitting tensile strength, confirming the importance of considering interactions among mixture parameters during optimization [7].

A subsequent study extended this approach to sustainable concrete containing POC and nano-POFA and evaluated workability and strength characteristics using RSM. The results indicated that combining agricultural waste-derived materials with nanotechnology can produce concrete with competitive performance while providing economic and environmental benefits. The application of RSM allowed the researchers to identify suitable mixture proportions based on multiple performance criteria rather than relying on individual experimental comparisons [6].

Optimization of high-performance concrete using nanomaterials has also been investigated through systematic experimental approaches. Research on nano-modified high-performance concrete demonstrated that nanomaterials can be used to improve the overall performance of concrete composites. The effectiveness of these materials is strongly dependent on their dosage and interaction with the other mixture components, emphasizing the necessity of optimized mixture design rather than simply increasing nanoparticle content [8].

The use of nanomaterials in reactive powder concrete has provided further evidence of their potential for improving cement-based composites. The incorporation of metakaolin and nanomaterials into reactive powder concrete has been investigated to enhance its mechanical and microstructural performance. Such studies indicate that nanomaterials can contribute to matrix densification and improved performance through their filler and hydration-related effects [10].

Recycled materials have also become an important component of sustainable nano-modified concrete research. The optimization of recycled concrete containing nano- CaCO_3 has been investigated by considering environmental, economic, and mechanical responses simultaneously. This approach demonstrates that nanomaterials can be integrated with recycled aggregates to compensate for some of the performance limitations associated with recycled concrete while maintaining the broader objective of sustainable construction [9].

Similarly, recent research has focused on the optimization of recycled brick aggregate concrete using nano-silica and graphene oxide in OPC–LC3 binder systems. The combination of nanomaterials with alternative binder systems provides an opportunity to improve the performance of recycled aggregate concrete while reducing the environmental impacts associated with conventional cement-based materials [11]. Such multi-component systems highlight the increasing shift from single-property optimization toward multi-performance concrete design.

Graphene oxide has also emerged as a promising nanomaterial for cement-based composites. Its high surface area and distinctive physicochemical characteristics can influence the microstructure and mechanical behavior of cementitious materials. Recent research has investigated graphene oxide in self-compacting concrete with a focus on achieving a balance between durability and structural performance. The results support the potential of graphene oxide as a sustainable nano-modification strategy, although the optimum content remains an important consideration because nanoparticle agglomeration and changes in workability may occur at higher dosages [12].

The combination of different nanomaterials has recently been explored in geopolymer concrete as well. The simultaneous incorporation of graphene oxide and nano-nickel oxide has been investigated using RSM to develop multifunctional sustainable composites. This type of research demonstrates the growing importance of synergistic nanomodification, in which different nanoparticles are selected to provide complementary effects on mechanical, durability, and functional properties [13].

In addition to conventional strength-based optimization, researchers have increasingly adopted multicriteria optimization techniques. For example, roller-compacted concrete pavement containing crumb rubber and nano-silica has been optimized using a multicriteria-based approach. Such research demonstrates that sustainable concrete design should consider several competing performance indicators simultaneously rather than optimizing a single mechanical property [14]. This approach is particularly important when waste materials are incorporated because improvements in one property may sometimes be accompanied by reductions in another.

Recent developments have further emphasized the use of waste-derived nanomaterials for high-early-strength concrete. A recent RSM-based study investigated hybrid waste-derived nanomaterials and combined mixture optimization with microstructural analysis. Such research represents a transition toward multifunctional concrete systems in which waste utilization, nanotechnology, early-age performance, and microstructural modification are considered together [15].

Overall, the reviewed studies demonstrate that nanomaterials have considerable potential for improving the mechanical, durability, microstructural, and sustainability characteristics of concrete. Nano-silica, nano- CaCO_3 , nano- TiO_2 , graphene oxide, nano-POFA, nano-nickel oxide, and other nanomaterials can modify cement-based systems through mechanisms such as particle packing, pore refinement, accelerated hydration, and improvement of the interfacial transition zone [1], [3], [5]. At the same time, the literature indicates that the benefits of nanomaterials are highly dependent on their type, dosage, dispersion, and interaction with other constituents.

3 | Research Methodology

Today, concrete is recognized as one of the most widely consumed construction materials worldwide and as a major building material of the twenty-first century. Lightweight construction is one of the emerging topics in building science and has been continuously developing. This technology involves reducing the final weight of a structure through the use of modern construction techniques, new materials, and optimized construction methods. Reducing the weight of a building can not only save costs, time, and energy but also mitigate the damage caused by natural hazards such as earthquakes and minimize the adverse effects associated with excessive structural weight.

Despite its considerable compressive strength, the relatively low tensile strength and high brittleness of concrete limit its application in structural elements that are primarily subjected to tensile stresses. This fundamental drawback of concrete is generally addressed by reinforcing it with steel bars positioned in the direction of the tensile forces. Since reinforcement constitutes only a small portion of the cross-sectional area, it is not appropriate to consider a reinforced concrete section as a homogeneous and isotropic material. In order to improve the isotropic behavior of concrete and reduce its brittleness and fragility as much as possible, the use of thin and relatively long nanofibers dispersed throughout the concrete matrix has become increasingly common in recent decades.

Compared with conventional concrete, concrete containing nanomaterials exhibits significantly different performance due to the chemical interactions between nanomaterials, cement particles, and calcium hydroxide crystals present in the cement matrix. These interactions can substantially affect the behavior of the concrete composite. Therefore, the present study investigates the effects of nanosilica and fibers on the properties and performance of concrete.

3.1 | Materials

3.1.1 | Cement

Cement is a product obtained by grinding clinker, which primarily consists of calcium silicates and calcium aluminates, together with certain calcium sulfates added during the manufacturing process. It is one of the construction materials that is widely available worldwide. Calcareous materials, such as limestone and shale, and argillaceous materials, such as clay and blast-furnace slag, are the principal raw materials used in the production of Portland cement.

When cement is mixed with water, a cement paste with plastic properties is produced for a relatively short period. During this stage, the mixture can be stirred and remixed without significant adverse effects. However, as the reaction between cement and water continues, the mixture gradually loses its plastic properties. This initial stage of hardening is referred to as the initial setting time.

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

Table 1. Chemical composition of the cement used.

Chemical Component	SiO ₂	MgO	CaO	SO ₃	Fe ₂ O ₃	Al ₂ O ₃	K ₂ O	Na ₂ O
Content (%)	21.32	3.44	62.02	2.09	2.98	3.83	0.12	0.73

3.1.2 | Sand and Gravel

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 irregular, while the fine aggregate consisted of naturally occurring and crushed sand.

The aggregate gradation 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.

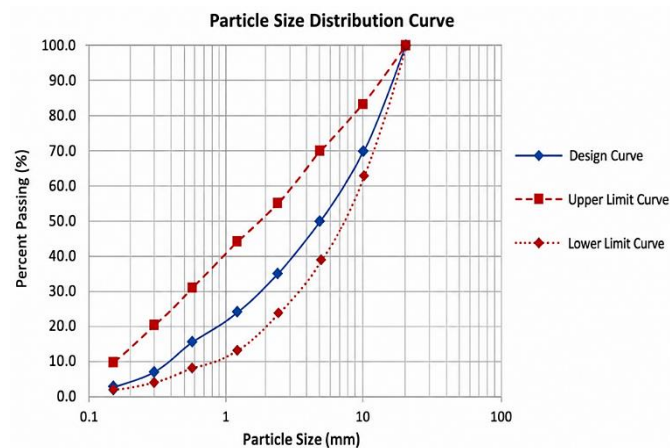


Fig. 1. Particle size distribution curve of the aggregates used in the study.

Table 2. Physical properties of the aggregates used.

Aggregate	Water Absorption (%)	Density (g/cm ³)	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 | Microsilica

Microsilica, also known as silica fume, is a by-product of electric arc furnaces generated during the production of silicon metal and ferrosilicon alloys. During the past decade, with the increasing development of self-compacting concrete, microsilica has been widely used as a filler in concrete mixtures and as an effective binding material. The filling of voids between cement particles by the very fine microsilica particles reduces the porosity of concrete and contributes to the densification of the cement matrix.

3.1.4 | Nanosilica

Nanotechnology deals with structures and materials whose dimensions are in the nanometer range, approximately one billionth of a meter. A nanostructured material is generally defined as a solid material whose constituent crystals or structural components have dimensions at the nanometer scale. The prefix nano means 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 in construction materials research.

Nanosilica can be produced over a wide range of specific surface areas, typically from approximately 50 to 1000 m²/g. In addition, various production methods are used for manufacturing nanosilica. In general, nanosilica can be classified into colloidal nanosilica, pyrogenic nanosilica, precipitated nanosilica, and nanosilica gels.

It should be noted that nanosilica with a specific surface area of 50 m²/g cannot be expected to have the same effect on concrete properties as nanosilica with a specific surface area of 1000 m²/g. Furthermore, the properties of nanosilica produced by different methods may vary considerably and consequently affect its behavior in cementitious materials. For example, some types of nanosilica are present in agglomerated form, whereas others consist of individually dispersed particles.

In the present study, colloidal silica was used as the nanosilica. The physical properties of the nanosilica solution used in the experimental program are presented in *Table 3*.

Table 3. Physical properties of the nanosilica solution used.

Property	Solid Particles (%)	Viscosity (cP)	Specific Gravity (g/cm ³)	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, with a diameter of 0.02 micron, and were manufactured by Pars Beton Company. The physical and mechanical properties of the polypropylene fibers are presented in *Table 4*.

Table 4. Properties of the polypropylene fibers.

Property	Specific Gravity (g/cm ³)	Reaction with Water	Tensile Strength	Melting Point (°C)	Length (mm)
Value	0.9	Hydrophobic	3000–4000	175	18

3.1.6 | Superplasticizer

A Superplasticizer 260, manufactured by Nam Karan Company, was used as the chemical admixture. This product is an effective high-range water-reducing admixture used for producing high-quality concrete. The admixture complies with ASTM C494 Type F and Iranian Standard 2930, Type G requirements.

Table 5. Properties of the superplasticizer.

Property	Color	pH	Specific Gravity (g/cm ³)
Value	Brown	7	1.12

3.1.7 | Water

Ordinary municipal potable water was used for mixing and curing the concrete specimens.

3.1.8 | Lightweight expanded clay aggregate

The lightweight aggregate used in this study was Lightweight Expanded Clay Aggregate (LECA) produced domestically. The aggregate had a particle size of approximately 5 mm, a density of 1225 kg/m³, and a 24-hour water absorption of 32%. LECA was used as a partial replacement for sand in the lightweight concrete mixtures.

3.1.9 | Specimen molds

For the compressive strength, ultrasonic pulse velocity, and electrical resistivity tests, 100 × 100 × 100 mm cubic steel molds were used. For the indirect tensile strength test, 100 × 200 mm cylindrical steel molds were employed. Before casting the concrete, the inner surfaces of the molds were coated with oil to prevent adhesion between the concrete and the mold surfaces and to facilitate demolding after hardening.

3.2 | Conventional Concrete Containing Nanosilica and Polypropylene Fibers

Based on the tests performed on the aggregates and cement, the cement content for the conventional concrete mixture was considered to be 436.2 kg/m³. The water-to-cement ratio obtained from the concrete mix design based on the ACI method was 0.47. After accounting for the moisture content of the aggregates, the effective water-to-cement 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. Mix proportions of conventional concrete.

Material	Gravel (kg/m ³)	Sand (kg/m ³)	Cement (kg/m ³)	W/C
Quantity	1025	660	436.2	0.38

3.3 | Lightweight Concrete Containing Nanosilica and Polypropylene Fibers

Based on the tests conducted on the aggregates and cement, the cement content of the lightweight concrete was considered to be 500 kg/m³. Due to the relatively high-water absorption of the LECA used in the experimental program, and because dry LECA was used during mixing, the water-to-cement ratio was increased to 0.50, considering the aggregate moisture condition, in order to avoid a significant reduction in slump.

The proportions of the constituent materials were determined using the absolute-volume method specified in ACI 211, taking into account the characteristics of the constituent materials and the required properties of the concrete mixture. The quantities of materials required for one cubic meter of lightweight concrete are presented in *Table 7*.

Table 7. Mix proportions of lightweight concrete.

Material	Gravel (kg/m ³)	Sand (kg/m ³)	Cement (kg/m ³)	W/C
Quantity	455	500	500	0.50



Fig. 2. Polypropylene fibers used in the experimental program.

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 was considered as the control mix consisting of conventional concrete, while the other mixes contained different replacement percentages of nanosilica. The experimental program was conducted at the ages of 7, 28, 90, and 180 days. All mixtures had 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/m ³)	Cement (kg/m ³)	Nanosilica (%)	Nanosilica Content (kg/m ³)	Superplasticizer/Cement (%)	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

4 | Analysis and Interpretation of Results

This section presents the results obtained from the experimental investigation of the concrete mixtures. Following the determination of the quantities of materials and the proportions of nanosilica and polypropylene fibers used in the mix designs, a series of tests, including compressive strength, tensile strength, water permeability, and electrical resistivity, were conducted on the prepared specimens.

The tests were performed at the ages of 7, 28, 90, and 180 days. The results of these experiments are presented and interpreted in the following sections to evaluate the effects of nanosilica and polypropylene fibers on the mechanical and durability properties of the concrete.

4.1 | Compressive Strength Test

According to 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 in a concrete mixer and thoroughly mixed. Water was then gradually added to the mixture, and mixing was continued until the fine and coarse aggregate particles were uniformly distributed throughout the concrete matrix.

Before casting the concrete, the internal surfaces of the molds were coated with a thin layer of mineral oil to prevent adhesion between the concrete and the mold walls and to facilitate the removal of the hardened specimens.

The compressive strength test is one of the fundamental tests used to determine the load-bearing capacity of concrete. Concrete specimens are subjected to an increasing compressive load until failure, and the compressive strength is determined from the maximum failure load. The compressive strength is generally calculated by dividing the failure load by the cross-sectional area over which the load is applied. This test is commonly performed at different ages following concrete curing.

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

The compressive strength of concrete is commonly reported in Megapascals (MPa) in the SI system and in pounds per square inch (psi) in the U.S. customary system. Conventional concrete generally has compressive strengths ranging from approximately 10 to 60 MPa, while specially designed high-performance concretes may achieve considerably higher strengths.

In this study, the compressive strength test 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 2000 kN-capacity compression testing machine at a loading rate of 2.5 kN/s. The testing procedure was conducted in accordance with ASTM C39.

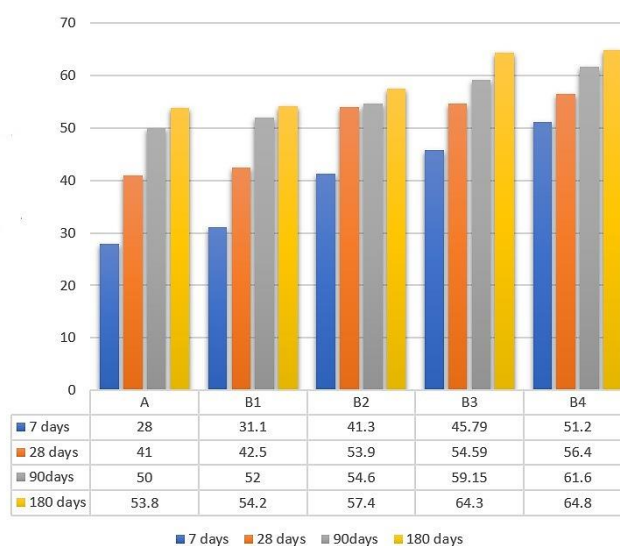


Fig. 3. Compressive strength test results (MPa).

4.2| Indirect Tensile Strength Test

The splitting tensile strength test is used to determine the tensile strength of concrete specimens prepared in cylindrical molds or obtained through core sampling. In general, the indirect tensile strength of concrete determined by the splitting method is greater than the direct tensile strength and lower than the flexural 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 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 steel plays 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 length of the cylindrical concrete specimen until failure occurs. This loading condition generates tensile stresses along the plane subjected to the applied load, accompanied by relatively high compressive stresses.

Tensile failure occurs earlier than compressive failure because the regions beneath the loading surfaces are subjected to a state of triaxial compression. Consequently, these regions can withstand substantially higher compressive stresses than those experienced in a uniaxial compressive strength test. Thin plywood bearing strips are used during loading to distribute the applied load uniformly along the length of the cylinder.

Procedure for determining the splitting tensile strength of concrete (Brazilian Test)

- I. Using a suitable device, draw diametrical lines at both ends of the specimen so that the lines lie in a plane passing through the longitudinal axis of the specimen.
- II. Determine 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.
- III. 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 cylinder.
- IV. Align the center of one of the plywood bearing strips with the center of the lower bearing support.
- V. Place the specimen on the lower bearing strip so that the marked lines at both ends of the cylinder are perpendicular to the axis of the bearing strip and positioned at its center.
- VI. After positioning the specimen, the following conditions must be satisfied:
 - *The plane passing through the two marked lines at the ends of the specimen must pass through the center of the upper bearing support.*
 - *When auxiliary bearing plates are used, the center of the specimen must be positioned directly beneath the center of the spherical loading block.*
- VII. 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.
- VIII. Record the maximum applied load measured by the testing machine and note the type and characteristics of the failure.

IX. The splitting tensile strength of the specimen can be calculated using *Eq. (1)*.

$$T = \frac{2P}{\pi ld}. \quad (1)$$

T: Splitting tensile strength of concrete, expressed in MPa.

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

L: Length of the specimen, expressed in millimeters (mm).

d: Diameter of the specimen, expressed in millimeters (mm).

The indirect tensile strength (splitting tensile strength) of the cylindrical concrete specimens was determined using specimens measuring 100×200 mm. The test was performed using the same testing machine employed for the compressive strength test, at a loading rate of 80 kN/min, in accordance with ACI requirements.

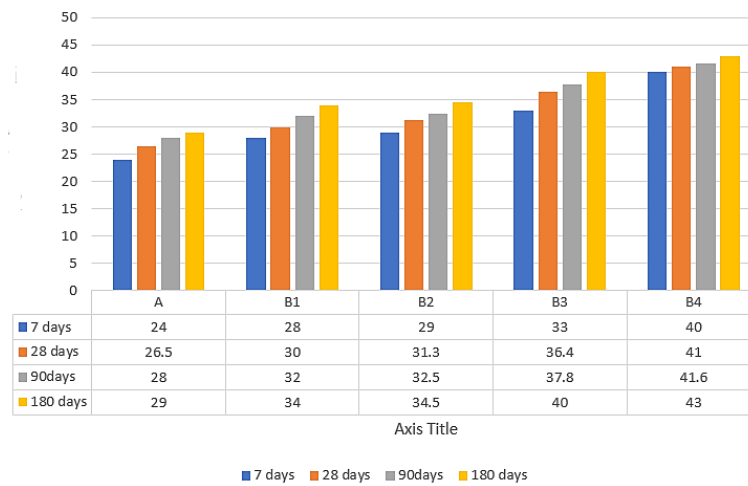


Fig. 5. Tensile strength test results (MPa).

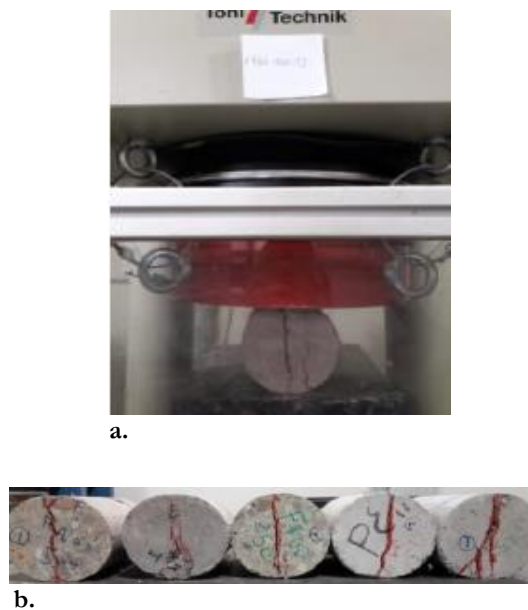


Fig. 6. Tensile strength test of the specimens; a. Specimen positioning under the loading jack, and b. Crack propagation in the specimens after testing.

4.3 | Water Penetration Test

In this test, the amount of water absorbed by the horizontal surface of a concrete specimen or a portion of a precast concrete element is determined. The water depth is kept relatively low, with a maximum height of 200 mm, so that only a limited hydraulic pressure is applied to the specimen. At different time intervals, the amount of absorbed water is measured and reported in grams or milliliters per unit surface area (m^2).

The permeability of concrete and the rate at which substances are transported through concrete depend primarily on its internal structure. To characterize the permeability of a concrete structure, its permeability coefficient must be determined. The permeability coefficient is defined as the volume of liquid or gas passing through a unit cross-sectional area per unit time under a unit hydraulic gradient. The hydraulic gradient is generally defined as the ratio of the hydraulic head, expressed as one meter of water, to the flow path, corresponding to the thickness of the concrete in meters. In practice, the permeability of concrete is commonly characterized by the coefficient of fluid flow, which is determined using standardized indices based on the penetration of water or gas.

Concrete permeability is one of the most important properties affecting concrete durability. High permeability allows water and other fluids to penetrate through the concrete and transport harmful and deteriorating substances into its internal structure. Consequently, reducing concrete permeability is an important factor in improving its durability and service life.

The water penetration test was conducted in accordance with BS EN 12390-8:2000 at the ages of 7, 28, 90, and 180 days using cubic specimens measuring 150 mm $\times$ 150 mm $\times$ 150 mm. The specimens were subjected to a water pressure of 5×10^5 Pa. After the application of water pressure, the specimens were split and the depth of water penetration was measured. The reported water penetration value for each specimen was calculated as the average penetration depth measured at different locations along the 150-mm thickness of the specimen.

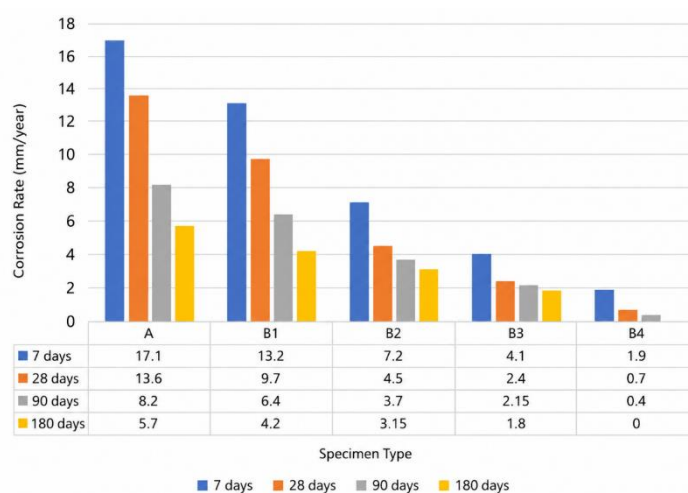


Fig. 7. Water penetration test results.

4.4 | Electrical Resistivity

Corrosion is an electrochemical process in which the reinforcing steel acts as the anode and the surrounding concrete acts as the cathode, resulting in the development of an electrical current between the reinforcement and the concrete surface. This process is associated with the movement of ions through the concrete. The easier and more rapid the ionic movement, the lower the resistance to ionic transport and, consequently, the higher the electrical conductivity of the concrete. Conversely, an increase in electrical resistivity reduces ionic mobility and, therefore, can help inhibit the corrosion of reinforcing steel embedded in concrete.

The surface electrical resistivity of concrete was measured using a four-electrode Wenner probe with an equal electrode spacing of 40 mm. Saturated cylindrical specimens measuring 100×200 mm were used at each testing age. Four measurements were taken at different locations around the circumference of each specimen, and the average of the four readings was considered as the representative electrical resistivity value for the specimen.



Fig. 8. Electrical resistivity measurement device.

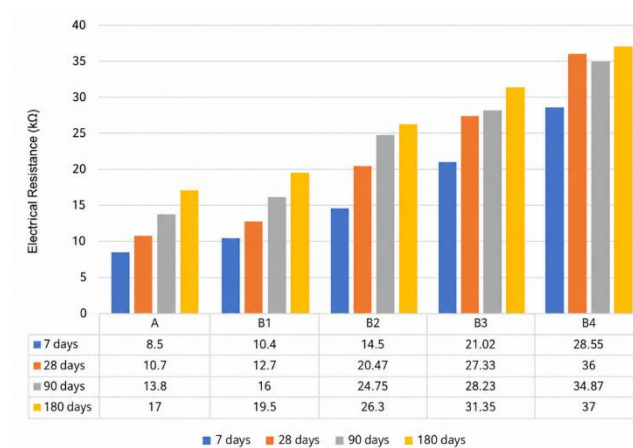


Fig. 9. Electrical resistivity test results.

4.5 | Inferential Analysis of the Experimental Results

4.5.1 | Analysis of Compressive Strength Test Results

As shown in *Fig. 3*, the compressive strength of the specimens containing nanosilica was higher than that of specimen A, which contained no nanosilica, at all testing ages. Reducing particle size to the nanoscale creates a large number of atomic-scale irregularities, which intensify chemical reactions. Therefore, nanosilica possesses high surface energy, and the atoms located on its surface exhibit high activity. This promotes reactions with surrounding atoms and consequently results in high pozzolanic activity of nanosilica, particularly at early ages.

Fig. 3 also indicates that the rate of strength development in the nanosilica-containing specimens was highest up to the age of 7 days and gradually decreased as the age of the specimens increased. For example, the improvement in compressive strength of the specimen containing 8.5% nanosilica compared with specimen A was approximately 18% and 83% at 7 and 180 days, respectively. Furthermore, at the ages of 90 and 180 days, only a small difference was observed among the specimens containing 4.5%, 6.5%, and 8.5% nanosilica.

4.5.2 | Analysis of Tensile Strength Test Results

In conventional concrete, an increase in the nanosilica content is generally expected to improve tensile strength. However, when the nanosilica content exceeds approximately 6%, the rate of tensile strength improvement becomes slower. This behavior can be attributed to the pozzolanic activity of nanosilica. As the amount of nanosilica increases, a portion of the nanosilica particles may behave similarly to cement particles, thereby increasing the water demand of the mixture. Therefore, appropriate measures, such as optimizing the water-to-binder ratio or using suitable chemical admixtures, are required to overcome this limitation.

4.5.3 | Analysis of Water Penetration Test Results

As shown in *Fig. 7*, water penetration decreases as the age of the specimens increases. This reduction indicates the progressive completion of hydration reactions and the consequent reduction in porosity, capillary pores, and their interconnectivity.

The results also demonstrate that the incorporation of nanosilica is effective in reducing water penetration. Moreover, increasing the nanosilica content in the mixture results in a further reduction in permeability. This improvement can be attributed to the filler effect of nanosilica, which enables the nanoparticles to fill the voids and pores within the concrete matrix and contributes to the formation of a denser microstructure.

For the mixtures containing 8.5% nanosilica, no water penetration was observed at the age of 180 days. Furthermore, when the nanosilica content exceeded 4.5%, only minor changes in water penetration were observed between 28 and 180 days. This behavior suggests that a substantial portion of the hydration process in these mixtures had already been completed by the age of 28 days.

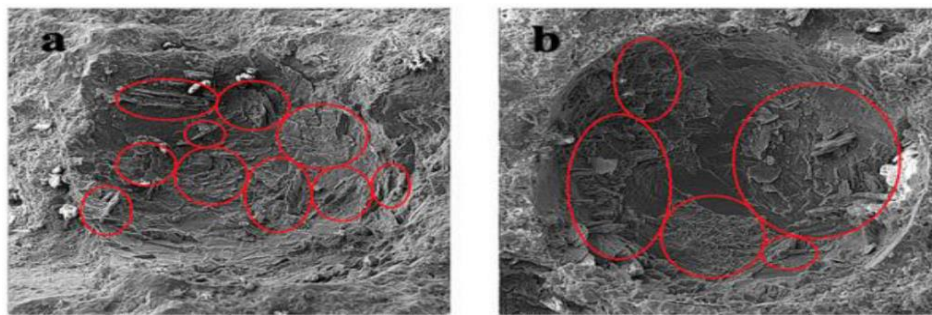


Fig. 10. Pore-filling effect of 1% nano-clay by weight.

4.5.4 | Analysis of electrical resistivity results

As shown in *Fig. 10*, the incorporation of nanosilica increases the electrical resistivity of concrete. Furthermore, increasing the nanosilica content results in a further increase in electrical resistivity. According to the experimental results, replacing 8.5% of cement with nanosilica increased the electrical resistivity of the specimens at the age of 180 days by approximately 120%. This increase in electrical resistivity can reduce ionic transport through the concrete and consequently contribute to protecting the reinforcing steel against corrosion.

4.6 | Discussion

Due to the widespread use of concrete structures under various environmental and climatic conditions, deterioration of these structures and the resulting need for repair and maintenance have become major concerns for engineers and researchers. At the nanoscale, nanoparticles exhibit unique physical and chemical properties compared with conventional materials. Self-compacting concrete is an innovative technology in the construction industry that can fill formwork under its own weight without the need for external or internal vibration while maintaining adequate homogeneity.

At the same time, nanotechnology has introduced significant developments into the concrete industry. The incorporation of nanomaterials into cementitious materials has resulted in considerable improvements in the strength and durability of concrete. Therefore, the present study aimed to develop suitable mixture proportions for concrete and to investigate the effects of nanosilica in different forms, including powder, gel, and colloidal nanosilica solutions produced domestically by knowledge-based companies. LECA was also used as a lightweight aggregate to replace a portion of the conventional aggregate materials. 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 nanosilica on both normal-weight and lightweight concrete containing nanosilica solution was investigated at different curing ages, and the results were compared with those of reference specimens without nanosilica.

The incorporation of nanosilica had a significant positive effect on the compressive and tensile strengths of concrete. In addition, nanosilica reduced concrete permeability, which consequently decreased moisture absorption and could improve the insulating performance of concrete under different climatic conditions. The incorporation of nanomaterials also reduced ionic transport through the concrete and consequently contributed to reducing the risk of corrosion and deterioration of reinforcing steel.

5 | Conclusion

Based on the experimental investigation, the incorporation of different nanomaterials into concrete produced positive effects on several concrete properties. However, particular attention should be paid to the dosage of nanosilica and nanofibers, since excessive amounts of these highly reactive materials may reduce workability and increase the consistency and viscosity of the concrete mixture.

One of the objectives of this research was to investigate the feasibility and economic justification of using nanosilica-containing concrete in construction projects. As previously discussed, the quality-related benefits of this type of concrete compared with conventional concrete can be significant. However, the effects of construction time and, particularly, the costs associated with material production and placement require further detailed investigation and economic assessment. This assessment should initially compare the construction requirements of conventional concrete with those of nanosilica-modified concrete, including changes in labor requirements and their effects on overall project costs. Subsequently, the material costs associated with producing conventional and nanosilica-containing concrete mixtures with comparable mechanical properties should be estimated.

The main findings of the present experimental study can be summarized as follows:

- I. The mechanical properties of concrete, including compressive and tensile strength, increased with increasing nanosilica content up to approximately 6%. However, excessive nanosilica content may adversely affect the performance of concrete and may result in a reduction in strength or workability.
- II. Before incorporating nanosilica into the concrete mixture, it should be thoroughly dispersed in water to prevent particle agglomeration and ensure relatively uniform distribution throughout the concrete.
- III. When nano-calcium-based materials are incorporated into the mixture, they should be properly blended with cement to achieve a uniform distribution throughout the concrete matrix.
- IV. The incorporation of nanosilica was effective in reducing concrete permeability and capillary water absorption. This improvement can be attributed primarily to the high pozzolanic activity of nanosilica, its pore-filling effect, and its ability to reduce the size and connectivity of fine pores within the cementitious matrix.
- V. The results of the water absorption and accelerated chloride-ion penetration tests indicate that partial replacement of cement with nanosilica can improve the permeability classification of conventional concrete, potentially changing it from medium or high permeability to low or very low permeability.

- VI. The dosage of nanosilica should be controlled according to relevant standards and optimized mixture proportions. Excessive nanosilica may have an adverse effect, provide no significant additional benefit, and increase the overall cost of concrete production.
- VII. Many engineering structures, particularly underground structures, require high early-age concrete strength. The experimental results indicated that nanosilica significantly increased early-age compressive strength. At 7 days, the increase in compressive strength reached approximately 70% compared with conventional concrete, while at 28 days the improvement was approximately 30%.
- VIII. Achieving a uniform distribution of nanoparticles within concrete is one of the major challenges associated with the use of nanomaterials. Due to their very small particle size and high surface energy, nanoparticles tend to agglomerate during mixing and may therefore not be uniformly dispersed throughout the concrete matrix.
- IX. The incorporation of nanosilica reduced the cumulative amount of charge passed compared with conventional concrete during the specified testing periods. This finding demonstrates the role of nanosilica in reducing defects and discontinuities within the cement paste and consequently improving the resistance of concrete to the penetration of aggressive ions.

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