

**INVESTIGATING THE EFFECTS OF NANOSILICA ON SOME
MECHANICAL PROPERTIES OF CONCRETE**

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PLAGIARISM

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DEDICATION

I dedicate this project work to Almighty God whose grace and guidance made it possible for me to reach this phase of my academic pursuit.

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ABSTRACT

This study investigated the effect of nanosilica (NS) as a partial replacement for ordinary Portland cement (OPC) on the mechanical and durability properties of concrete. The aim was to assess the suitability of nanosilica in improving concrete performance and to determine its optimum replacement level for sustainable construction applications in Nigeria.

Concrete was produced using a nominal mix ratio of 1:2:4 and a constant water–cement ratio of 0.5. Nanosilica was used to replace cement at levels of 0%, 1%, 2%, and 3% by weight. Tests carried out included slump test, setting time determination, compressive strength test, flexural strength test, and water absorption test. Statistical analysis of the results was performed using one-way analysis of variance (ANOVA).

Results showed that workability increased with increasing nanosilica content, while both initial and final setting times decreased. Compressive and flexural strengths increased up to an optimum nanosilica content of 2%, where 28-day values of 24.4 N/mm² and 5.25 N/mm² were recorded, compared to 22.5 N/mm² and 4.67 N/mm² for the control mix. Water absorption reduced to 7.3% at 2% nanosilica replacement compared to 9.7% for the control, indicating improved durability. ANOVA results showed no significant differences in compressive strength, flexural strength, and workability ($p > 0.05$), while setting time showed significant variation ($p < 0.05$). The study concluded that 2% nanosilica replacement provided the best overall performance and is recommended for producing stronger and more durable concrete.

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ACRONYMS

OPC- Ordinary Portland Cement

NS- Nanosilica

BS- British Standard

BS EN- British Standard European Norm

ASTM- American Society for Testing and Materials

w/c- Water-to-Cement Ratio

ANOVA- Analysis of Variance

SD- Standard Deviation

CHAPTER ONE

INTRODUCTION

1.1 Background of study

Concrete is the most extensively used construction material across the world because of its adaptability, affordability, durability, and ability to be shaped into various structural forms (Neville, 2011). It plays a vital role in the development of buildings, bridges, highways, tunnels, and other forms of infrastructure, primarily due to its capacity to withstand high compressive stresses.

However, despite these advantages, conventional concrete also has inherent weaknesses. Its low tensile strength often leads to cracking when subjected to bending or tension. These cracks not only reduce structural appeal but also allow the entry of water and harmful substances such as chlorides, sulfates, and carbon dioxide, which accelerate steel corrosion and reduce service life (Mehta & Monteiro, 2014). In addition, inadequate mixing or curing can increase porosity, further diminishing durability.

To address these shortcomings, research has shifted towards modifying concrete through the use of supplementary cementitious materials (SCMs) and advanced technologies that enhance performance. One of the most promising innovations in this regard is nanotechnology, which deals with materials at the nanometre scale (1–100 nm). At this level, materials display unique chemical and physical characteristics arising from their large surface area and reactivity (Sanchez & Sobolev, 2010).

Among the various nanomaterials explored, nanosilica (NS) has attracted significant attention. Its inclusion in cement-based composites enhances strength and durability by filling micro-pores and promoting pozzolanic reactions that form additional calcium silicate hydrate (C–S–H) gel (Chekravarty et al., 2022). Nanosilica particles, which are typically amorphous and extremely fine, act as fillers that reduce void spaces between cement grains, resulting in a denser microstructure.

Furthermore, nanosilica reacts with calcium hydroxide—a byproduct of cement hydration that contributes little to strength—to form more C–S–H gel, which strengthens the concrete matrix and improves resistance to chemical attack (Said et al., 2012). This dual action of pore filling and secondary hydration makes nanosilica a valuable additive for producing high-performance, durable, and sustainable concrete suitable for modern construction needs.

1.2 Statement of problem

Cement remains one of the most essential construction materials worldwide due to its versatility and strong binding properties. Global production now exceeds 4 billion tonnes annually, a process that consumes vast energy resources and emits large quantities of carbon dioxide — the leading greenhouse gas responsible for climate change (Bhatta et al., 2022). Reducing the cement content in concrete mixtures has therefore become a major environmental and economic priority.

Despite its critical importance in construction, conventional concrete still exhibits mechanical limitations that challenge engineers and material scientists. Its inherently low tensile strength makes it prone to cracking, which weakens structures and allows the ingress of moisture and aggressive ions. Over time, this can cause corrosion of steel reinforcement, reduce cross-sectional area, and ultimately lead to structural deterioration.

Researchers have sought various solutions by incorporating additives and supplementary materials to improve concrete's mechanical and durability properties. Traditional supplementary cementitious materials such as fly ash, silica fume, and slag have shown benefits, but recent developments in nanotechnology offer new opportunities for designing high-performance concrete with enhanced characteristics.

Although nanosilica has shown strong potential as a cement replacement material, several critical issues remain unresolved. Determining the optimal dosage that maximizes strength while maintaining workability is one major challenge. Excessive nanosilica can cause particle agglomeration, which reduces dispersion efficiency and may impair performance. Additionally, achieving a uniform distribution of nanosilica within the cement matrix requires careful mixing procedures.

While nanosilica has been widely studied internationally, its practical use in Nigeria's construction industry is still limited. Questions remain about its compatibility with locally produced Ordinary Portland Cement (OPC) and its performance under Nigeria's environmental and climatic conditions. Furthermore, there is insufficient research on the optimum nanosilica dosage suited for local materials.

Another limitation in existing studies is the focus on early-age strength development, with relatively little attention paid to long-term durability under variable environmental exposure. These gaps highlight the need for locally relevant, comprehensive research that evaluates nanosilica's influence on key concrete properties such as strength, workability, and water absorption under controlled laboratory conditions.

1.3 Aim and objectives

The aim of this research is to evaluate the effects of nanosilica incorporation in some properties of concrete. The objectives are to:

- i. Formulate a cement blend comprising OPC and NS at 0%, 1%, 2% and 3% respectively.
- ii. Determine the workability of nanosilica concrete and plain concrete using slump test.
- iii. Investigate the setting time of nanosilica replacement with cement in comparison to the control ordinary portland cement.
- iv. Evaluate compressive and flexural strength of concrete with nanosilica in comparison to plain concrete.
- v. Assess the durability performance of nanosilica concrete via water absorption and chloride ingress test.

1.4 Scope of the study

This research is confined to the experimental assessment of concrete incorporating nanosilica as a partial replacement for cement. The study is primarily focused on evaluating some of the mechanical properties, specifically workability, setting time, compressive strength, flexural strength, and water absorption test under controlled laboratory conditions. The British standardized procedures will be followed for mixing, casting, curing, and testing to ensure consistency and reliability of results. Additionally, economic analyses, life cycle assessments, and field-scale validations are beyond the scope of this study. Nonetheless, the findings from this work are expected to provide critical baseline information for further investigations and practical applications of nanosilica in enhancing concrete performance. The percentage variation for this

study will be confined to 0% (control), 1%, 2%, and 3% nanosilica as a partial replacement of cement content by weight accordance to past scientific findings.

1.5 Justification of the study

Concrete remains the most widely used construction material globally; however, its intrinsic limitations—particularly low tensile strength, high cracking propensity, and susceptibility to water ingress leading to reinforcement corrosion—continue to undermine structural durability and longevity (Neville, 2011). These deficiencies not only compromise the structural integrity of concrete-based structures but also result in increased maintenance costs and reduced service life, posing significant economic and environmental challenges within the construction industry. Consequently, there is a critical need for material innovations that can enhance concrete performance and durability. Nanosilica has gained considerable attention as a nanomaterial with the potential to address these challenges. Its ultra-fine particle size and high surface reactivity significantly influence the hydration kinetics of cementitious systems. The incorporation of nanosilica leads to a densified microstructure, refinement of pore networks, accelerated formation of calcium silicate hydrate (C-S-H), and a consequent reduction in permeability and porosity (Said et al., 2012; Jo et al., 2007). Furthermore, the partial replacement of cement with nanosilica offers an avenue for more sustainable construction practices. Given that the cement industry is responsible for approximately 7–8% of global CO₂ emissions (Li et al., 2004), the use of nanosilica as a supplementary cementitious material (SCM) aligns with efforts to reduce environmental impact. This approach not only decreases the demand for clinker but also promotes the development of greener and more resource-efficient concrete without compromising, and potentially enhancing, structural performance.

This study is academically significant as it seeks to the understanding of nanosilica's role in improving some mechanical, and durability properties of concrete such as, setting time, workability, compressive strength, flexural strength and water transport mechanism of NS and conventional concrete. It also contributes to the broader discourse on sustainable material development in civil engineering, aiming to bridge the gap between performance enhancement and environmental responsibility in concrete technology.

CHAPTER TWO

LITERATURE REVIEW

2.1 Review of related works

A wide array of scientific investigations has been conducted over the past two decades to evaluate the incorporation of nanosilica into cementitious construction materials. These studies collectively emphasize the notable improvements that nanosilica brings to the mechanical performance, durability, and internal microstructure of concrete. Researchers widely agree that due to its nanometric particle size and exceptionally high pozzolanic reactivity, nanosilica interacts vigorously with hydration products, particularly calcium hydroxide, leading to the formation of additional calcium-silicate-hydrate (C-S-H) gel. This reaction not only contributes to early strength development but also leads to a denser, more refined microstructure, which enhances the material's resistance to environmental degradation.

Recent studies have shown that replacing a small portion of cement with nanosilica can significantly enhance concrete's strength characteristics. For example, Rakesha et al. (2024) evaluated M25-grade concrete with 0.5% to 2% nanosilica replacing cement and found that 1.5% gave the best improvements in compressive, tensile, and flexural strength due to better packing and the formation of additional C-S-H gel (IRJAEH, 2024).

Similarly, Adamu et al. (2021) carried out research on normal-strength concrete in Nigeria where 1.5% nanosilica was used to replace cement. The results showed a 30% rise in compressive strength and a 23.3% increase in tensile strength after 7 days of curing. Microscopic analysis confirmed that nanosilica improved the concrete matrix by increasing the production of calcium silicate hydrate, thus making the structure denser and stronger (Ajol, 2021).

Additionally, research by Gonzalez-Corrochano et al. (2023) evaluated the use of nanosilica in concrete with recycled fine aggregates. Their findings showed that nanosilica not only boosted mechanical strength but also improved the material's resistance to high temperatures, making it suitable for structures exposed to heat (Springer, 2023).

While these improvements are clear, the effectiveness of nanosilica is highly dependent on the dosage. Most studies agree that an optimal range lies between 1.5% and 3% replacement by weight of cement. Replacements beyond this range may lead to clumping of particles, which can impair workability and even reduce strength if not well dispersed (Wiley, 2022).

According to the setting time investigation by Zang et al. (2012), incorporating 2% nanosilica resulted in a reduction of the initial and final setting times by 95 minutes and 105 minutes, respectively, compared to the conventional cement mix. In comparison to the control sample, incorporating nano-silica accelerated the initial setting time of the cement paste to 30 minutes with 1% nano-silica and to 100 minutes with 2% nano-silica. Additionally, the setting times for mixes containing 0.5% and 1% nano-silica were reduced by 15 minutes and 10 minutes, respectively, relative to the control. However, the mix with 2% nano-silica exhibited a 20-minute increase in setting time, attributed to higher water absorption, as reported by (Kotsley, 2017).

The carried out by (Kumar and Singh, 2018), showed that incorporating up to 3.5% nano-silica enhances the strength of cement mortar with a water-to-binder ratio of 0.35. Nano-silica particles, ranging in size from 0.2 to 0.3 microns, were used to replace cement at varying proportions of 1%, 2%, 3%, 4%, 5%, and 6% by weight. The findings revealed that the setting time increases as the nano-silica content rises.

In a study conducted by Said et al., (2012), nanosilica was employed as a partial substitute for cement at replacement levels of 1%, 3%, and 5% by weight. The results demonstrated notable improvements in compressive strength, particularly at the 3% replacement level. The researchers attributed these enhancements to the nanosilica's pozzolanic activity, which promotes the formation of additional calcium silicate hydrate (C-S-H) gel. Additionally, nanosilica contributed to refining the pore structure by filling microvoids in the cement paste, thereby improving the overall density and integrity of the matrix.

Zhuang, C. and Chen, 2019 investigated the addition of nano-SiO₂ is beneficial to the compressive strength of concrete. The compressive strength of nano-SiO₂ modified concrete increases with increased nano-SiO₂ content toward the threshold content. Above the threshold value, a higher amount of nano-SiO₂ leads to a decrease of the compressive strength. Nano-silica concrete with a nano-SiO₂ content of 1.5% provides the highest compressive strength. The compressive strength of Nano-silica modified concrete increases by 16%-25% at 7 days and 12%-17% at 28 days,

Similarly, Jo et al. (2007) explored the performance of high-performance concrete mixtures in which nanosilica was used to replace cement in quantities up to 10%. Their findings revealed that a 6% cement replacement with nanosilica yielded the most significant improvements in both compressive and flexural strength. This was primarily due to the dual role of nanosilica: first, as a highly reactive pozzolanic material contributing to secondary hydration reactions, and second, as an effective filler that reduced the porosity and improved the interfacial transition zone (ITZ) between the cement paste and aggregates.

In another important study, Said and Zeidan (2009) investigated the early-age strength development and microstructure of concrete containing nanosilica as a partial replacement for cement. Their experiments indicated that substituting 2% to 4% of cement with nanosilica resulted in substantial increases in early compressive strength and reduced total porosity. However, when the replacement level exceeded 5%, the performance gains began to diminish. This decline was likely due to poor dispersion and agglomeration of nanoparticles, which can lead to defects and inconsistencies within the matrix.

Further research by Givi et al. (2010) evaluated the impact of cement replacement with nanosilica at levels between 1% and 3% on the mechanical performance of concrete. Their study concluded that 2% replacement yielded optimal results in terms of compressive, tensile, and flexural strengths. They also emphasized the importance of proper dispersion techniques, noting that the high surface area of nanosilica can negatively affect workability if not adequately managed, potentially leading to issues such as rapid slump loss and mix stiffening.

In addition, Kumar et al. (2016) examined the influence of nanosilica as a cement substitute under various curing regimes. Their experimental findings showed that concrete mixes containing 1.5% to 2% nanosilica not only demonstrated improved compressive strength but also exhibited superior resistance to water penetration and reduced capillary porosity. The researchers highlighted the critical role of mix design optimization and effective nanoparticle dispersion in realizing these benefits.

Beyond improvements in strength, nanosilica also positively affects durability. For instance, Kumar et al. (2022) examined high-performance concrete with copper slag and observed that a 2%

nanosilica replacement increased compressive and tensile strength over a 90-day period. This enhancement was linked to a more compact microstructure and smaller pore sizes (Wiley, 2022).

Collectively, these studies establish that the partial replacement of cement with nanosilica—typically within the range of 1% to 6% by weight—can lead to substantial improvements in concrete’s mechanical properties and durability. The enhancements are primarily attributed to the increased production of C-S-H through pozzolanic reactions and the nanoscale particle packing effect, which leads to a denser and more refined microstructure. However, the effectiveness of nanosilica is highly dependent on proper dispersion techniques and careful mix proportioning. Excessive replacement levels or poor mixing can result in particle agglomeration, reduced workability, and, ultimately, a decline in performance. In the research carried out by Shoeib and Mohamed, (2014) the percentage replacement of NS was 1.00%, 2.00% and 3.00% of cement content. Their result showed that, there was a significant increase in the flexural and compressive strength of concrete and the optimal dosage was at 3%.

An experimental study was done, designed to examine the water permeability and setting time of Portland cement mortar with nano-SiO₂ admixed at 0.5, 1, 1.5, and 2 wt% of cement. The percentage, velocity, and coefficient of water absorption tests results showed that the incorporation of nano-SiO₂ particles improved the water penetration resistance of the binary-blended concrete. Such improvements were especially significant when using 2 wt% of nano-SiO₂. The experimental results revealed that the admixing of nano-SiO₂ particles not only led to denser cement mortar but also changed the morphology of cement hydration products. (Givi et al., 2011).

According to Kashyap et al. (2023), reported that incorporating 1–3% nanosilica (NS) into concrete resulted in a consistent reduction in water absorption, as observed from the water

absorption tests. This indicates that the partial replacement of cement with nanosilica enhances the concrete's resistance to water ingress. The improvement is attributed to the nanoparticles' ability to refine the pore structure, effectively blocking capillary pathways and limiting moisture penetration within the concrete matrix. The water cement ratio was 0.4.

Rajput and Pimplikar (2022), found that increasing nanosilica content in M30 and M40 concretes significantly reduced water absorption. For M30, water absorption decreased by 5.15%, 30.15%, and 35.66% with 1%, 2%, and 3% NS, respectively. Similarly, M40 showed reductions of 1.47%, 30.40%, and 58.97% for the same NS levels compared to the control mix. From the Durability test carried out by (Rekesha et al., 2024), incorporating nanosilica into concrete significantly reduced the water absorption of about 1.26%. The mixing proportion in their experiment was (0.5%, 1.0%, 1.5%, and 2.0%) replacement of cement.

Thus, the existing body of research supports the potential of nanosilica as an effective cement replacement material, provided that it is used judiciously within optimal dosage limits and with attention to processing techniques. These findings are significant for both performance enhancement and environmental sustainability in concrete production.

2.2 Concrete

Concrete is one of the most widely used construction materials because of its strength, availability, and adaptability. It is primarily made from a mixture of cement, water, and fine and coarse aggregates that, when combined, form a compact, stone-like mass through the process of hydration (Neville, 2011). During hydration, chemical reactions occur between water and cement to produce compounds such as calcium silicate hydrate (C-S-H), which gives concrete its mechanical strength and durability (Taylor, 1997).

Concrete performs exceptionally well under compression, making it suitable for structural components like beams, columns, slabs, and foundations. However, it has low tensile strength and brittle behaviour, which is why reinforcement is often required to resist cracking and tension forces (Mehta & Monteiro, 2014). Its performance characteristics depend on several factors, including the water–cement ratio, aggregate properties, cement composition, and curing environment (Mindess et al., 2003).

A key microstructural feature of concrete is the interfacial transition zone (ITZ), located between the cement paste and aggregate surfaces. This region usually exhibits higher porosity and lower density compared to the surrounding matrix, making it a common site for crack initiation and chemical attack (Scrivener & Gartner, 2018). Improving the ITZ through appropriate mix design and the use of supplementary materials helps enhance the overall strength, durability, and service life of concrete structures.

2.2.1 Constituents of concrete

Concrete is a versatile and widely used composite material composed primarily of a cementitious binding medium in which various sizes of aggregates—either coarse or fine—are embedded (Mehta and Monteiro, 2011). The interaction between the binder and the aggregates results in a solid, stone-like material that possesses significant compressive strength, making it suitable for a wide range of structural and non-structural applications.

Depending on its density, or unit weight, concrete can be broadly categorized into three main types: normal-weight, lightweight, and heavyweight concrete. Normal-weight concrete, the most common variety used in general construction, typically consists of natural sand along with gravel or crushed stone as aggregates. This type of concrete has an average density of approximately 2400

kg/m³ and is widely adopted for buildings, bridges, pavements, and other standard infrastructure projects (Kett, 2009).

In cases where structural weight needs to be minimized without significantly compromising strength, lightweight concrete is preferred. This variant usually has a density of less than 1800 kg/m³ and is produced by using low-density aggregates, either naturally occurring (such as pumice) or manufactured through pyro-processing methods (Kett, 2009). Reducing weight makes it ideal for applications such as precast panels, roofing elements, and high-rise structures where dead load reduction is beneficial.

On the opposite end of the spectrum lies heavyweight concrete, which is designed to serve specialized roles—particularly in shielding applications such as nuclear facilities or medical radiation therapy rooms. This type of concrete is made with high-density aggregates, such as barite, magnetite, or hematite, resulting in a material with a unit weight exceeding 3200 kg/m³ (Kett, 2009).

Concrete is also classified based on its compressive strength, a critical parameter in structural engineering. It can be grouped into three general strength categories:

- a.** Low-strength concrete, with compressive strength below 20N/mm², is typically used in non-load-bearing elements or temporary structures.
- b.** Moderate-strength concrete, ranging from 20 to 40N/mm², commonly referred to as ordinary or normal concrete, is the most widely used for standard structural components such as beams, columns, slabs, and foundations.
- c.** High-strength concrete, with compressive strength exceeding 40N/mm², is generally employed in demanding construction projects like high-rise buildings, long-span bridges,

and heavily loaded industrial floors, where enhanced load-bearing capacity is required (Kett, 2009).

2.2.2 Aggregates

Aggregates are inert, granular materials commonly used in the production of concrete and other construction composites (Neville, 2011). These include natural materials such as sand, gravel, and crushed stone, as well as recycled aggregates. Aggregates typically constitute between 60% and 75% of the total volume of concrete, serving to reduce shrinkage, enhance durability, and improve mechanical strength (Mehta & Monteiro, 2014).

According to BS EN 12620:2013, aggregates are classified as either fine aggregates, which pass through a 4 mm sieve (e.g. natural sand), or coarse aggregates, which are retained on a 4 mm sieve (e.g. gravel or crushed rock). The physical properties of aggregates—such as particle size distribution, shape, surface texture, and grading—play a crucial role in determining the workability, compactability, and strength development of concrete (Mindess et al., 2003).

Well-graded and clean aggregates promote better particle packing and ensure improved bonding with the cement matrix, leading to higher strength and better durability of the hardened concrete (Neville, 2011). The importance of selecting appropriate aggregates, in both type and proportion, is emphasised in BS 8500-1:2015, which outlines guidance for their use in structural and non-structural applications.

Thus, a thorough understanding of aggregate characteristics and their interaction with other components is essential for producing high-performance, cost-effective, and durable concrete structures (Mehta & Monteiro, 2014).

2.2.3 Fine aggregates

Fine aggregates are materials that pass through a 4 mm sieve, typically consisting of natural sand or crushed rock fines, as specified in BS EN 12620:2013. They play a key role in filling voids between coarse aggregates and contribute to the workability, cohesiveness, and surface finish of fresh concrete (Mehta & Monteiro, 2014). The properties of fine aggregates—such as grading, cleanliness, shape, and surface texture—significantly influence the water demand, strength development, and bond with the cement paste (Mindess et al., 2003).

The use of clean, well-graded fine aggregates improves the uniformity and stability of the mix, reducing issues such as segregation and bleeding (Neville, 2011). Standards such as BS EN 13139:2002 (Aggregates for mortar) and BS EN 12620:2013 (Aggregates for concrete) provide specifications to ensure quality, suitability, and consistency in their application.

Proper selection and proportioning of fine aggregates are essential for producing concrete that is not only durable and economical, but also consistent in performance across various structural and environmental conditions.

2.2.4 Coarse aggregates

Coarse aggregates are granular materials that are retained on a 4 mm sieve, commonly derived from crushed stone, gravel, or recycled concrete, as defined in BS EN 12620:2013. They form the backbone of concrete by contributing significantly to its compressive strength, stiffness, and load-bearing capacity (Mehta & Monteiro, 2014).

The performance of coarse aggregates in concrete is influenced by their particle size, shape, surface texture, density, and strength. These characteristics affect not only the workability and compaction of fresh concrete but also its durability and mechanical behaviour once hardened (Neville, 2011).

While angular, rough-surfaced aggregates enhance mechanical interlock and bond with the cement paste, they may reduce the ease of mixing and placing due to higher internal friction (Mindess et al., 2003).

Using well-graded and clean coarse aggregates improves packing density, reduces void content, and limits the amount of cement paste required to fill gaps—resulting in stronger, more durable, and cost-effective concrete. Standards such as BS EN 12620:2013 provide detailed specifications to ensure the quality and suitability of coarse aggregates for structural and non-structural concrete applications.

2.2.5 Cement

Cement serves as the principal binding material in concrete, responsible for holding the fine and coarse aggregates together once hydration occurs. It is a finely ground, inorganic substance that, when mixed with water, undergoes chemical reactions to form a hard, stone-like mass with significant strength and durability (Neville, 2011).

Among the different types of cement, Ordinary Portland Cement (OPC) is the most widely used in the construction industry due to its versatility, availability, and ability to develop adequate strength under various environmental conditions (Mindess et al., 2003). OPC is primarily composed of four main compounds: tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and tetracalcium aluminoferrite (C_4AF). These compounds are responsible for different aspects of cement performance — C_3S and C_2S mainly contribute to strength development, while C_3A and C_4AF influence setting time and resistance to sulfate attack (Taylor, 1997).

The hydration process begins immediately after water is added to cement, producing various compounds such as calcium silicate hydrate (C–S–H) and calcium hydroxide (CH). The C–S–H gel forms the main binding phase, providing strength and cohesion to the hardened concrete, whereas CH contributes little to strength and may increase permeability (Mehta & Monteiro, 2014). The overall rate and extent of hydration depend on factors such as the fineness of the cement, the water–cement ratio, and the curing environment.

To enhance performance or meet specific project requirements, other forms of cement such as Portland Pozzolana Cement (PPC), Rapid Hardening Cement, and Sulphate-Resisting Cement are used in practice (Shetty, 2009). These varieties differ in composition and hydration characteristics but serve the same primary function — to provide a strong and durable matrix capable of binding aggregates together effectively.

Proper storage and handling of cement are crucial to maintain its reactivity. Exposure to moisture or humidity can cause partial hydration before use, leading to strength loss and poor performance (Neville, 2011). Hence, cement should be kept in dry, well-ventilated spaces and used within its shelf life to ensure consistent results in concrete production.

2.2.6 Water

Water is essential in concrete production as it initiates the hydration process that binds cement and aggregates into a solid mass (Neville, 2011). The quality of water greatly affects concrete's strength and durability; it should therefore be clean and free from substances like acids, salts, or oils that could disrupt hydration or cause corrosion (Mehta & Monteiro, 2014). Generally, water suitable for drinking is also appropriate for mixing and curing concrete (BS EN 1008:2002).

The water–cement ratio (w/c) is a key factor influencing strength and permeability. Lower ratios reduce porosity and enhance strength, while excessive water leads to a weaker, more porous structure (Mindess et al., 2003). Adequate curing water must also be provided to sustain hydration and prevent early shrinkage (Taylor, 1997).

2.3 Some properties of concrete

- a. **Workability:** Workability refers to how easily fresh concrete can be mixed, placed, compacted, and finished without segregation or bleeding (Shetty, 2009). It is a critical property that influences construction efficiency and the final structural quality. Factors such as the water-to-cement ratio, aggregate characteristics, admixtures, and ambient conditions affect workability. According to Mehta and Monteiro (2014), maintaining good workability ensures proper compaction, reduces the risk of honeycombing, and improves strength development.
- b. **Compressive Strength:** Compressive strength is the most fundamental mechanical property of concrete, indicating its capacity to withstand axial loads without failure. It is typically assessed using cube specimens tested after 28 days, in accordance with BS EN 12390. This parameter serves as a primary criterion in structural design. British Standards, such as BS EN 1992-1-1 (Eurocode 2), underline the importance of compressive strength in influencing design choices and its strong correlation with the durability and long-term performance of concrete structures.
- c. **Tensile Strength:** Tensile strength refers to concrete’s resistance to forces that try to pull it apart. Though much lower than its compressive strength—usually around 8–15%—it is crucial for controlling cracking and improving durability. Since concrete is inherently weak in tension, reinforcement is necessary in structural applications. Mindess, and Darwin

(2003) explained that the tensile capacity affects crack width and spacing under service loads, making it vital for structural integrity.

- d. Flexural Strength:** Flexural strength, often referred to as the modulus of rupture, represents concrete's capacity to resist bending stresses and is especially relevant in structural elements such as slabs and pavements where flexural action predominates. As per BS EN 12390-5, flexural strength is determined using beam specimens under third-point loading. Typically, it ranges from 10% to 20% of the compressive strength, influenced by factors such as mix composition and curing conditions. According to Neville (2011), flexural strength also provides valuable insight into the tensile behaviour of concrete, particularly in beam applications.
- e. Water Absorption:** Water absorption reflects the porosity and permeability of concrete, influencing its susceptibility to deterioration. As explained by Mehta and Monteiro (2014), reducing water absorption is essential for enhancing long-term performance, especially in marine or chemically aggressive environments.
- f. Hydration:** Hydration is the chemical reaction between cement particles and water that forms calcium silicate hydrate (C-S-H), the primary binding compound in concrete. This reaction is responsible for the setting and hardening process, and its rate and completeness directly affect strength development. Mehta and Monteiro (2014) describe hydration as a complex, multi-stage process that begins with an initial reaction, followed by dormant, acceleration, deceleration, and steady-state phases, all of which influence mechanical performance and heat evolution.
- g. Concrete curing:** Curing involves maintaining adequate moisture, temperature, and time conditions to allow the hydration of cement to proceed effectively. Proper curing enhances

the strength and durability of concrete, while inadequate curing can lead to surface cracking, reduced strength, and lower resistance to environmental attacks. Neville (2011) notes that a significant portion of potential strength may be lost if concrete is not cured appropriately in its early stages.

2.4 Workability of concrete

Workability describes how easily fresh concrete can be handled during mixing, transportation, placement, and compaction, without the risk of segregation or excessive bleeding. It plays a vital role in ensuring that the concrete achieves full compaction and a uniform finish, particularly in elements with dense reinforcement or intricate formwork (Mehta & Monteiro, 2014). Adequate workability improves the overall quality and performance of the concrete structure.

This property is influenced by several factors, including the water-to-cement ratio, the type and grading of aggregates, the use of chemical admixtures, and environmental conditions such as temperature and humidity (Neville, 2011). While adding more water can increase workability, it may also weaken the concrete by increasing its porosity. For this reason, admixtures like plasticizers and superplasticizers are often used to enhance workability without compromising strength (Mindess, Young & Darwin, 2003)

- i. **Water-Cement Ratio:** One of the most critical factors is the water-to-cement ratio. Increasing the amount of water enhances fluidity and improves workability. However, excessive water leads to higher porosity and reduced strength in the hardened concrete (Neville, 2011).
- ii. **Aggregate Characteristics:** The size, shape, and grading of aggregates play a significant role. Rounded aggregates reduce internal friction, thus improving workability, while

angular aggregates increase resistance to flow. Well-graded aggregates, which include a range of particle sizes, help in achieving better packing and reduce voids, enhancing the cohesiveness of the mix (Mehta & Monteiro, 2014).

- iii. **Cement Content:** A higher cement content increases the paste volume, which acts as a lubricant between aggregates and improves the mix's workability. However, overly rich mixes may also lead to higher shrinkage and cost (Mindess, Young, & Darwin, 2003).
- iv. **Use of Admixtures:** Chemical admixtures, including plasticizers and superplasticizers, are widely employed to enhance the workability of concrete mixes without increasing the water content. These additives reduce water demand while improving mix fluidity. Furthermore, admixtures such as retarders and accelerators are used to adjust the setting time, thereby influencing overall workability. Their use is guided by standards such as BS EN 934-2, which specifies requirements for admixtures in concrete.
- v. **Mix Proportioning:** Proper proportioning of materials ensures a balanced mix. A well-designed mix provides adequate paste to coat the aggregates, improving flow and finish ability (Neville, 2011).
- vi. **Temperature and Weather Conditions:** Ambient temperature significantly affects workability. High temperatures cause rapid water loss and accelerate setting, reducing workability, whereas low temperatures slow hydration and can stiffen the mix prematurely (Mehta & Monteiro, 2014).
- vii. **Time of Transport and Placement:** Concrete begins to lose moisture and stiffen over time. Delays in transport or placement can reduce workability unless properly managed with admixtures or re-tempering (Mindess et al., 2003).

viii. **Mixing Process and Duration:** Proper and consistent mixing is essential to ensure uniform distribution of materials within the concrete, which directly contributes to improved workability. However, excessive mixing can lead to segregation and a loss of cohesiveness. According to BS EN 206 and BS 8500, maintaining appropriate workability is critical for achieving a high-quality surface finish, strong bonding among components, and long-term durability. It also facilitates ease of placement and minimizes the risk of defects during construction.

2.5 Nanosilica

Nanosilica (NS) is an ultrafine form of amorphous silica with particle sizes typically below 100 nanometres. It is one of the most widely studied nanomaterials in cement and concrete technology because of its high surface area and strong pozzolanic reactivity (Sanchez & Sobolev, 2010). When incorporated into concrete, nanosilica fills microvoids within the cement matrix and reacts with calcium hydroxide (CH) produced during hydration to form additional calcium silicate hydrate (C–S–H) gel, which improves density and strength (Jo et al., 2007; Said et al., 2012).

The addition of nanosilica enhances both mechanical and durability properties of concrete. It refines pore structure, reduces permeability, and improves resistance to chloride penetration, sulphate attack, and carbonation (Adamu et al., 2021). However, due to its extremely fine particles, nanosilica can significantly reduce workability by increasing water demand; therefore, superplasticizers are often used to maintain desired flow (Givi et al., 2010).

Nanosilica can be produced through various methods, including sol–gel processes, precipitation, and flame hydrolysis. Its effectiveness in concrete depends largely on factors such as particle size, dosage, and dispersion technique (Zhang et al., 2012). Proper dispersion prevents agglomeration

and ensures uniform distribution within the cement matrix, which is essential for achieving consistent performance improvements.

Overall, nanosilica serves as both a filler and a reactive additive, improving the microstructure and long-term durability of concrete. Its use aligns with sustainable construction goals by reducing cement consumption and promoting high-performance materials (Chekravarty et al., 2022).

2.5.1 Constituents of nanosilica

Nanosilica, or silicon dioxide nanoparticles, is primarily composed of silicon and oxygen, with the chemical formula SiO_2 (Iler, 1979). The elemental composition of pure silica typically includes 46.83% silicon and 53.33% oxygen by weight, consistent with the stoichiometry of SiO_2 (Greenwood & Earnshaw, 2012). These nanoparticles appear as a fine white powder and can be derived from natural sources such as quartz, sand, or produced synthetically using methods like sol-gel or fumed processes (Luther et al., 2014).

2.5.2 Characteristics of nanosilica

- a. Particle Size:** Nanosilica particles typically range from 5 to 100 nanometers (nm), which allows them to penetrate and fill micro-voids in the cement matrix, improving the packing density and reducing porosity (Zhang et al., 2011).
- b. High Specific Surface Area:** With a surface area often exceeding $200 \text{ m}^2/\text{g}$, nanosilica has an enhanced ability to interact with hydration products, leading to better performance in concrete (Senff et al., 2010).
- c. Amorphous Structure:** Nanosilica is usually amorphous, which is more chemically reactive than crystalline silica and facilitates rapid pozzolanic reactions in cementitious systems (Jo et al., 2007).

- d. **High pozzolanic activity:** Nanosilica reacts with calcium hydroxide (Ca(OH)_2), a byproduct of cement hydration, to form additional calcium silicate hydrate (C-S-H), which enhances the strength and durability of concrete (Li et al., 2004)
- e. **Surface Chemistry:** The surface of nanosilica is rich in silanol (Si-OH) groups, making it hydrophilic and highly reactive. Surface modification is often necessary to improve its dispersion in cement pastes (Quercia & Brouwers, 2014).
- f. **Mechanical Strength Enhancement:** Studies show that the use of nanosilica increases both early-age and long-term compressive and flexural strength due to matrix densification and improved hydration (Givi et al., 2010).
- g. **Improved absorption-based durability:** Nanosilica refines the pore structure of concrete and significantly reduces water absorption, which limits moisture ingress and enhances the overall durability and longevity of concrete structures (Said et al., 2012).
- h. **White, Powdery Appearance:** Nanosilica typically appears as a fine, white powder and is commercially available in both powder and colloidal forms for ease of use in concrete applications (Björnström et al., 2004).

2.5.3 Properties of nanosilica

i. **Physical Properties**

- a. **Particle Size:** Nanosilica particles usually measure between 1 and 100 nanometers, which results in unique surface-dominated behavior (Zhang et al., 2011).
- b. **Specific Surface Area:** These particles have a very large surface area—often exceeding 100 m^2/g —enhancing their chemical reactivity and interaction with surrounding materials (Li et al., 2006).

- c. **Porosity:** Depending on the synthesis method, nanosilica can be engineered to be mesoporous or non-porous, allowing for various applications such as catalysis or adsorption (Fernandez et al., 2010).
 - d. **Shape:** Most nanosilica particles are spherical, although other morphologies can be synthesized for specialized functions (Xu and Sancaktar, 2014).
 - e. **Density:** The true density is about 2.2 g/cm³, similar to amorphous silica, but its bulk density is significantly lower due to particle agglomeration (Rezaei et al., 2015).
- ii. **Chemical Properties**
- a. **Composition:** Composed of amorphous silicon dioxide (SiO₂), nanosilica is chemically similar to traditional silica but much more reactive due to its size (Li et al., 2006).
 - b. **Surface Chemistry:** It features abundant silanol (-SiOH) groups on the surface, which make it hydrophilic and enable surface modification for compatibility with different matrices (Fernandez et al., 2010).
 - c. **Chemical Stability:** Despite its reactivity, nanosilica is chemically stable in a variety of environments, including acidic and alkaline solutions (Rezaei et al., 2015).
- iii. **Mechanical Properties (in composites)**
- a. **Strength Enhancement:** When incorporated into materials like cement or polymers, nanosilica significantly improves compressive and tensile strength by refining the microstructure (Jo et al., 2007).
 - b. **Durability:** It reduces permeability and increases resistance to aggressive agents, thereby enhancing the long-term durability of the material (Givi et al., 2010).
 - c. **Microstructural Densification:** Its ultrafine size allows it to fill microscopic voids, leading to a more compact and durable material matrix (Senff et al., 2012).

2.6 Workability of nanosilica concrete

The inclusion of nanosilica in concrete mixtures significantly affects the workability of fresh concrete. Because nanosilica particles possess an extremely high specific surface area, they require more water to wet their surfaces, which leads to a noticeable reduction in slump and fluidity (Givi et al., 2010). The fine particles also increase inter-particle friction, making the mix stiffer and more cohesive (Said et al., 2012).

Most studies have reported that as nanosilica content increases, workability decreases sharply, especially beyond 2–3% replacement by weight of cement (Adamu et al., 2021). To counteract this effect, superplasticizers are often added to improve flow while maintaining strength and density (Rakesha et al., 2024).

The reduced workability is not entirely disadvantageous; the increased cohesiveness of the mix minimizes segregation and bleeding, resulting in better surface finish and compaction when properly mixed (Changjiang et al., 2021). However, poor dispersion or excessive nanosilica content can cause particle agglomeration, leading to uneven texture and inconsistent strength development (Zhang et al., 2012).

In summary, nanosilica enhances microstructure and performance but requires careful control of dosage, water content, and admixtures to achieve workable and durable concrete.

2.7 Setting time of nanosilica concrete

Zang et al. (2012) reported that incorporating 1.0% nano-silica (SiO_2) into concrete reduced both the initial and final setting times by approximately 20 minutes compared to the control mix. Increasing the nano-silica content to 2% resulted in a more pronounced reduction, shortening the initial setting time by 90 minutes and the final setting time by 100 minutes. Similarly, Changjiang

et al. (2021) observed that the control mix exhibited an initial setting time of 344 minutes and a final setting time of 478 minutes. Their findings further revealed that, at a constant water–binder ratio of 0.6, increasing nanosilica content led to a progressive reduction in both initial and final setting times. This effect is attributed to the high pozzolanic reactivity of nanosilica, which accelerates the hydration process and thus shortens the setting time of concrete. Their study evaluated nanosilica dosages ranging from 0.25% to 3.0% as partial replacements for cement.

2.8 Compressive strength of nanosilica concrete

Nanosilica (NS) has been shown to significantly improve the compressive strength of concrete, mainly due to its fine particle size and high reactivity. As reported by Givi et al. (2010), NS enhances the hydration process by reacting with calcium hydroxide to produce additional calcium silicate hydrate (C–S–H), leading to a denser and stronger microstructure. Jo et al. (2007) found that incorporating a small amount of nanosilica—typically between 1% and 2% by weight of cement—can result in noticeable strength gains, particularly during the early stages of curing. Said et al. (2012) attributed these improvements not only to chemical interactions but also to better packing density and reduced pore size, which strengthen the bond at the interfacial transition zone. Nevertheless, Li et al. (2004) cautioned that overdosing nanosilica can cause particle agglomeration, potentially weakening the concrete. Therefore, when properly dosed and evenly dispersed, nanosilica acts as an effective additive to enhance concrete’s compressive strength.

2.9 Water absorption of nanosilica concrete

Water absorption plays a vital role in determining the durability of concrete, and incorporating nanosilica notably decreases this characteristic. The fine nanosilica particles fill the tiny pores in the cement matrix, creating a more compact and less permeable material that restricts the

penetration of water (Almeida et al., 2021). Additionally, by limiting water uptake, nanosilica enhances the durability and service life of concrete exposed to harsh environmental conditions (Li et al., 2019). The inclusion of nano-silica in high performance concrete decreases its water absorption. This effect is due to the high pozzolanic reactivity of nano-silica, which leads to the formation of more hydration products that fill the capillary pores and reduce their connectivity, (Ghafari, et al., 2014). The densification of the concrete mix due to Nano-silica reduces water absorption, improving the concrete's resilience to water-related issues and environmental effects (Althoey et al., 2023).

2.10 Flexural strength of nanosilica concrete

Adding nanosilica to concrete mixtures has been found to enhance flexural strength by improving the internal structure and promoting additional pozzolanic reactions. Through its fine particle size, nanosilica effectively fills voids and reacts with calcium hydroxide to form more calcium silicate hydrate (C-S-H), which strengthens the concrete matrix (Said et al., 2012). This refinement of the interfacial transition zone (ITZ) contributes to better crack resistance and stress distribution during flexural loading (Jo et al., 2007).

Research has shown that incorporating nanosilica in small proportions—typically between 1% and 3% of the cement weight—can significantly boost the flexural strength of concrete compared to mixes without it (Nazari and Riahi, 2011). Moreover, when used in combination with other supplementary cementitious materials such as fly ash or slag, nanosilica can produce even greater improvements in bending strength (Zhang et al., 2014).

These enhancements make nanosilica concrete especially suitable for structures exposed to repeated loading, aligning with goals for more durable and efficient construction materials (Gonzalez et al., 2016).

2.11 Significance of nanotechnology in Nigeria's construction industry

Nanotechnology is becoming increasingly significant in the construction industry globally, and its relevance is growing rapidly in Nigeria as well. With Nigeria experiencing fast-paced urbanization and infrastructure expansion, the demand for innovative, durable, and cost-effective building solutions is higher than ever (Ogunsemi & Jagboro, 2019). Nanotechnology introduces advanced materials such as nanosilica, carbon nanotubes, and nano-clays, which enhance the mechanical properties and durability of conventional construction materials. For instance, nanosilica improves compressive strength and reduces permeability, which is crucial in Nigeria's diverse and sometimes harsh climatic conditions (Sahmaran et al., 2018).

In addition to enhancing strength, nanomaterials also contribute to sustainability by increasing the lifespan of concrete structures and minimizing the frequency and cost of repairs (Almeida et al., 2021). This is particularly relevant for Nigeria, where infrastructure often faces challenges such as rapid deterioration due to environmental exposure and insufficient maintenance budgets (Adeyemi et al., 2020). Moreover, nanotechnology enables the development of smart and multifunctional construction materials that can improve energy efficiency and reduce environmental impact, aligning with global trends towards green building practices (Li et al., 2019).

Given these advantages, the integration of nanotechnology in Nigeria's construction sector holds the promise of producing more resilient infrastructure that meets international standards. It also provides opportunities for local industries to innovate and compete globally by adopting cutting-

edge materials and techniques (Ogunsemi & Jagboro, 2019). Therefore, promoting research, development, and practical implementation of nanotechnology in construction could significantly contribute to Nigeria's sustainable urban development and economic growth.

Some other benefits are listed below:

i. Strengthening and Increasing Durability of Concrete

Nanomaterials such as nanosilica are utilized to boost the compressive strength and reduce the permeability of concrete, enhancing the longevity of infrastructure, which is essential for withstanding Nigeria's challenging environmental conditions (Sahmaran et al., 2018).

ii. Creation of Self-Cleaning and Corrosion-Resistant Coatings

Nano-based coatings are applied to building exteriors and steel reinforcements to protect against corrosion, dirt accumulation, and microbial attack, helping structures endure Nigeria's humid and polluted environments (Almeida et al., 2021).

iii. Enhancement of Thermal Insulation Properties

Nanotechnology improves insulation materials by reducing heat transfer, which enhances energy efficiency and indoor comfort in Nigeria's predominantly hot climate (Li et al., 2019).

iv. Manufacture of Lightweight and High-Strength Building Materials

The use of nanotechnology facilitates the production of lightweight composites and concrete with superior mechanical characteristics, supporting quicker construction processes and lowering structural load demands (Ogunsemi & Jagboro, 2019).

2.12 Research gap

From the review of existing studies, it is evident that nanosilica enhances concrete properties by increasing strength, reducing water absorption, and improving resistance. However, several research gaps remain unaddressed. These include inconsistencies in dosage and mixing methods, lack of consensus on the optimum dosage that balances performance, cost, and workability, and limited focus on long-term durability—particularly in hot and humid climates like Nigeria. Additionally, many studies rely on imported materials, raising concerns about the applicability of their findings to local contexts, and often overlook comprehensive testing or the use of statistical tools to validate results. This study seeks to bridge these gaps by using a defined range of nanosilica dosages with clear mixing procedures, assessing key concrete properties such as workability, strength and water absorption, utilizing locally available materials, incorporating durability tests under realistic curing conditions, and applying basic statistical analysis. The goal is to generate practical insights that support the effective use of nanosilica in Nigerian construction practices.

CHAPTER THREE

METHODOLOGY

3.1 Introduction

This chapter outlined the methodological framework that was adopted in the execution of this research. The study was experimental and laboratory-based, aimed at investigating the influence of nanosilica on the mechanical and durability properties of concrete. The methodology focused

on comparing conventional concrete with mixes containing varying nanosilica dosages. Standard British testing procedures guided material selection, mixing, casting, curing, and testing. Each step was designed to achieve the study's objectives on setting time, workability, compressive strength, flexural strength, and water absorption test. The one-way ANOVA and post hoc test were used for statistical analysis using the Microsoft Excel application. Density and heat of hydration tests were not conducted in this study due to equipment limitations and the focus on strength and absorption-based performance metrics. Future studies were recommended to assess these parameters for a more holistic understanding of concrete behaviour.

3.2 Materials

The materials required for this study were sourced from reliable local suppliers to ensure quality and availability. These materials were essential in carrying out various tests. The materials are highlighted below:

3.2.1 Nanosilica

Nanosilica powder typically felt very fine, soft, and smooth. However, due to its extremely small particle size, it could also feel slightly clingy or dusty to the touch, easily dispersing into the air

when disturbed. Commercially available nanosilica powder with particle sizes less than 100 nm was procured.



Figure 3.1 Sample of nanosilica

Table 3.0-1 Physical Characteristics of Nanosilica (Rakesha et al., 2024)

Property	Nature or value
Colour	White
Surface Area (m ² /g)	202
pH	4.12
Particle size	10-20 nm
Specific gravity	2.4
Unit weight (kg/m ²)	505

3.2.2 Cement

Ordinary Portland Cement (OPC), specifically Grade 42.5N, was used. This strength class of cement was known for its wide availability and binding characteristics. It was procured from local market vendors in Benin City, Nigeria.

3.2.3 Fine aggregate

Clean, well-graded river sand that met BS EN 12620:2013 standards was used. Upon procurement, the sand was air-dried and sieved using a standard 4.75 mm sieve to remove oversized particles, debris, or organic impurities. This ensured uniformity and good bonding with the cement matrix.

3.2.4 Coarse aggregate

Crushed granite with a nominal maximum size of 10 mm, in line with BS EN 12620:2013, was used as coarse aggregate. After procurement, the granite was washed to remove dust and fines, and then sieved to ensure conformity to the required size distribution and cleanliness.

3.2.5 Water

Potable water, free from impurities, salts, and organic materials, suitable for concrete mixing and curing (as specified in BS EN 1008:2002), was sourced from the laboratory's water supply system.

3.3 Mix design and proportioning

3.3.1 Mix design

A nominal mix ratio of 1:2:4, which corresponded to M20 concrete grade, was adopted for the control mix. A constant water–cement ratio of 0.50 was maintained across all mixes to ensure consistency in workability.

The cement was partially replaced with nanosilica at 0%, 1%, 2%, and 3% by weight to create four different mix variations based on literature reviews carried out in the past by other researchers.

Table 3.0-2 Mix Proportions for M20 Concrete with Nanosilica Replacement by Weight

Mix ID	NS Replacement	Cement (g)	Nanosilica (g)	Fine Aggregate (g)	Coarse Aggregate (g)	Water (g)	w/c Ratio
M0	0%	400	0	600	1200	200	0.50
M1	1%	396	4	600	1200	200	0.50
M2	2%	392	8	600	1200	200	0.50
M3	3%	388	12	600	1200	200	0.50

3.3.2 Batching by Weight

All mix constituents — cement, sand, coarse aggregate, water, and nanosilica — were measured and batched by weight to ensure accuracy and uniformity in the concrete mixtures. A digital scale with high precision was used for nanosilica and cement measurements due to their critical proportions.

3.3.3 Mixing Procedure

The concrete was mixed in a rotating drum mixer using the following steps:

- i. The dry components (cement, nanosilica, sand, and coarse aggregates) was thoroughly mixed for about 2–3 minutes.

- ii. Water was gradually added, and mixing continued for another 3–5 minutes to achieve a uniform and workable mix.

3.4 Laboratory tests

3.4.1 Chemical Analysis (X-Ray Fluorescence, XRF)

The chemical composition of the cement and nanosilica used in this study was determined using X-Ray Fluorescence (XRF) analysis. This test was conducted to identify and quantify the major oxide constituents such as silica (SiO_2), alumina (Al_2O_3), ferric oxide (Fe_2O_3), calcium oxide (CaO), magnesium oxide (MgO), and other trace elements.

In this procedure, powdered samples of both ordinary Portland cement and nanosilica were prepared and analyzed using an XRF spectrometer. The instrument was calibrated with standard reference materials to ensure accuracy and precision. The samples were exposed to an X-ray beam, causing the atoms to emit secondary (fluorescent) X-rays characteristic of their elemental composition.

The resulting spectra were processed using the equipment's analytical software to obtain the percentage composition of each oxide present in the materials. The data obtained from this analysis provided a basis for assessing the purity and chemical suitability of the nanosilica for use as a partial cement replacement in concrete production.

3.4.2 Particle size distribution (Sieve analysis) test

Sieve analysis is a method used to determine the particle size distribution of aggregates. It helps in assessing whether the aggregates meet the required grading for concrete production. Well-graded aggregates improve the packing density, reduce voids, and contribute to the overall strength

and workability of concrete. This test was performed on both fine and coarse aggregates, following the specifications of BS EN 933-1-1997.

Sieve analysis apparatus

- i. Standard set of sieves
- ii. Weighing balance
- iii. Oven
- iv. Steel tray
- v. Brushes
- vi. Scoop

Experimental procedure for sieve analysis

A representative sample of each aggregate type was collected and oven-dried to a constant weight. The sample was then passed through a standard set of sieves arranged in descending order of aperture size. For coarse aggregate, sieves ranging from 10 mm to 4.75 mm were used, while sieves from 4.75 mm down to 75 μm were used for fine aggregate.

The retained weight on each sieve was recorded, and the cumulative percentage passing through each sieve was calculated. The results were plotted on a grading curve to determine the uniformity and fineness modulus of the aggregates. These findings were used to ensure that the selected aggregates met the specified grading requirements and were suitable for concrete production.

3.4.3 Workability test (Slump test)

The workability of concrete was assessed using the slump test method, in accordance with BS EN 12350-2:2009. This test provided a quick and practical measure of the consistency and flowability

of fresh concrete, which were key indicators of its workability. It helped determine how easily the concrete could be mixed, placed, and compacted without segregation.

There are three main types of slump that may be observed during the test:

- True slump – a uniform subsidence of the concrete indicating good cohesion.
- Shear slump – where one side of the concrete shears off; this may suggest a lack of cohesion.
- Collapse slump – where the concrete completely falls apart, indicating very high workability or excessive water content.

The slump test was conducted for both the control mix (without nanosilica) and mixes incorporating varying percentages of nanosilica. This helped evaluate the influence of nanosilica on the fresh properties of the concrete.

Workability test apparatus

- i. Slump cone (100 mm diameter at the top, 200 mm diameter at the bottom and 300 mm high)
- ii. Tamping rod (600 mm long, 16 mm diameter)
- iii. Flat base plate
- iv. Weighing balance
- v. Trowel and scoop

Experimental procedure for workability test

- i. The internal surface of the slump cone was moistened and placed on a smooth, horizontal, non-absorbent base.

- ii. Freshly mixed concrete was filled into the cone in three layers, each approximately one-third of the cone's height.
- iii. Each layer was tamped 25 times using the rounded end of the tamping rod to ensure compaction.
- iv. The top surface was leveled, and the cone will be carefully lifted vertically.
- v. The concrete slumped, and the vertical difference between the top of the cone and the displaced concrete was measured in millimeters.

All mixing and testing procedures was conducted under ambient laboratory conditions, with room temperatures ranging between 18°C and 22°C.

3.4.4 Initial and final setting time test

The initial setting time of concrete refers to the period when the cement paste begins to harden. It is measured from the moment water was added to the cement until a 1mm square needle fails to penetrate 5-7mm from the bottom of the paste in a Vicat's mould while the final setting time refers to the point at which the cement paste has hardened enough that a 1mm needle leaves an impression in the mould, while a 5mm needle no longer makes any impression. The test was done in accordance to BS EN 196-3,

Initial and final setting time test apparatus

- i. Vicats apparatus
- ii. sensitive weighting machine
- iii. Measuring cylinder
- iv. Stop watch
- v. Glass plate
- vi. Enamel tray

vii. Trowel.

Experimental procedure for initial and final setting time test

- i. The needle of the Vicat's apparatus was replaced with the needle having a circular attachment.
- ii. The cement was considered finally set when, upon applying the needle gently to the surface of the test block, the needle made an impression thereon and the attachment failed to do so.
- iii. This time was recorded as the final setting time (T).

3.4.5 Compressive strength test

The compressive strength test was conducted to determine the load-bearing capacity of both the control concrete and the nanosilica-modified concrete mixes. This test was essential for assessing the structural performance of concrete, as compressive strength is a critical property in most structural applications. The test was carried out in accordance with BS EN 12390-3:2002.

Concrete cubes of standard dimensions 100 mm × 100 mm × 100 mm were cast and cured in tap water at a controlled temperature range between 18°C and 22°C. Water was changed weekly, and temperature was monitored daily using a digital thermometer to maintain consistency. The compressive strength was tested at curing ages of 7, 14, and 28 days.

Compressive strength test apparatus

- i. Compression testing machine
- ii. Steel moulds
- iii. Weighing balance
- iv. Trowel, tamping rod, and compacting tools
- v. Curing tank or water bath
- vi. Metallic sheet

vii. Vibrator

Experimental procedure for compressive strength test

- i. Fresh concrete was placed into lubricated cube moulds in three layers, each layer being compacted either by hand (25 strokes of a tamping rod) or using a vibrating table.
- ii. The surface was leveled and the specimens will be left to set for 24 hours at room temperature.
- iii. After demoulding, the cubes were cured by immersion in clean water until the designated testing age.
- iv. At the end of each curing period (7, 14 and 28 days), the cubes were removed from the curing tank, surface-dried, and tested using a compression testing machine.
- v. Each cube was placed centrally between the plates of the machine and loaded continuously at a constant rate of 0.6 N/mm² until failure.

The compressive strength was calculated using the formula:

$$f_c = \frac{F}{A} \quad (3.1)$$

Where:

f_c = compressive strength (N/mm²)

F= maximum load applied at failure (N)

A= cross-sectional area of the cube (mm²)

The average strength of three cubes per mix per age was recorded and compared across the different nanosilica percentages to assess the influence of nanosilica on the compressive performance of the concrete.

3.4.6 Flexural strength test

The flexural strength test was conducted to evaluate the ability of concrete to resist bending or flexural stress. This property was particularly relevant for elements such as pavements, beams, and slabs where tensile stresses were induced. The test followed the procedures outlined in BS EN 12390-5:2009, which specifies the method for determining the flexural strength of hardened concrete.

This test was performed on both the control mix (without nanosilica) and nanosilica-modified concrete mixes to examine the influence of nanosilica on the tensile performance of concrete.

Specimen preparation

Concrete was cast in prismatic moulds of 100 mm × 100 mm × 500 mm. The specimens were compacted using a vibrating table or by hand rodding, covered to prevent moisture loss, and demoulded after 24 hours. The specimens were cured in controlled water at room temperature for 28 days in the Civil/Structural Laboratory at the University of Benin, Edo State.

Apparatus for flexural strength test

- i. Flexural testing machine (or universal testing machine with flexural setup)
- ii. Prismatic moulds (100 × 100 × 500 mm)
- iii. Metallic sheet
- iv. Tamping rod and trowel

Experimental procedure for flexural strength test

- i. The beam specimen was positioned on two supporting rollers, spaced 400 mm apart, forming a simply supported beam.

- ii. Two loading points was applied symmetrically at one-third spans to create a constant bending moment in the central region (two-point loading).
- iii. The load was applied continuously and uniformly until the specimen fails.
- iv. The maximum load at failure was recorded.

$$f = \frac{F.L}{b.d^2} \quad (3.2)$$

Where:

f= Flexural strength (N/mm²)

F= Maximum applied load (N)

L= Span length between supports (mm)

b= Width of the specimen (mm)

d= Depth of the specimen (mm)

3.4.6 Water absorption test

The water absorption test was carried out to assess the porosity and permeability characteristics of the hardened concrete. This property was important as it provided an indirect measure of the concrete's durability, especially in terms of its resistance to water ingress and chemical attack. The test was conducted in accordance with BS 1881-122:2011.

Both the control mix and nanosilica-modified concrete were tested to determine the effect of nanosilica on the concrete's water absorption behavior.

Specimen preparation

Concrete cube specimens of 100 mm were cast and cured for 28 days. After curing, they were dried and tested for water absorption as outlined in the procedure.

Apparatus for water absorption test

- i. Oven
- ii. Weighing balance
- iii. Water tank
- iv. Stopwatch

Experimental procedure for water absorption test

- i. The concrete specimens were removed from the curing tank after 28 days and allowed to dry in an oven at 105°C for 72 hours to achieve constant mass.
- ii. Once dry, the specimens were cooled to room temperature and weighed (W_1).
- iii. The specimens were then immersed in clean water at room temperature for 24 hours.
- iv. After immersion, the surface water was wiped off with a damp cloth and the specimens will be weighed again (W_2).

$$\text{Water Absorption}(\%) = \frac{W_2 - W_1}{W_1} \times 100 \quad (3.3)$$

Where:

W_1 = Oven-dry weight (g)

W_2 = Weight after water immersion (g)

An average of three specimens per mix will be used to ensure reliable and consistent results.

3.5 Statistical analysis

The ANOVA test is a data analytic approach of computing data by grouping into multiples (Editage, 2023). Evaluation the effects of nanosilica incorporation on the fresh and hardened properties of concrete in varying proportions of 0% (control), 1%, 2%, and 3% in partial replacement of cement with nanosilica will be analyzed using Microsoft Excel application by adopting the one way ANOVA and post-hoc test approach. . This will help in verifying whether the observed improvements or reductions in performance metrics are statistically meaningful rather than due to random variation. Furthermore, the compressive strength test, flexural test, setting time, workability test and water absorption test will be represented graphically using error bars.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Chemical analysis (X-Ray Fluorescence, XRF)

The elemental composition of the nanosilica was determined using X-ray fluorescence (XRF) spectroscopy. The results (Table 4.1) show that the sample contained 98.13 wt.% SiO₂, indicating a high-purity silica material suitable for use in concrete. Minor quantities of Fe₂O₃ (0.10%), CaO (0.18%), SO₃ (0.37%) and Cl (0.76%) were detected, while other oxides were present in trace amounts (<0.1%). The high SiO₂ content confirms the chemical quality of the nanosilica and supports its expected pozzolanic reactivity in the concrete mixes.

Table 4. 1 Results of chemical analysis of nanosilica

Component	Oxide	Concentration (wt. %)
Silicon dioxide	SiO ₂	98.13
Iron(iii)oxide	Fe ₂ O ₃	0.10
Chromium(iii)oxide	Cr ₂ O ₃	0.11
Calcium oxide	CaO	0.18
Sulphur trioxide	SO ₃	0.37
Chlorine	Cl	0.76
Others(combined)	-	0.35

Total	-	-100%
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4.2 Particle size distribution

The sieve analysis determined the distribution of particle sizes within the fine and coarse aggregates. This helped assess the grading and suitability of the materials for concrete production.

The test was performed in line with the British Standard BS 812-103.1:1985.

4.2.1 Sieve analysis of fine aggregate

The particle size distribution curve obtained from the sieve analysis showed that the fine aggregate was well graded, with most particles falling within the standard limits specified for fine aggregates.

The gradual reduction in percentage passing with decreasing sieve size indicates a uniform spread of particle sizes, which contributes to good workability and dense packing in the concrete mix.

Based on the curve, the aggregate can be classified as medium-grained sand, suitable for general concrete production in accordance with BS 882:1992

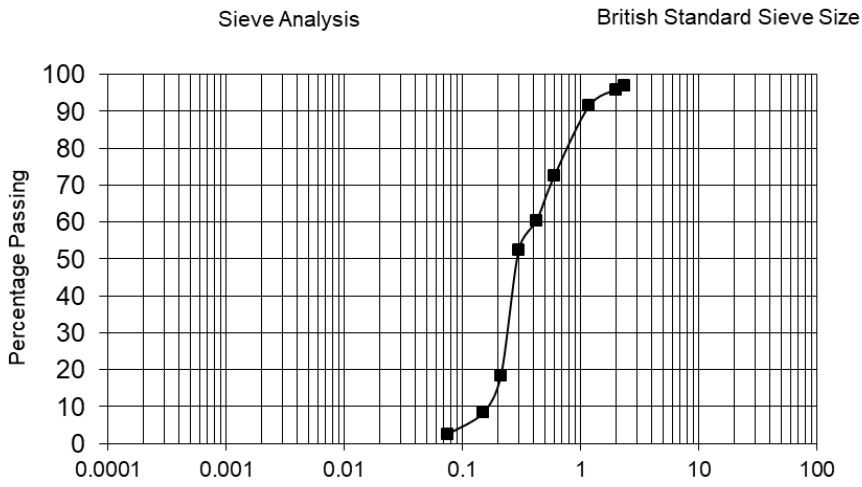


Figure 4. 1 Graph showing sieve analysis of fine aggregate

4.2.2 Sieve analysis of coarse aggregate

The particle size distribution curve for the coarse aggregate indicated that the material was uniformly graded, with a well-balanced range of particle sizes within the standard limits. The results show a consistent reduction in percentage passing as sieve size decreases, confirming proper gradation and minimal presence of fines. Such distribution enhances interlocking between particles, reduces voids, and improves the overall strength and stability of the concrete mix. The grading conforms to the requirements of BS 812: Part 103.1:1985 for coarse aggregates used in concrete production.

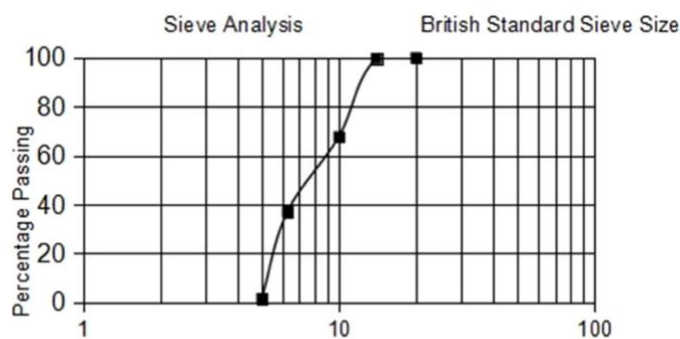


Figure 4. 2 Graph showing sieve analysis of coarse aggregate

4.3 Workability test assessment

The workability of concrete mixes was evaluated using the slump test in accordance with BS EN 12350-2:2009. This test measures the ease with which freshly mixed concrete can flow and be placed without segregation.

The results, as shown in Figure 4.3, indicate a steady increase in slump with higher nanosilica content. The recorded true slump values were 11 mm for the control mix, 15 mm for 1% nanosilica, 25 mm for 2% nanosilica, and 30 mm for 3% nanosilica. This trend suggests improved workability due to better particle packing and the filler effect of nanosilica, which enhances the lubrication between cement particles. Similar findings were reported by Gharehbaghi et al. (2020) and Patel and Shah (2018), who observed that the incorporation of nanosilica up to an optimum level improved the flowability of concrete as a result of its fine particle size and uniform dispersion. However, excessive nanosilica content beyond the optimum level may lead to loss of cohesion or segregation if not properly mixed.

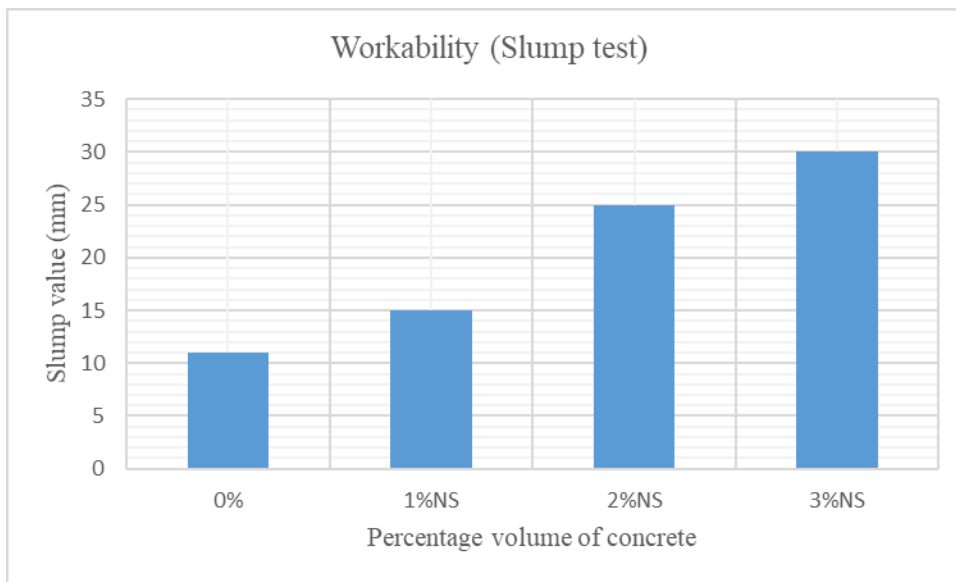


Figure 4. 2 Graph showing workability test results

4.4 Initial and final setting time result

The setting time test was conducted to determine the rate at which the cement paste transitioned from a fluid to a hardened state. The test was performed in accordance with BS EN 196-3:2016,

using the Vicat apparatus to measure both the initial and final setting times. The average results obtained for the control and nanosilica-modified mixes are presented in Figure 4.4.

The results show a progressive reduction in both initial and final setting times with increasing nanosilica content. The control mix recorded an initial setting time of 65 minutes and a final setting time of 172 minutes, while the 3% nanosilica mix showed shorter times of 54 minutes and 151 minutes, respectively. This indicates that nanosilica accelerated the hydration process due to its high surface area and strong pozzolanic reactivity, which provide additional nucleation sites for the formation of hydration products.

Similar observations were reported by Li et al. (2012) and Zhang and Islam (2019), who found that nanosilica reduces the setting time of cementitious materials by enhancing early hydration kinetics. However, excessive nanosilica content may lead to rapid stiffening, which can affect workability if not properly controlled.

In summary, the incorporation of nanosilica shortened both the initial and final setting times of concrete, indicating accelerated hydration and faster setting behaviour with increasing nanosilica dosage.

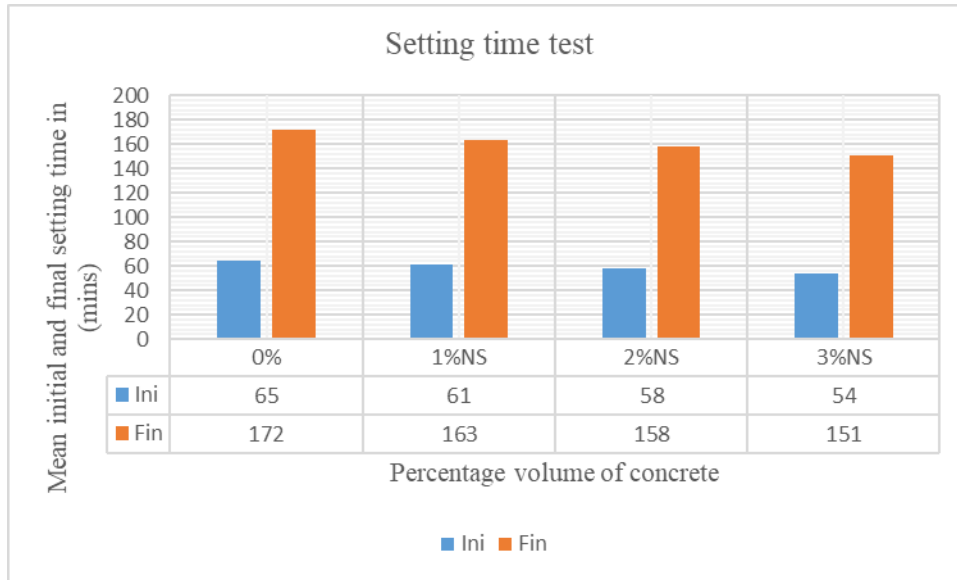


Figure 4.3 Graph showing initial and final setting time results

4.4.1 ANOVA analysis of initial and final setting time results

A one-way ANOVA was performed to assess the effect of nanosilica addition on the setting time of cement paste. The results revealed statistically significant differences in both the initial and final setting times among the mixes. The initial setting time yielded a p-value of 0.0097, while the final setting time produced a highly significant p-value of 0.0000087, both of which are below the 0.05 significance level. This indicates that nanosilica incorporation accelerated the setting process of the cement paste. The trend observed, with the initial and final setting times reducing progressively from 65 to 54 minutes and from 172 to 151 minutes respectively, suggests that nanosilica enhances the rate of cement hydration.

Table 4. 2 ANOVA analysis of initial setting time results

ANOVA						
<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	184.25	3	61.41667	7.677083	0.009682	4.066181
Within Groups	64	8	8			
Total	248.25	11				

Table 4. 3 ANOVA analysis of final setting time results

ANOVA						
<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	702	3	234	58.5	8.73E-06	4.066181
Within Groups	32	8	4			
Total	734	11				

4.5 Compressive strength result

The compressive strength test was carried out to determine the load-bearing capacity of the concrete specimens at different curing ages. The test was performed on cubes measuring 100 mm × 100 mm × 100 mm in accordance with BS EN 12390-3:2019. The results obtained for the control and nanosilica-modified mixes at 7, 14, and 28 days are presented in Figure 4.5.

The results show that compressive strength increased with age for all mixes, indicating continuous hydration and strength development over time. The highest strength at 28 days (24.4 N/mm²) was recorded for the 2% nanosilica mix, representing an improvement over the control (22.5 N/mm²). This enhancement can be attributed to the pozzolanic reaction of nanosilica, which refines the microstructure and increases the density of the cement matrix. However, beyond the optimum dosage, as observed in the 3% mix, a reduction in strength occurred, likely due to particle agglomeration and poor dispersion of nanosilica.

Similar findings were reported by Quercia and Brouwers (2010) and Singh et al. (2019), who noted that nanosilica addition up to an optimum level improves compressive strength, while excessive quantities may negatively affect the mix due to reduced workability and uneven distribution.

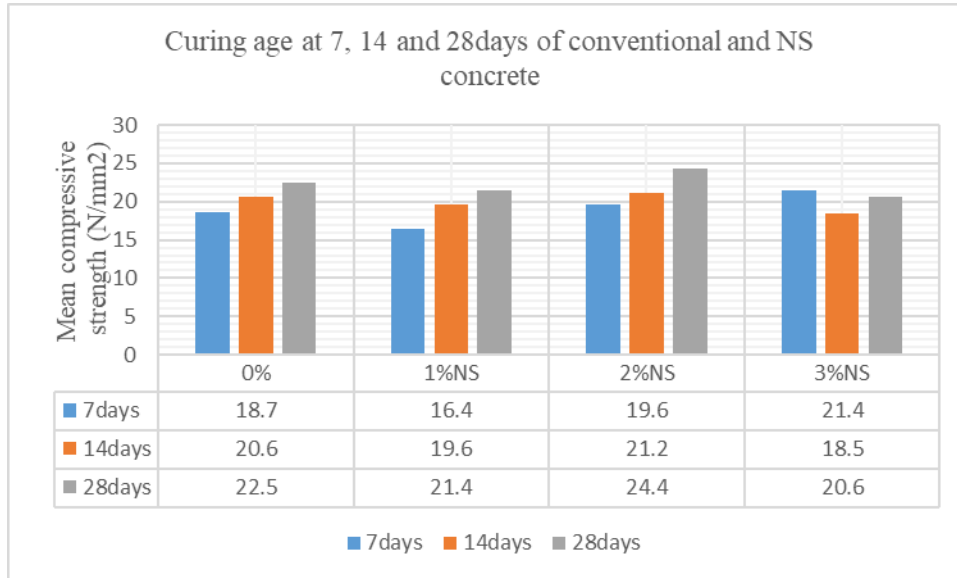


Figure 4. 4 Graph showing compressive strength results

The relationship between workability and compressive strength was examined for all concrete mixes containing 0%, 1%, 2%, and 3% nanosilica. The results showed that as the nanosilica content increased, the slump value decreased, indicating reduced workability. However, the compressive strength increased across the same range of mixes. This inverse relationship suggests that the improved particle packing and pozzolanic reactivity of nanosilica contributed to strength enhancement, even though the mix became stiffer.

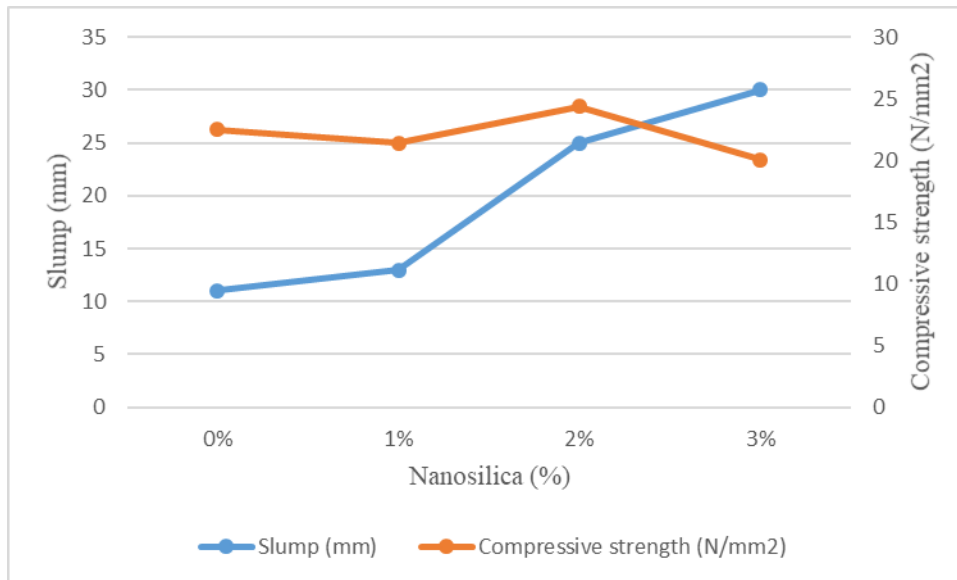


Figure 4.5 Graph showing comparison of workability and compressive strength

The comparison indicates that increasing nanosilica content reduces workability due to its high surface area and water demand. However, the same characteristic enhances the formation of additional C–S–H gel, leading to higher compressive strength. This trade-off suggests that while nanosilica reduces ease of placement, it significantly improves the mechanical performance of hardened concrete.

4.5.1 ANOVA analysis of compressive strength results

A one-way analysis of variance (ANOVA) was carried out on the average compressive strength values for the various nanosilica dosages (0%, 1%, 2%, and 3%) to determine if the differences observed were statistically significant. The results yielded $F(3, 8) = 0.61$ and $p = 0.63$, which is greater than the 0.05 significance level. This indicates that there is no statistically significant difference among the compressive strengths of the mixes. However, the 2% nanosilica mix exhibited a higher mean compressive strength, suggesting that while the strength improvement. A post-hoc Tukey test was also conducted to identify specific differences among the mix groups. The

results showed that none of the pairwise comparisons between the control and nanosilica-modified mixes were statistically significant ($p > 0.05$). This further confirms that while the inclusion of nanosilica, particularly at 2%, produced a numerical increase in compressive strength, the differences observed were not statistically significant. The minor variations could be attributed to normal experimental inconsistencies, curing conditions, or material heterogeneity rather than a definitive effect of nanosilica dosage is evident, it is not statistically conclusive within the tested range.

Table 4. 4 ANOVA analysis of compressive strength results

ANOVA						
<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	12.7025	3	4.234167	0.607484	0.628588	4.066181
Within Groups	55.76	8	6.97			
Total	68.4625	11				

4.6 Flexural strength result

The flexural strength test was performed to determine the ability of the concrete specimens to resist bending under applied load. The test was carried out on beams measuring 100 mm × 100 mm × 500 mm in accordance with BS EN 12390-5:2009. The results obtained for the control and nanosilica-modified mixes at 7 and 28 days are presented in Figure 4.6.

The results show that the flexural strength increased with curing age for all mixes, indicating continuous hydration and improved bond within the cement matrix. The 2% nanosilica mix recorded the highest strength values of 4.06 N/mm² at 7 days and 5.25 N/mm² at 28 days, compared to the control's 3.2 N/mm² and 4.67 N/mm² respectively. This improvement can be attributed to

the pozzolanic activity of nanosilica and its ability to refine the microstructure, enhancing the bond between the cement paste and aggregates.

However, a decline in flexural strength was observed at 3% nanosilica content, likely due to particle agglomeration and reduced homogeneity within the mix. Similar trends were reported by Zhang et al. (2012) and Mukharjee & Barai (2014), who found that moderate nanosilica additions improve the flexural strength of concrete, while excessive dosages can lead to poor dispersion and weaker interfacial bonding.

In summary, the results indicate that nanosilica enhances flexural strength up to an optimum content of 2%, beyond which strength reduction occurs.

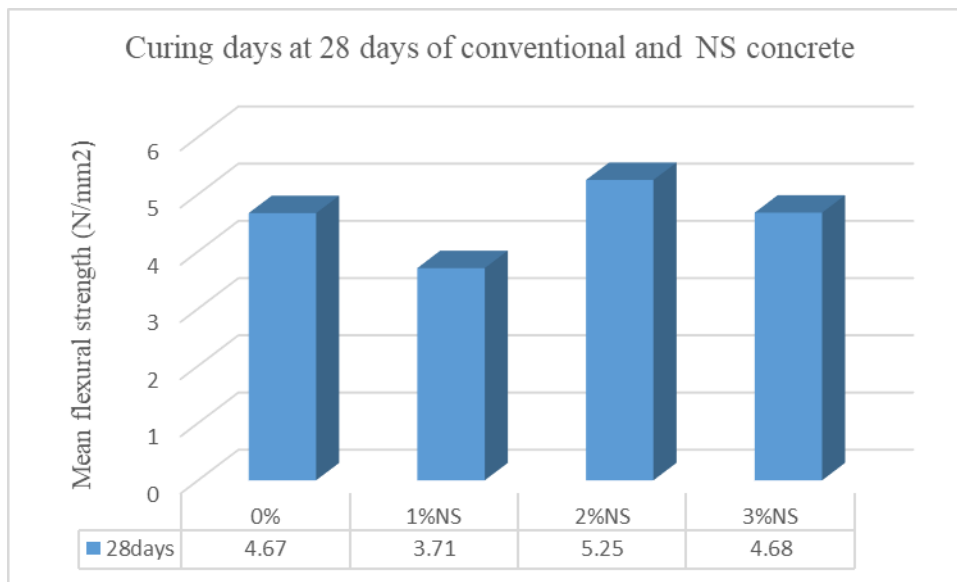


Figure 4. 5 Graph showing flexural strength test results

4.6.1 ANOVA analysis of flexural strength results

A statistical analysis using ANOVA was conducted on the 28-day flexural strength values of all concrete mixes to assess whether the differences among the groups were significant. The analysis yielded a p-value of 0.00004, which is well below the 0.05 significance level. This indicates that the differences observed in flexural strength between the control and nanosilica-modified concretes were statistically significant. The result confirms that nanosilica incorporation, particularly at 2% replacement, had a pronounced positive effect on the flexural performance of the concrete.

Table 4. 2 ANOVA analysis of flexural strength results

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	3.143692	3	1.047897	38.91912	4.05E-05	4.066181
Within Groups	0.2154	8	0.026925			
Total	3.359092	11				

4.7 Water absorption test

The water absorption test was carried out to evaluate the permeability and durability characteristics of the nanosilica-modified concrete. The results obtained showed a general reduction in water absorption with the incorporation of nanosilica up to an optimum level of 2%. The control mix recorded a water absorption of 9.7%, while the mixes containing 1%, 2%, and 3% nanosilica had values of 8.6%, 7.3%, and 9.2% respectively.

The observed trend indicates that nanosilica enhanced the impermeability of the concrete up to 2% replacement, beyond which absorption increased slightly. This improvement at lower dosages is attributed to the pozzolanic reaction and filler effect of nanosilica, which refined the pore structure

and reduced capillary voids within the concrete matrix. However, at higher dosage (3%), particle agglomeration may have occurred, leading to microvoids that slightly increased water penetration.

Overall, the inclusion of nanosilica improved the concrete's resistance to water absorption, suggesting enhanced durability and a denser internal structure at the 2% replacement level.

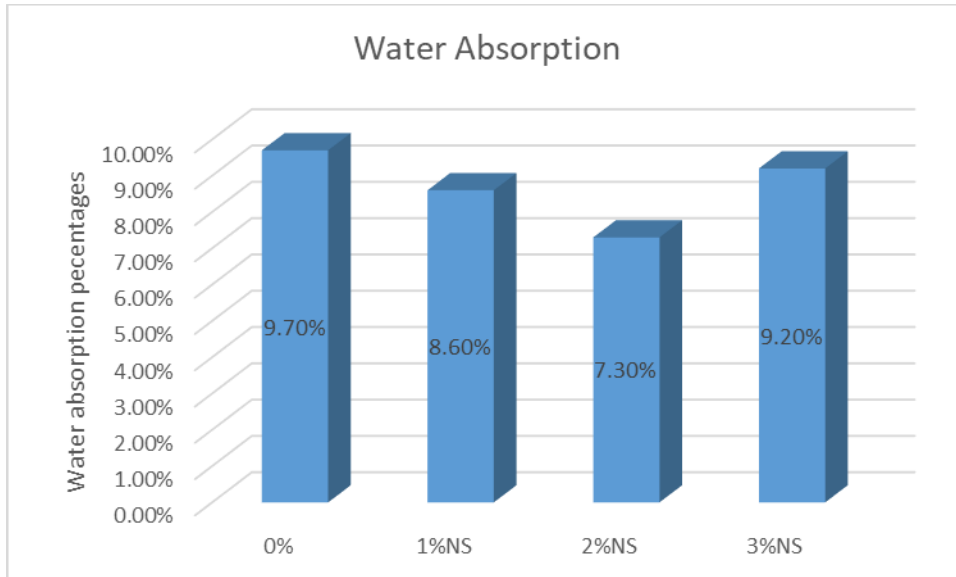


Figure 4. 6 Graph showing water absorption test results

The relationship between water absorption and compressive strength was investigated for concrete mixes containing different nanosilica dosages. The results indicated that as the nanosilica content increased, water absorption decreased, while compressive strength increased. This inverse trend suggests that nanosilica reduced the porosity of the concrete matrix through pore refinement and the formation of additional calcium silicate hydrate (C-S-H) gel, resulting in a denser and more durable structure.

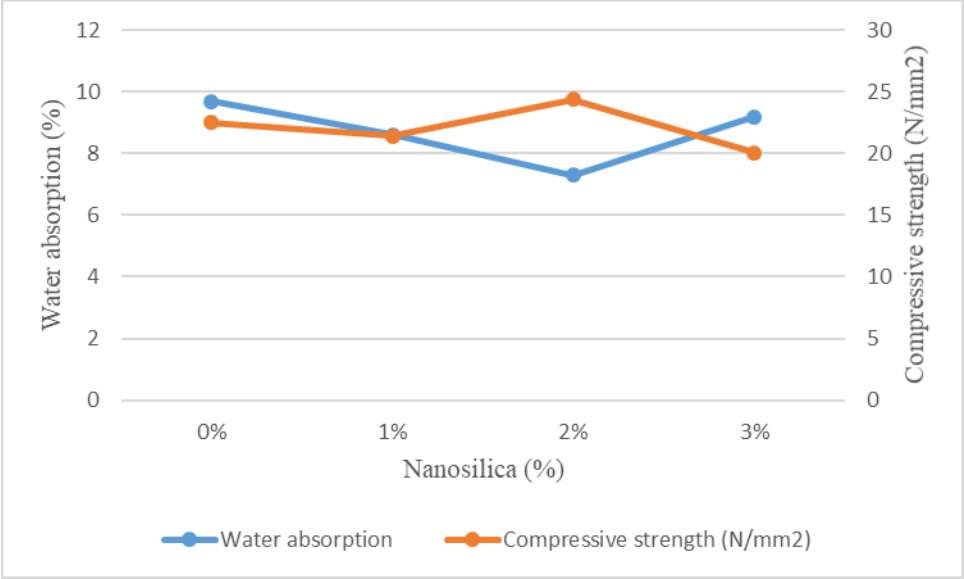


Figure 4.7 Graph showing comparison of water absorption and compressive strength results

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study investigated the effect of nanosilica (NS) on the properties of concrete produced with ordinary Portland cement (OPC). The major findings and conclusions drawn in relation to the study objectives are as follows:

- i. Concrete mixes were successfully formulated using OPC partially replaced with nanosilica at 0%, 1%, 2%, and 3%. The blending process produced uniform and workable mixtures suitable for laboratory testing.
- ii. The chemical analysis confirmed that the nanosilica used possessed a high silica (SiO_2) content, indicating its strong pozzolanic potential. This composition supports its reactivity and suitability for partial cement replacement.
- iii. The slump test results showed an increase in workability with higher nanosilica content. The control mix recorded the lowest slump (11 mm), while the 3% nanosilica mix had the highest (30 mm). This improvement in workability was attributed to the filler effect of nanosilica and the well-graded nature of the aggregates, which enhanced lubrication and flow.
- iv. Both the initial and final setting times decreased with increasing nanosilica content, indicating accelerated hydration. The control mix recorded 65 minutes and 172 minutes for initial and final setting times respectively, while the 3% nanosilica mix recorded 54 minutes and 151 minutes. This demonstrates that nanosilica promotes early setting due to its fine particle size and high surface reactivity. ANOVA results ($p = 0.009682$ for initial

and $p = 8.73E-06$ for final setting time) confirmed that the observed differences were statistically significant, proving nanosilica's measurable influence on cement setting behaviour.

- v. The inclusion of nanosilica improved both compressive and flexural strengths up to an optimum level of 2%. At 28 days, the 2% nanosilica mix achieved a compressive strength of 24.4 N/mm² and a flexural strength of 5.25 N/mm², higher than the control mix. Beyond 2%, a decline in strength was observed, likely due to particle agglomeration and reduced dispersion efficiency. ANOVA analysis indicated that compressive strength variations were not statistically significant ($p = 0.628588$), while Tukey's post-hoc test further confirmed the differences among mixes were minor. Nonetheless, the overall strength trend demonstrated nanosilica's beneficial effect when optimally dosed.
- vi. The durability results showed a reduction in water absorption from 9.7% for the control mix to 7.3% at 2% NS, indicating enhanced pore refinement and reduced permeability. Although ANOVA computation for this test produced an error due to limited data range, the results still showed a clear improvement in durability performance at the optimal 2% nanosilica replacement.

Overall, this study successfully filled the existing research gap by generating experimental data using locally sourced materials in Nigeria, thereby providing context-specific insights into nanosilica's performance under indigenous material and environmental conditions. The findings demonstrated that 2% nanosilica replacement yields the most balanced improvement across all parameters, offering a practical guideline for the Nigerian construction industry.

5.2 Recommendations

From the findings of this study, it is recommended that nanosilica be used as a partial replacement for cement in concrete at an optimum dosage of 2%. At this level, the material exhibited the most favourable balance of improved mechanical strength, workability, and setting characteristics. Higher replacement levels beyond 2% are not advised, as they tend to reduce performance due to particle agglomeration and uneven distribution.

To ensure maximum benefit, proper dispersion techniques should be adopted during mixing to avoid clustering of nanosilica particles and promote uniform reactivity within the cement matrix. The incorporation of nanosilica has shown great potential in enhancing the performance of concrete and should therefore be encouraged in practical construction applications, especially within Nigeria's construction industry where there is an increasing demand for durable, high-performance materials.

Furthermore, it is recommended that additional studies be carried out to assess the long-term durability behaviour of nanosilica concrete, including resistance to sulphate attack, chloride ingress, and carbonation. These will provide a more comprehensive understanding of its performance under diverse environmental exposures. Economic analysis should also be conducted to evaluate the cost-effectiveness and feasibility of nanosilica use in large-scale construction projects. Such investigations will help establish nanosilica as a sustainable and economically viable supplementary material for modern concrete production.

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APPENDIX

APPENDIX A

TABLE OF RESULTS

Table A 1 Compressive strength result of 7 days curing age

Specimen	Load (KN)			Area of Specimens	Compressive strength (N/mm ²)			Average Compressive strength (N/mm ²)
0%NS	193.45	174.68	192.91	1000	19.3	17.5	19.3	18.7
1%NS	167.16	128.29	197.79	1000	16.7	12.8	19.8	16.4
2%NS	225.47	150.81	211.96	1000	22.5	15.1	21.2	19.6
3%NS	211.71	210.09	223.36	1000	21.2	21.0	22.2	21.4

Table A 2 Compressive strength result of 14 days curing age

Specimen	Load (KN)			Area of Specimen	Compressive strength (N/mm ²)			Average Compressive strength (N/mm ²)
0%NS	206.39	219.33	191.08	10000	20.7	21.9	19.1	20.6
1%NS	225.47	150.81	211.96	10000	22.5	15.1	21.2	19.6
2%NS	234.77	201.996	198.78	10000	23.5	20.2	19.9	21.2
3%NS	191.35	182.65	179.64	10000	19.1	18.3	18.0	18.5

Table A 3 Compressive strength result of 28 days curing

Specimen	Load (KN)			Area of Specimens	Compressive strength (N/mm ²)			Average Compressive strength (N/mm ²)
0%NS	194.37	243.28	236.75	10000	19.4	24.3	23.7	22.5
1%NS	211.27	210.09	222.36	10000	21.2	21.0	22.2	21.4
2%NS	248.32	219.75	271.48	10000	24.8	22.0	27.1	24.4
3%NS	224.86	193.75	203.91	10000	22.5	19.4	20.04	20.06

Table A 4 Flexural strength result for 7 days curing

Specimen	Load(KN)		Average load(KN)	I(mm)	D1(mm)	D2(mm)	Mean flexural strength(N/mm ²)
0%NS	8.76	7.31	8.04	300	100	100	3.22
1%NS	10.33	9.41	9.87	300	100	100	3.95
2%NS	8.93	11.68	10.31	300	100	100	4.06
3%NS	7.28	6.11	13.39	300	100	100	2.68

Table A 5 Flexural strength results for 28 days curing

Specimen	Load(KN)		Average load(KN)	I(mm)	D1(mm)	D2(mm)	Mean flexural strength(N/mm ²)
0%NS	12.05	11.35	11.71	300	100	100	4.67
1%NS	11.55	11.78	11.75	300	100	100	4.69
2%NS	13.35	12.92	13.14	300	100	100	5.25
3%NS	8.76	9.81	9.28	300	100	100	3.71

Table A 6 Water absorption results after 28 days curing

Replacement	0%NS	1%NS	2%NS	3%NS
M ₁ (kg)	2.250	2.325	2.320	2.334
M ₂ (kg)	2.468	2.524	2.491	2.549
Water Absorption (%)	9.7	8.6	7.3	9.2

Table A 7 Sieve analysis results of fine aggregate

Sieve No (mm)	Mass retained (g)	Percentage(%) mass retained	Cumulative mass(%) retained	Cumulative mass(%) passing
2.360	3.1	3.1	3.1	96.9
2.000	1.0	1.0	4.1	95.9
1.180	4.5	4.5	8.6	91.4
0.600	18.9	18.9	27.5	72.5
0.425	12.1	12.1	39.6	60.4
0.300	7.9	7.9	47.5	52.5
0.212	34.1	34.1	81.6	18.4
0.150	10.1	10.1	91.7	8.3

0.075	5.8	5.8	97.5	2.5
Receiver	2.34	2.34	99.84	0.16

Table A 8 Results of sieve analysis of coarse aggregate

Sieve No (mm)	Mass retained (g)	Percentage(%) mass retained	Cumulative mass(%) retained	Cumulative mass(%) passing
19	0	0	0	100
14	0.010	0.33	0.33	99.67
10	0.952	31.73	32.06	67.94
8	0.928	30.93	62.99	37.01
5	1.061	35.36	98.35	1.65
Receiver	0.0390	1.30	99.651	0.35

Table A 9 Results of workability (slump) test

Specimen	Height of cone (mm)	Height of unsupported cone(mm)	Slump(mm)
0%	300	289	11

1%NS	300	285	13
2%NS	300	275	25
3%NS	300	270	30

Table A 10 Results of initial and final setting time test

Specimen	Initial setting time (min)	Final setting time (mm)
0%	65	172
1%NS	61	165
2%NS	58	158
3%NS	54	151

APPENDIX

APPENDIX B



Plate B 1 Author carrying out various experiments



Plate B 2 Sample of nanosilica used



Plate B 3 Specimen inside compressive strength machine