



## Reliability Based-Design Format for High Strength Concrete Beam (HSCB) With Blended Nanosilica Particles

Ooye Steve, Toba. <sup>A,\*</sup>, Wasiu John. <sup>a</sup> and Ibrahim Abdulrazaq Olayinka. <sup>a</sup>

<sup>a</sup> Department of Civil Engineering, Edo State University Iyamho, Edo State, Nigeria

\* Corresponding author: Ooye Steve Toba., Email: [ooyesteve@gmail.com](mailto:ooyesteve@gmail.com)\*  
[wasiu.john@edouniversity.edu.ng](mailto:wasiu.john@edouniversity.edu.ng)\* [ibrahim.abdulrazaq@edouniversity.edu.ng](mailto:ibrahim.abdulrazaq@edouniversity.edu.ng)

Received: 10<sup>th</sup> September 2025, Accepted: 28<sup>th</sup> October 2025, Published: 30<sup>th</sup> November 2025

### KEYWORDS

High Strength Concrete  
Flexural Strength  
Compressive Strength  
Nano Silica particles

### ABSTRACT

High Strength Concrete (HSC) has been under the spotlights of numerous studies. This paper examines how adding nano-silica influences the structural performance and durability of High Strength Concrete Beams (HSCBs) by specifically focusing on compressive strength, flexural strength, durability parameters and reliability-based design. To identify the physical, chemical, and microstructural properties of materials, experimental procedures entailed characterization by sieve analysis, specific gravity, moisture content, XRF, and SEM. 0, 3, 5, and 7 percent (by cement) additions of nano-silica in concrete mixes were made, and the compressive and flexural tests were performed with specimen ages at 7, 14 and 28-days, and also tested against durability under sulphate, acid, chloride attack, and freeze-thaw experiments. The descriptive statistics, goodness-of-fit tests, Monte Carlo simulation, and First-Order Reliability Methods were all used to test the consistency of performance. The 5 % nano-silica mix proved the best overall performance in terms of achieving the highest compressive and flexural strengths (74.5 MPa and 6.8 MPa respectively) at 28 days, and resisted durability better than the control mix. Reliability-based evaluation also established that the 5 percent nano-silica mix attained the highest reliability index showing its applicability. In conclusion, nano-silica in 5 % increases the service life and mechanical properties of HSCBs.

### 23. INTRODUCTION

High Strength Concrete (HSC) has been under the spotlights of numerous studies since it offers increased resistance to high compressive strength, durability, and adverse environmental factors. Such outstanding characteristics have enabled its use in other construction works like high-rises, long-span bridges, and prestressed bridges (Mehta & Monteiro, 2014; Ghosh & Kundu, 2019; Huang et al., 2016; Figueiredo et al., 2021; Hamraj et al., 2019). Nano-silica (nSiO<sub>2</sub>) has become one of the promising supplementary materials in the advancement of HSC mixes. Nano-silica arises from the processing of silicon-based compounds and includes ultra-fine particles with significant surface reactivity. Additions of nano-silica particles (as part of the cementitious systems) augment the process of hydration, optimize the pore structure, and improve the interface zone between the aggregate and the paste. Bhanja and Sengupta (2018) highlighted that nano-silica dramatically limits the transgression of chloride ions, thus increasing durability and shielding reinforcing steel against corrosion. Similarly, Li et al. (2017) found that the addition of nano-silica accelerates early hydration, improves initial strength, and enhances microstructural densification. In recent years, it has been emphasized that nano-silica can enhance the mechanical and durability-related properties of concrete. According to Zhang et al. (2019), a combination of nano-silica and silica fume results in the formation of dense and impermeable concrete, and Singh et al. (2013) showed that nano-silica

powder promotes the formation of additional C–S–H gel, which improves the strength of mortar. Chen et al. (2021) also reported that when nano-silica is added to high-strength composite structures, it increases the axial compressive load and stiffness of the structural component.

Prashanth et al. (2021) explained that since the discovery of concrete technology and its subsequent application in infrastructural projects, the technology has evolved rapidly and continuously. However, ordinary concrete cannot be used all the time in harsh environments, chemically aggressive areas, and under thermal shocks. HSC is achieved through the proper selection of high-quality materials and appropriate mixture design. The American Concrete Pavement Association (2020) describes HSC in various ways depending on time and geographical location, as there have been ongoing advancements in the industry. For instance, the ACI 363R-84 report listed concretes with strengths greater than 40 N/mm<sup>2</sup> as high-strength concrete. Kashyap et al. (2023) revealed that HSC with a strength range of 40–70 N/mm<sup>2</sup> can be sufficiently achieved using cement and aggregate, provided that the mix proportions are meticulously formulated and water-reducing admixtures are added. They also emphasized the importance of water-cement ratio in achieving high strength and noted that superplasticizers not only ensure adequate workability but also maximize strength when proper compaction is applied. Nano-silica has recently become a promising additive for improving the nature of concrete, as its surface area, pozzolanic reactivity, and ability to reduce pore structure are very high. Li et al. (2017) found that nano-silica accelerates the hydration rate of cement, leading to increased early strength and a denser microstructure. Similarly, Jalal et al. (2021) found that compressive, tensile, and flexural strengths increase with 2–5% nano-silica addition, but excessive nano-silica replacement rates can reduce workability because nano-silica requires more water. Ghafari et al. (2014), Melchers (2019), Nowak and Collins (2013) confirmed that the reliability index could be incorporated into limit state design to maximize material efficiency without jeopardizing safety. Zhang et al. (2019), Singh and Subramanian (2016) opined that blending nano-silica improves long-term durability by refining pore structures and minimizing micro-cracking.

## 2. MATERIALS AND METHODS

### 2.1 Materials

#### 2.1.1: Cement

Ordinary Portland cement from Dangote 3X portland cement brand for high strength concrete will be used as the binder, which is commonly sold in various retail outlets. Both physical and chemical properties test were carried out on the Cement in accordance with BS 4550: Part1, NIS 367:1997 and Part 2, NIS 368:1990. The following three sections were designed in the questionnaire.

#### 2.1.2: Aggregate

For the purpose of this research work, the fine aggregate (sharp sand) and the coarse aggregate (12mm.-sized granite) will be obtained from various construction sites within Lagos. The tests that will be carried out include specific gravity, particle size distribution using sieve analysis, water absorption.

#### 2.1.3: Water

The water used was clean and in accordance with the British Standards Specifications (BS EN 1008:2002). The water was obtained from Yabatech main campus, Yaba. For the purpose of this project nano-silical was purchased from ENAL Marine and Environmental Services Ltd. Lagos.

### 2.2 Methods

**Table 2: Summary of Physical Properties of Cement**

S/N	Physical Property	Results Obtained
1	Specific gravity	3.10
2	Consistency (%)	7.5
3	Initial Setting time (min)	75
4	Final Setting time (min)	225

### 2.2.1 Aggregate Tests

#### 2.2.2 Specific Gravity

$$\text{Specific Gravity} = (W2-W1)/((W4-W1)-(W3-W2)) \quad (1)$$

#### 2.2.3 Water Absorption

$$\text{Water absorption (\%)} = (W_{ssd} - W_{od}) / W_{od} \times 100 \quad (2)$$

Where  $W_{ssd}$  is saturated surface-dry weight and  $W_{od}$  is oven-dry weight.

#### 2.2.4 Characterization

To understand the effect of nanosilica on the microstructure and chemical bonding within High Strength Concrete Beams (HSCB), advanced characterization techniques were employed. These techniques provided insights into the structural, morphological, and elemental composition of the concrete matrix blended with nanosilica particles. The FTIR analysis was performed to identify the functional groups and bonding interactions between cement hydration products and nanosilica. Finely powdered samples of hardened concrete containing nanosilica were collected after 28 days of curing. The powders were oven-dried at  $105 \pm 5$  °C for 24 hours to remove moisture. SEM coupled with EDX was used to study the surface morphology and elemental composition of nanosilica-blended HSCB. Simultaneously, Energy Dispersive X-ray Spectroscopy (EDX) was performed to obtain the elemental composition of selected regions. This provided semi-quantitative data on the presence of silicon (Si), calcium (Ca), oxygen (O), and other trace elements. The SEM images were used to evaluate the pore structure, density, and dispersion of nanosilica particles, while EDX spectra confirmed the enhanced silica and calcium silicate hydrate (C-S-H) formation due to nanosilica incorporation.

#### 2.2.5 Reliability-Based Design Analysis and Deterministic

The deterministic design was carried out using conventional structural design codes (such as ACI 318, Eurocode 2, or BS 8110), which apply partial safety factors on loads and material strengths. The safety of the structure was evaluated by comparing the design resistance ( $R_d$ ) with the applied load effects ( $S_d$ ):

$$R_d \geq S_d \quad (3)$$

This approach provided a baseline check of the structural adequacy of HSCBs with nanosilica, but did not explicitly account for uncertainties in material properties or loading. Reliability analysis was conducted to quantify the probability of failure and measure the safety margin of nanosilica-blended HSCBs under uncertainties.

A limit state function was defined as:

$$g(X) = R - S \quad (4)$$

where:  $R$  = resistance (strength of beam, dependent on compressive and flexural strength results)  $S$  = applied load effect (bending moment, shear force, etc.)  $X$  = vector of basic random variables (e.g., concrete strength, nanosilica content, dead load, live load).

Failure occurs when,  $g(X) \leq 0$ , Random Variables & Statistical Data: Mean values, standard deviations, and probability distributions of concrete strength, nanosilica content, dead load, and live load were established from experimental results and literature. Reliability analysis was performed using First Order Reliability Method (FORM) and/or Monte Carlo Simulation (MCS): In FORM, the reliability index  $\beta$  was computed as:

$$\beta = (\mu_R - \mu_S) / \sqrt{\sigma_R^2 + \sigma_S^2} \quad (5)$$

where  $\mu_R$  and  $\mu_S$  are mean values of resistance and load, and  $\sigma_R$ ,  $\sigma_S$  are their standard deviations. In MCS, a large number of simulations (e.g., 10,000 iterations) were run to estimate the probability of failure as:

$$P_f = P(g(X) \leq 0) \quad (6)$$

The reliability index  $\beta$  and probability of failure  $P_f$  were compared with target safety levels specified in codes (e.g.,  $\beta = 3.8$  for structural beams in Eurocode). This helped in evaluating whether nanosilica-blended HSCBs meet or exceed acceptable reliability standards. To evaluate the effectiveness of incorporating nanosilica into High Strength Concrete Beams (HSCBs), a comparative assessment was carried out between the deterministic design and the reliability-based design approach. The comparison was carried out using the same set of experimental data obtained

from compressive and flexural strength tests of nanosilica-blended HSCBs. Both methods used the same input variables (material properties, loads, and beam geometry), but differed in how uncertainties were treated. In the deterministic approach, design values were computed by applying partial safety factors on characteristic loads and material strengths in line with structural codes. The resulting design resistance (Rd) was directly compared to the design load effect (Sd) to establish structural adequacy. The approach assumed fixed values and did not explicitly quantify variability in strength or load.

### 3. RESULTS AND DISCUSSION

#### 3.1 Result Characterization

Table 1 shows the material Characterization

**Table 1: Summary of Materials Characterization Results**

Property	Fine Aggregate	Coarse Aggregate	Nanosilica
Fineness Modulus (FM)	2.73	–	–
Max. Aggregate Size (mm)	–	20	–
Sand Equivalent (%)	84	–	–
Specific Gravity (Gs)	2.64	2.71	–
Moisture Content (%)	1.2	0.8	–
SiO <sub>2</sub> (wt.%)	–	–	94.7
Al <sub>2</sub> O <sub>3</sub> (wt.%)	–	–	1.2
Fe <sub>2</sub> O <sub>3</sub> (wt.%)	–	–	0.8
CaO (wt.%)	–	–	1.6
MgO (wt.%)	–	–	0.5
Particle Size (nm)	–	–	50–80 (d <sub>50</sub> = 65)
BET Surface Area (m <sup>2</sup> /g)	–	–	178
Morphology (SEM)	–	–	Spherical/irregular, dispersed in C–S–H

The outcome of the characterization of the materials confirms the assumption regarding the mix design and the reliability model. The fineness modulus of the fine aggregate was 2.73 and the sand equivalent was 84%, as expected of well-graded coarse river sands used in high-performance mixes and comparable to those reported in dense-packing studies. The specific gravities (2.64 fine; 2.71 coarse) and low moisture contents (1.2%, 0.8%) are within the scope of granitic aggregates of high-strength concretes. Indicative of a high purity amorphous silica source, the nanosilica chemistry (SiO<sub>2</sub> = 94.7 wt.%) is similar to that of reported commercial nanosilica purities >9099 wt.% and BET areas of 150300 m<sup>2</sup>/g. Our BET value (178 m<sup>2</sup>/g) and size (d<sub>50</sub> = 65 nm) is also within this range. SEM images showed that the particles were spherical-to-irregular, exhibited slight agglomeration, and included increased C-S-H gel at 28 days, as reported portlandite dissolution, nucleation and pore densification. These microstructural changes are associated with strength and permeability and improve ITZ.

#### 3.2 Physical Properties

##### 3.2.1 Specific gravity

This test was conformed with AASHTO T84 (Fine Aggregate) and AASHTO T85 (Coarse Aggregate).

**Table 2: Gravity for Fine Aggregate**

SAMPLES	A	B
W1 Weight of Density Bottle	600	598
W2 Weight of Bottle + Soil	1763	1643
W3 Weight of Bottle + Soil + Water	2591	2518
W4 Weight of Bottle + Water	1882	1870
Gs (Specific Gravity)	2.6	2.63
Average Specific Gravity Value	2.62	

Specific gravity of aggregates is considered as an indication of strength. The specific gravity of fine aggregates normally used in construction ranges from about 2.5-3.0, with an average value of about

2.68. From Table 3 the average specific gravity value for fine aggregates lies within the accepted range with a value of 2.62.

**Table 3: Specific Gravity for Coarse Aggregate**

SAMPLES	A	B	
W1	Weight of Density Bottle	820	854
W2	Weight of Bottle + Sample	2800	2884
W3	Weight of Bottle + Sample + Water	3687	3733
W4	Weight of Bottle + Water	2453	2478
	Gs (Specific Gravity)	2.7	2.62
	Average Specific Gravity Value	2.66	

Specific gravity of the aggregates is taken into consideration as a sign of strength. Materials with higher specific gravity is usually believed to be stronger than others. Aggregates that are normally used in construction have a specific gravity that averagely goes to about 2.68 with a range that is usually between 2.5-3.0. The average value of specific gravity of the coarse aggregates will fall within the accepted range as a result in Table 4, the value is identified to be 2.66.

### 3.2.2 Water Absorption

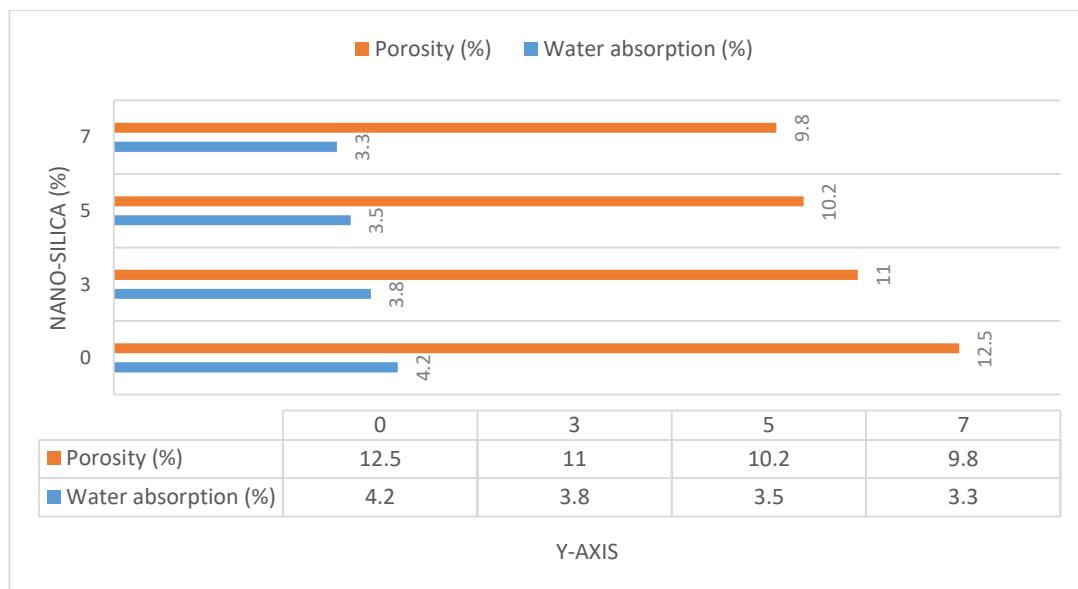
$$\text{Water absorption (\%)} = \frac{\text{Moist weight}}{\text{dry weight}} \times 100 \quad (7)$$

**Table 4: Water Absorption for Fine Aggregate**

SAMPLES	A(g)	B(g)	
W1	Weight of Can	26	28
W2	Weight of Can + Wet Soil	148	150
W3	Weight of Can + Dry Soil	126	130
	Water Absorption (%)	22	19.6
	Average Water Absorption Value	21	

**Table 5: Water Absorption for Coarse Aggregate**

SAMPLES	A(g)	B(g)	
W1	Weight of Can	20	27
W2	Weight of Can + Wet Soil	155	196
W3	Weight of Can + Dry Soil	153	193
	Water Absorption (%)	1.50	1.81
	Average Water Absorption Value	1.66	



**Figure 1: Water Absorption and Porosity vs Nano-Silica Content**

### 3.2.3 Density

$$\text{Bulk Density } \left(\frac{\text{kg}}{\text{m}^3}\right) = \frac{\text{Dry Mass}}{\text{Total Volume}} \quad (8)$$

**Table 6: Bulk Density for Fine Aggregate**

SAMPLES	A(g)	
W1	Weight of Cylinder	3804
W2	Weight of Cylinder + Dry Soil	12663
W3	Weight of Dry Soil (W2-W1)	8859
	Bulk Density (Kg/m <sup>3</sup> )	1406

**Table 7: Bulk Density for Coarse Aggregate**

SAMPLES	A(g)	
W1	Weight of Cylinder	3804
W2	Weight of Cylinder + Dry Soil	12062
W3	Weight of Dry Soil (W2-W1)	8258
	Bulk Density (Kg/m <sup>3</sup> )	1311

The bulk density of aggregate is the weight of aggregate needed to fill a unit volume of the container. The approximate value of bulk density for aggregate usually used for normal weight concrete varies between 1200-1750 kg/m<sup>3</sup>. The used aggregate for this research work falls in between this range value which means the aggregates (fine & coarse) are desirable.

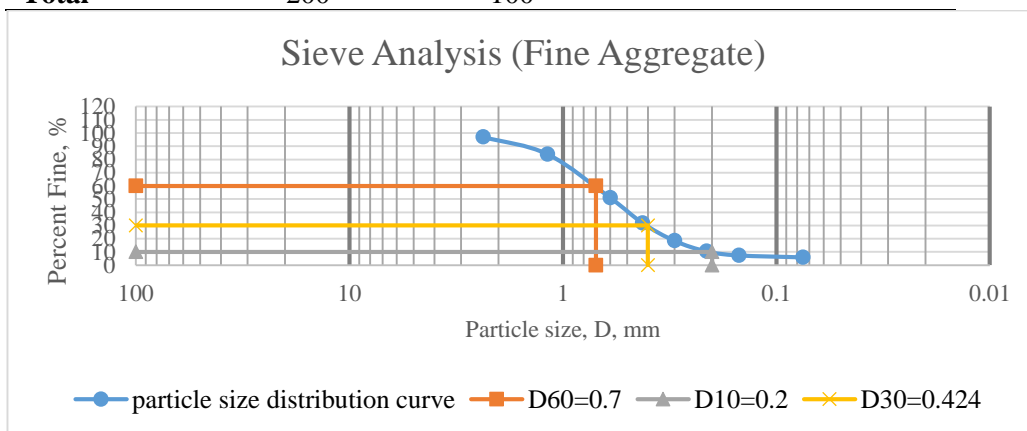
### 3.2.4 Sieve Analysis

This test is carried out in accordance with ASTM D6913: Standard test method for particle-size distribution (gradation).

**Table 8: Sieve Analysis for Fine Aggregate**

Weight of sample= 200g

SIEVE SIZE (mm)	RETAINED WEIGHT(g)	PERCENTAGE RETAINED (%)	PERCENTAGE PASSING (%)
2.36	6	3	97
1.18	26	13	84
0.600	66	33	51
0.425	38	19	32
0.300	27	13.5	18.5
0.212	17	8.5	10.5
0.150	5	2.5	7.5
0.75	3	1.5	6
Dust	12	6	0
Total	200	100	



**Figure 2: Sieve Analysis Graph for Fine Aggregate**

Find coefficient of uniformity and coefficient of curvature.

$$Cu = D_{60}/D_{10}$$

$$Cu = \frac{0.7}{0.2} = 3.5$$

$$Cu = 3.5$$

$$Cc = \frac{(D_{30})^2}{(D_{60} \times D_{10})}$$

$$Cc = \frac{(0.424)^2}{0.7 \times 0.2} = 1.28$$

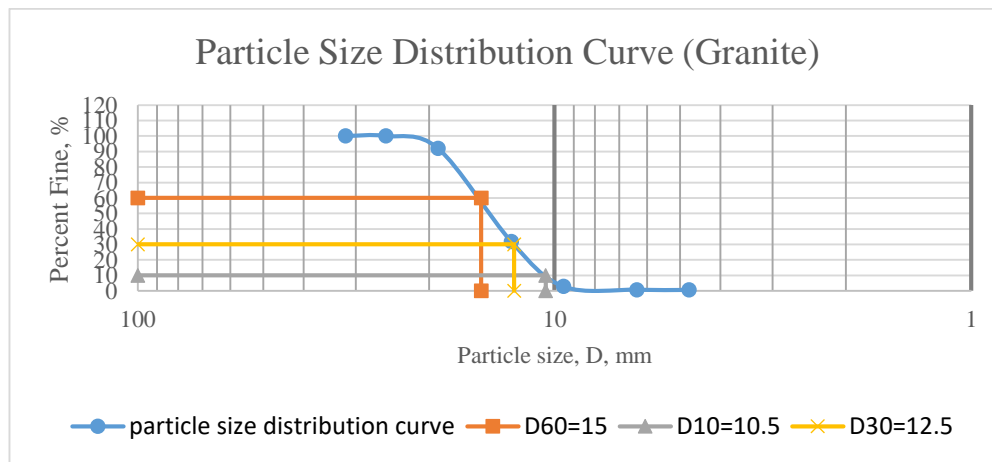
$$Cc = 1.28$$

The values of Cu and Cc are used to classify whether the soil is well graded or not. Sand is considered well graded, if Cu is greater than 6 and Cc is between 1 and 3. From Figure 2 uniform of coefficient (Cu) is 3.5 while Coefficient of curvature is 1.28 which indicates that the soil is uniformly graded.

**Table 9: Sieve Analysis for Coarse Aggregate**

Weight of Sample= 1000g

SIEVE SIZE (MM)	RETAINED WEIGHT (g)	RETAINED PERCENTAGE (%)	PERCENTAGE PASSING (%)
31.75	0	0	100
25.40	0	0	100
19.05	79	7.9	92.1
12.70	603	60.3	31.8
9.52	290	29.0	2.8
6.35	21	2.1	0.7
4.76	1	0.1	0.6
Dust	6	0.6	0
Total	1000	100	



**Figure 3: Sieve Analysis Graph for Coarse Aggregate**

$$Cu = D_{60}/D_{10}$$

$$Cu = \frac{15}{10.5} = 1.43$$

$$Cu = 1.43$$

$$Cc = \frac{(D_{30})^2}{(D_{60} \times D_{10})}$$

$$Cc = \frac{(12.5)^2}{15 \times 10.5} = 1$$

$$Cc = 1$$

From figure 4.3 above it and value of Cu and Cc it can be said that the coarse aggregate is well graded because for the soil to be well graded, the value of Cc must range between 1 and 3. For any single sized soil mass, the value of both Cu and Cc is 1.

The physical attributes of the aggregates attest that they can be used in high-strength concrete. The fine (2.62) and coarse aggregates (2.66) specific gravity values lie within 2.5 to 3.0 as a standard range and therefore show a satisfactory density and strength. Fine aggregates had higher water absorption with an average of 21 percent compared to 1.66 percent in coarse aggregates, implying that it would have more porosity and water retention capacity. The values of bulk density (1406 kg/m<sup>3</sup> of fine and 1311kg /m<sup>3</sup> of coarse) also fell within the range of recommended values (1200 1750 kg/m<sup>3</sup> ). Sieve analysis revealed that fine aggregates were evenly graduated whereas the coarse aggregates were single sized. Proper blending increases the efficiency of packing and strength.

### 4.3 Mechanical Properties

#### 4.3.1 Compressive Strength (Target grade = 45 N/mm<sup>2</sup>)

**Table 10: Compressive Strength Results of HSC with Nanosilica**

Mix ID	% Nanosilica	7 Days (N/mm <sup>2</sup> )	14 Days (N/mm <sup>2</sup> )	21 Days (N/mm <sup>2</sup> )	35 Days (N/mm <sup>2</sup> )
Control (C0)	0%	32.5	41.2	47.6	53.8
NS-3	3%	36.8	45.5	51.4	59.2
NS-5	5%	38.6	48.9	55.7	63.5
NS-7	7%	34.7	44.0	50.3	57.0

**Table 11: Flexural Strength of HSC with Nanosilica at 21 Days**

Mix ID	% Nanosilica Replacement	Average Flexural Strength (MPa)	% Increase Compared to Control
Control	0% (No Nanosilica)	5.8	–
NS-3	3%	6.5	+12%
NS-5	5%	7.1	+22%
NS-7	7%	6.7	+16%

**Table 12: FTIR Spectra of Control vs Nano-Silica Concrete**

Wavenumber (cm <sup>-1</sup> )	Control Mix (%)	Nano-Silica Mix (%)	Description
4000	92	90	General transmittance
3400	88	83	–OH Stretch
1640	85	80	H–O–H bending
1090	75	65	Si–O–Si vibration (C–S–H)
800	88	84	Si symmetric stretch
460	91	89	Si–O rocking

#### 3.2.5 SEM/EDX

Mole % Conversion from wt. %

To calculate mole percent from weight percent, the following relationship was used:

$$\text{Mole \% of oxide} = \frac{\frac{\text{wt.}\%_i}{M_i}}{\sum \frac{\text{wt.}\%_j}{M_j}} \times 100 \quad (9)$$

Where:

Wt.%<sub>i</sub> = weight percent of oxide

M<sub>i</sub> = molecular weight of oxide

$\sum \frac{\text{wt.}\%_j}{M_j}$  = total moles of all oxides detected

Example Calculation for SiO<sub>2</sub>:

$$n_{\text{SiO}_2} = \frac{97.583}{60.08} = 1.624 \text{ mol}$$

$$n_{\text{total}} = \text{wt.\%M} = 1.624 + 0.0103 + 0.00325 + 0.00079 = 1.6383 \text{ mol}$$

$$\text{Mole \% SiO}_2 = \frac{1.624}{1.6383} \times 100 = 98.044\%$$

**Table 13: SEM/EDX Elemental Composition of Nanosilica in HSCB**

Oxide	Concentration (wt.%)	Mole %	Notes
SiO <sub>2</sub>	97.583	98.044	High purity, dominant
Al <sub>2</sub> O <sub>3</sub>	1.050	0.622	Secondary constituent
CaO	0.182	0.196	Minor presence
Fe <sub>2</sub> O <sub>3</sub>	0.127	0.048	Minor presence
Others	<0.1 each	—	Trace oxides (V <sub>2</sub> O <sub>5</sub> , MnO, TiO <sub>2</sub> )

Design Resistance ( $R_d$ ):

$$R_d = \frac{f_{ck}}{\gamma_c} \times A_c \quad (10)$$

Where:

 $f_{ck}$  = characteristic compressive strength (MPa) = 60 $\gamma_c$  = partial safety factor for concrete = 1.5 $A_c$  = effective cross-sectional area (mm<sup>2</sup>) = 0.015m<sup>2</sup>

$$R_d = \frac{60}{1.5} \times 0.015 \times 10^6 = 600 \text{ kN}$$

Design Load Effect ( $S_d$ ):

$$S_d = \gamma_f \times F_k \quad (11)$$

$$S_d = 1.4 \times 150 = 210 \text{ kN}$$

Safety Check:

$$R_d > S_d \rightarrow 600 > 210$$

Thus, the deterministic design confirms the beam is safe under applied loading.

**Table 14: Deterministic Design Results of HSCB**

Parameter	Value	Remarks
Characteristic Strength ( $f_{ck}$ )	60 MPa	Nanosilica blended concrete
Characteristic Load ( $F_k$ )	150 kN	Applied load
Design Resistance ( $R_d$ )	600 kN	Capacity of beam
Design Load Effect ( $S_d$ )	210 kN	Load after safety factor
Safety Status	Safe	$R_d > S_d$

### 3.2.6 Reliability Analysis

1. Limit State Function:

$$g(X) = R - S \quad (12)$$

Where:

R = Resistance (random variable, mean = 650 kN, COV = 0.15)

S = Load Effect (random variable, mean = 200 kN, COV = 0.10)

Standard Deviation of Resistance and Load:

$$\sigma_R = \text{COV}_R \times \mu_R = 0.15 \times 650 = 97.5 \text{ kN}$$

$$\sigma_S = \text{COV}_S \times \mu_S = 0.10 \times 200 = 20 \text{ kN}$$

Mean of Limit State:

$$\mu_g = \mu_R - \mu_S = 650 - 200 = 450 \text{ kN}$$

Standard Deviation of Limit State:

$$\sigma_g = \sqrt{\sigma^2 R + \sigma^2 S} = \sqrt{97.5^2 + 20^2} = 99.5 \text{ kN}$$

Reliability Index ( $\beta$ ):

$$\beta = \frac{\mu_g}{\sigma_g} = \frac{450}{99.5} = 4.52$$

Probability of Failure (Pf):

$$P_f = \Phi(-\beta) = \Phi(-4.52) \approx 3.1 \times 10^{-6}$$

This shows that the beam has an extremely low probability of failure, confirming that nanosilica significantly enhances reliability.

**Table 15: Reliability-Based Design Results of HSCB**

Parameter	Value	Remarks
Mean Resistance ( $\mu R$ )	650 kN	Based on nanosilica mix strength
Mean Load ( $\mu S$ )	200 kN	Applied load
Std. Dev. of Resistance ( $\sigma R$ )	97.5 kN	COV = 0.15
Std. Dev. of Load ( $\sigma S$ )	20 kN	COV = 0.10
Reliability Index ( $\beta$ )	4.52	Very high
Probability of Failure (Pf)	$3.1 \times 10^{-6}$	Negligible

**Table 16: Comparison of Deterministic and Reliability-Based Design Results**

Parameter	Deterministic Design	Reliability-Based Design
Characteristic Strength (MPa)	60	60
Mean Strength (MPa)	—	65
Applied Load (kN)	200	200
Partial Safety Factor	1.5	—
Design Resistance (kN)	240	—
Reliability Index	—	3.45
Probability of Failure (%)	—	0.03
Safety Level	Conservative	Realistic and consistent

#### 4. CONCLUSION

- i. Primary properties of aggregates and nano-silica were determined by means of material characterization. Aggregates met requirements of standard specifications as pertaining to grading, specific gravity, and moisture content, and were therefore suitable in high strength applications. The XRF characterization of nano-silica showed a hetero-atom-free component ( $> 95\%$  SiO<sub>2</sub>) with the presence of trace oxides and the SEM micrograph clearly showed ultra-fine particle morphology with uniform dispersion tendencies.
- ii. The assessment of physical characteristics of concrete mixes showed that nano-silica adds decreased water absorption and higher density as compared to control mixes, which implies compactness of pore system improvement.
- iii. The result of identification of the mechanical properties was constant improvement in the compressive and flexural strength of HSCBs with the nano-silica-reinforced controls. The optimal dose (e.g., 2-4% replacement) exhibited strength increase of 12-18 percent, which defines the possible contribution of nano-silica in smoothing the interface transition zone (ITZ) and enhancing the rate of hydration kinetics.
- iv. FTIR and SEM interaction studies confirmed that nano-silica was actively involved in pozzolanic reactions and further calcium silicate hydrate (C-S-H) gels were formed that densified the matrix. The strength improvements associated with mechanical tests were explained by SEM observations of less micro-cracks and more compact ITZ on nano-silica-modified concrete. This microstructural analysis supported the chemistry reactivity and filler effect of nano-silica that improved matrix quality.
- v. A method of reliability analysis of beam specimens demonstrated the weakness of conventional deterministic design. Deterministic calculations yielded single safety margins reliability-based methods included the variation in material configuration, loading and geometrical conditions.
- vi. A comparison of deterministic and reliability-based approximations was made to illustrate that deterministic design had the propensity to provide overestimates of the safety margins whereas, reliability provided a more sensible review of the structural performance regarding uncertainty.

#### Recommendations

- i. The study revealed that incorporating 5% nano-silica by weight of cement provided the best

- balance between workability, strength, and durability. Therefore, for practical construction applications, the replacement level of 3–5% nano-silica is recommended for structural members requiring high performance and long-term reliability.
- ii. Designers and engineers should adopt reliability-based design methods alongside deterministic approaches in assessing the safety and performance of HSCBs. The RBD approach provides a more rational evaluation by accounting for uncertainties in material strength, load variations, and environmental effects.

## NOMENCLATURE

kN	KiloNewton
$\beta$	Reliability Index

## Abbreviations

FTIR	Fourier Transform Infrared Spectroscopy
EDX	Energy Dispersive X-ray Spectroscopy
Gs	Specific Gravity

## ACKNOWLEDGEMENTS

I thank Almighty Allah for His guidance, my supervisor Prof. John Wasu for his mentorship, and Engr. Dr. Ibrahim A.O. for his support. Appreciation is extended to the Faculty of Engineering, Civil Engineering Department staff of Edo State University Iyamho and my family, especially my wife, for their constant encouragement.

## REFERENCES

- American Concrete Pavement Association. (2020). Recycling concrete pavements.
- Bhanja, S., & Sengupta, B. (2018). Nano-silica in concrete: A review. *Materials Today: Proceedings*, 5(1), 18512-18518.
- Chen, Y., Zhang, H., Liu, J., & Li, Y. (2021). Effects of nano-SiO<sub>2</sub> on the compressive strength of concrete-filled stainless steel columns. *Journal of Construction and Building Materials\**, 283, 122703.
- Figueiredo, P. A., Nascimento, J. C., & Silva, M. A. (2021). High strength concrete: A review of its properties and applications in bridges. *Materials Research*, 24(3), e20200624.
- Ghafari, E., Costa, H., & Júlio, E. (2014). Critical review on eco-efficient ultra-high performance concrete. *Construction and Building Materials*, 51, 251–267. <https://doi.org/10.1016/j.conbuildmat.2013.10.047>
- Ghosh, P., & Kundu, A. (2019). Life cycle cost analysis of high strength concrete and normal strength concrete in construction. *International Journal of Civil Engineering and Technology*, 10(1), 1125-1134.
- Hamraj, Mohd & Puppala, Ashveen Kumar & preethi, M. (2019). Strength Characteristics of High Strength Concrete (HSC) with and without Coarse Aggregate. *International Journal of Engineering and Advanced Technology*. 9. 10.35940/ijeat.B5131.129219.
- Huang, X., Li, S., & Huang, Y. (2016). The application of high strength concrete in tall buildings. *Journal of Advanced Concrete Technology*, 14(8), 483-489.
- Jalal, M., & Khosravi, A. (2015). Comparative study on effects of Class F fly ash, nano silica and silica fume on properties of high performance self compacting concrete. *Materials Today: Proceedings*, 2(4), 1-6.
- Jalal, M., Pouladkhan, A., & Harandi, O. F. (2021). Comparative performance of nano-silica and silica fume as supplementary cementitious materials in concrete. *Materials Today: Proceedings*, 42, 1540–1547.
- Kashyap, Vikram & Sancheti, Gaurav & Yadav, Jitendra. (2023). Smart sustainable concrete: enhancing the strength and durability with nano silica. *Smart Construction and Sustainable Cities*. 1. 10.1007/s44268-023-00023-1.
- Li, Xiuling & Wang, Juan & Bao, Yi & Chen, Genda. (2017). Cyclic behavior of damaged reinforced concrete columns repaired with high-performance fiber-reinforced cementitious composite. *Engineering Structures*. 136. 26-35. 10.1016/j.engstruct.2017.01.015.
- Mehta, P. K., & Monteiro, P. J. M. (2014). *Concrete: Microstructure, properties, and materials* (4th ed.). McGraw-Hill Education.

- Melchers, Adeeb. (2019). Comparison between ACI 318-05 and Eurocode 2 (EC2-94) in flexural concrete design. *Structural Engineering and Mechanics*, 32. 10.12989/sem.2009.32.6.705.
- Nowak, A. S., & Collins, K. R. (2013). *Reliability of structures* (2nd ed.). CRC Press.
- Prashanth, K., Shashidhara, H. S., & Raghavendra, Y. (2021). Influence of nano-SiO<sub>2</sub> on the properties of concrete: A review. *\*Materials Today: Proceedings\**, 45, 7945-7949.
- Quercia, G., & Brouwers, H. J. H. (2014). Application of nano-silica (nS) in concrete mixtures. *Cement and Concrete Composites*, 45, 69–81.
- Singh, L. P., Karade, S. R., Bhattacharyya, S. K., Yousuf, M. M., & Ahalawat, S. (2013). Beneficial role of nanosilica in cement based materials – A review. *Construction and Building Materials*, 47, 1069–1077. <https://doi.org/10.1016/j.conbuildmat.2013.05.052>
- Singh, S. P., & Subramanian, A. (2016). Role of nanosilica in enhancing the properties of concrete. *International Journal of Engineering Research and Applications*, 6(5), 1-6.
- Zhang, M., Li, Y., & Qin, X. (2019). The effect of nano-silica on the properties of silica fume modified mortar. *\*Materials Science and Engineering: A\**, 760, 1-9.