

EXPERIMENTAL ASSESSMENT OF HIGH-STRENGTH CONCRETE CONTAINING WASTE SEASHELL POWDER AND NANO-SILICA

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ABSTRACT

As one of the top contributors to overall CO₂ emissions worldwide, a sustainable material solution is imperative without sacrificing performance from the concrete industry. This paper experimentally explores the combined effectiveness of two such materials: Waste Seashell Powder (SSP), which is a biogenic waste with relatively high calcium content, and Nano-Silica (NS), an effective pozzolanic nanomaterial in the production of High-Performance Concrete (HPC). The procedure included a well-designed experimental program whereby SSP (0, 6.5%, 7.5% and 9%) by weight substituted cement, whereas NS (2% and 3%) as weight was added. A complete data set was made by testing the fresh property (slump), mechanical properties (compressive strength at 7, 28, and 56 days), and the main durability parameters (water permeability and rapid chloride penetrability). Experimental values of modulus of elasticity (MOE) and compressive strength were compared to the predictive models from the international codes (ACI 318, CEB-FIP, BS 8110, Eurocode), using the coefficient of determination (R²), which is considered a primary comparison criterion. Trade-off The findings showed a trade-off, workability reduction up to 35.7% in the case of 9% SSP with and 3% NS. On the other hand, mechanical and durability characteristics were improved significantly. Compressive strength of the 7.5% SSP and 3% NS mix was highest, while the percentage reduction in chloride ion penetrability and water permeability coefficient was found to be maximum for the 9% SSP and 3% NS mix at 37.7 and 20%, respectively. The ACI 318 model was most efficient in forecasting MOE (R² = 0.881). In summary, the coupling of SSP and NS strategically converts an industrial waste into a high-order resource, enabling the development of a greener, better-performance concrete based on circular economy principles.

Keywords: *High-strength concrete, waste materials, nano-silica, concrete modification, durability properties.*

1. INTRODUCTION

Concrete is the dominant construction material, but it's emissions-intensive, partly because producing cement requires an extremely energy-intensive process [1]. In contrast, demand for sustainable options is growing, which both minimizes ecological impact and provides better performance. Waste seashell powder and nano-silica are two potential materials in this aspect. Waste seashell powder from shellfish-industry's waste has high quantities of calcium carbonate (CaCO_3) and can be utilized as a filler/partial replacement in cementitious systems [2]. Many studies have been conducted on the use of seashell powder in concrete, and, for example, a review demonstrated that most increases in mechanical strength were seen when the substance was used to replace cement up to 5%–15%, but with highly variable results between shell species, processing methods, and mix design [3]. Several studies have investigated the utilization of waste seashells as supplementary cementitious material, fine aggregate substitution, or alternative binder in concrete.

An even more recent review by Hadjadj, Guendouz [4] listed the various physical, mechanical, and performance properties of seashell-based cementitious mixes, concluding that, in general, while compressive strength at early ages can be lower, tensile properties and durability seemed to improve in some applications when using seashells. Further, Shetty, Rao [5] modified seashells to partially replace cement and/or fine aggregate, where a maximum increase of compressive strength of ~30% at the later stage was observed when the waste modified the mechanical properties of concrete with seashell waste. The results indicate that seashell waste can be an efficient, sustainable constituent to replace the mineral aggregates in concrete; however, it is a function of mix design, treatment of shell material, and the desired strength class of concrete.

Alongside seashell research, nano-silica (NS) application in concrete has received significant attention for improvement of microstructure, packing density, pozzolanic activity, and long-term durability. For example, in the study *The Effect of Nano Silica on Mechanical Properties and Durability of Normal Strength Concrete*, they found that the adding nano-silica led to increases in compressive strength and refinement with a reduction of pore size and chloride permeability for normal-strength concrete [6]. A recent review of the article reported that with nano-silica percentages around 2%–3% by cement weight receive impressive mechanical and durability benefits, i.e, they experience lower water absorption, sulfate, and acid resistance [7]. Further still, the effect of nano-silica on strength and durability was revealed, that 3% nano-silica resulted in the best increase in compressive strength with a significant reduction in sorptivity, but the cost above that became much slower while posing workability challenges [8]. These results stress the importance of nano-silica in the construction of concrete matrices that are denser and more durable.

Although both seashell powder and nano-silica have a wide range of standalone applications that are not limited, there is a growing trend to study how these two materials work on tasks. A study on *Exploring the influence of seashell powder and nano-silica in ultra-high-performance self-curing concrete* incorporated seashell powder and nano-silica into UHPCS, resulting in gains of moderate mechanical, durability properties, but also a decrease in compressive strength with an increase in seashell content [2]. In contrast, the prior report from Sun, Alqurashi [9], *Behavioral Study of Fresh and Mechanical Properties HSC in terms of Seashell Powder as a Cementitious Material Replacement with Waste Glass Powder as a Fine Aggregate* examined fresh (slump flow, T_{500}/T_{700}), mechanical, and microstructural properties of HSC where seashell powder replacing cement content was considered, side by side with waste glass powder replacing fine aggregate. An optimum replacement of ~5% seashell was considered to be applicable since further increase in its proportion led to slump flow and workability decreases. Cumulatively, these works of literature indicate a possible role for both materials (seashell waste and nano-silica) individually, but limited work is starting to investigate them with higher-strength concrete when they are together. Despite these recent developments, however, several crucial gaps still need to be addressed. Primarily, the majority of studies conducted to date on seashell-concrete are limited to low or medium strength mixes (e.g., 30–40mpa), with less research undertaken in true high-strength concrete (≥ 60 mpa) where

performance requirements are more pronounced. Secondly, although the use of nano-silica has been a common practice in normal and high-performance concrete, the effect of interaction (synergy) between seashell powder and nano-silica on high-strength concrete is not yet explored. The third point is that in most studies, emphasis has been placed on only mechanical properties (compressive and tensile strengths) rather than comprehensive durability (e.g., water absorption, permeability chloride penetration that arise during the loading of stress or shrinkage), fresh properties of concrete (workability, slump) when both additives are adopted together. Finally, the optimal content of seashell powder and nano-silica combination to balance workability, strength, and durability for high-strength concrete remains unsolved. The present work is conducted to fill these gaps by studying fresh, mechanical, and durability performance of high-strength concrete mix containing seashell powder at different levels (5%–15% replacement) along with nano-silica (1%–3%) addition systematically. In doing so, it will determine an optimal mixture for workability, strength, and durability, and provide a greater understanding of the interaction between these two materials within a high-strength concrete framework.

2.METHODOLOGY

Characterization and testing of all materials used in the study (cement, aggregates, nano-silica, seashell powder, and steel fiber) were as per the relevant ASTM standards to establish the suitability for production of HSC.

2.1 Materials

All concrete samples were made with the ordinary Portland cement (OPC) type I, obtained from local markets. The cement was of ASTM C150 standard and designed to have consistent quality and performance [10]. Natural river sand from Rupsha ghat at Khulna, Bangladesh, was used. The sand was washed, oven-dried, and then sieved by the standard sieve series available at the KUET materials laboratory. The physical properties of materials, such as SG, fineness modulus, water absorption, and wet rodded density, were determined according to ASTM C128 [11] and ASTM C29 [12]. 2.78, 1.62% for fineness modulus, water absorption. The coarse aggregate used was crushed stone locally available. The material was rinsed, dried, and screened to the desired particle size. Their physical properties, namely specific gravity, water absorption [13]. Fineness Modulus (FM) and Dry Rodded Unit Weight were established as per ASTM C127 and ASTM C128. Seashell powder (SSP) chemical analysis indicates that it exists in the form of predominantly calcium oxide (CaO), 68.20% which is largely responsible for imparting good bonding characteristics in the concrete. Other compounds, such as silicon dioxide (SiO₂) and iron oxide (Fe₂O₃), also affect its action, particularly in relation to longevity. The average particle size and the specific surface area of nano-silica, i.e., 200 used in this study, are 12nm and 200 m²/g, respectively, which also improve the pozzolanic reaction and microstructure refinement of concrete. Nano-silica is over 99.8% pure and adds more strength, density, and durability to concrete. Finally, the steel fibres, 12.5 mm in length with a diameter of 0.45 mm and an aspect ratio equal to 27.7, are used for reinforcing the concrete, increasing its tensile strength (1100 MPa) and crack resistance, and due to their high density (7850 kg/m³), they contribute effectively to strengthening the structural behaviour of the concrete. As a whole, these materials are important to enhance the mechanical strength and durability of high-performance concrete. Table 1 shows the chemical composition of ordinary portland cement. The physical properties of the aggregates are presented in Table 2. Chemical Composition of Seashell Powder is presented in Table 3. Properties of Nano Silica in this study (Data Provided by the Manufacturer) are presented in Table 4. Table 5 presents the characteristics of steel fiber. This test done by ASTM C1365 standard.

Table 1: Chemical Composition of Ordinary Portland Cement

Material	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	Na ₂ O	LOI	K ₂ O
OPC	18.80	5.8	4.1	63.50	1.92	2.4	1.205	1.24	2.76

Table 2: Physical Properties of Aggregates

Properties	Fine Aggregate	Coarse Aggregate
Specific Gravity	2.36	2.72
Absorption (%)	1.62	1.18
Fineness Modulus	2.78	4.27
Compacted Unit Weight (kg/m ³)	1566	1732

Table 3: Chemical Composition of Seashell Powder

Material	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	Na ₂ O	LOI	K ₂ O
SSP	0.89	0.16	0.78	68.20	0.96	0.21	1.05	27.65	0.10

Table 4: Properties of Nano Silica in this study (Data Provided by the Manufacturer)

Product Name	Average Particle Size (nm)	Specific Surface Area (m ² /gm)	Purity (%)	Manufacturer
AEROSIL 200	12	200 ± 25	>99.8	Degussa, Germany

Table 5: Characteristics of Steel Fiber

Material	Shape	Length (mm)	Diameter (mm)	Aspect Ratio	Tensile Strength	Density (kg/m ³)
Stainless Steel	Corrugated	12.5	0.45	27.7	1100	7850

2.2 Mixture and proportions

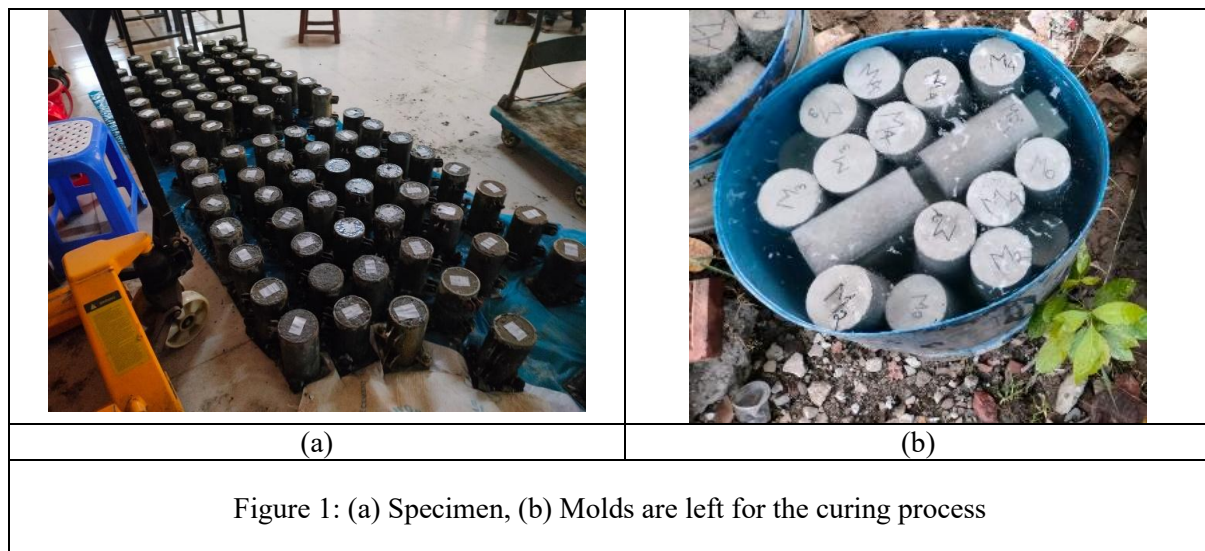
The water/binder ratio used in the present study and the HSC mix proportions were determined based on criteria provided in 211.4R-08 of the American Concrete Institute [14]. Mix proportions for each batch of HSC are shown in Table 3. In this study, seashell powder was used to substitute cement in concrete, and two different doses of NS (2% and 3%), which were also types of cementitious material, were added, whilst the SS powders' (50–150 μm) substitution ratios varied between 6.5% and 9%. The other HSC waves were assigned to the SSP6 batches. 5NS2, SSP7. 5NS2, SSP9NS2, SSP6. 5NS3, SSP7. (P5) NS3, 5NS3, and SSP9NS3, together with two negative controls termed SSP0NS2 and SSP0NS3, were determined. The water-to-binder ratio was fixed at 0.32 and the WR agent SP was used as a constant in all batch mixes. The mixing process was in conformity with the provisions of ASTM C192/C192M-18 [15]. The detailed mix composition is shown in Table 6.

Table 6: Concrete Mix Design (kg/m³)

Mix No	Mix ID	W/B	Cement (%)	NS (%)	SSP (%)	CA (%)	FA (%)	ST (%)	SP (%)
01	SSP0NS2	0.32	100	2	0	100	100	0	1.3
02	SSP6.5NS2		91.5		6.5			0	
03	SSP7.5NS2		90.5		7.5			1.5	
04	SSP9NS2		89		9			1.5	
05	SSP0NS3		100	3	0			1.5	
06	SSP6.5NS3		90.5		6.5			1.5	
07	SSP7.5NS3		89.5		7.5			1.5	
08	SSP9NS3		88		9			1.5	

2.3 Preparation of Specimen, Casting, and Curing

All samples complied with ASTM C192 [16]. Compressive strength tests were performed on the cylinder specimens with a 100 X 200 mm-diameter mold. After a short mixing time, the fresh properties of each new batch of concrete were measured. Pour fresh concrete into the mold side without vibration once coated with lubricating oil. The molds were filled with the fresh concrete carried out in three layers and were compacted with a 16 mm rod, subjected to 25 strokes per layer. Then, after 24 h, the samples were maintained at a temperature of 25 ± 2 °C and tagged with identification numbers. The specimens were soaked in potable water and cured in a plastic curing tank for 7, 28, and 56 days. The laboratory made and cured each sample following the guidelines of ASTM C192/C192M-18 [17]. The specimen (a) and the curing process (b) are shown in Figure 1.



2.4 Test Setup and Instrumentation

The workability of the mixtures was evaluated by standard tests. The consistency of the mix was determined by the slump test according to ASTM C143/C143M [18]. By performing these tests, each mix was able to achieve an adequate workability for a proper placement and finish. Mechanical behavior was characterized by compressive strength and splitting tensile strength experiments. Compressive strength was tested at the ages of 7, 28, 56 days according to ASTM C39/C39M for cube specimens [19]. Durability was also analyzed to determine the resistance of modified concretes to fluid and chemical penetration. The following tests were conducted: Sorptivity Tests (ASTM C1585) [20] Water penetration Test, according to BS EN 12390-8, for permeability depth under pressure. Rapid Chloride Penetration Test (RCPT) according to ASTM C1202 for the determination of resistance against chloride ion penetration.

3. RESULTS AND DISCUSSIONS

3.1 FRESH PROPERTIES

Figure 2 illustrates the slump test outcomes for both the reference mix and several additional combinations of high-strength concrete (HSC). The drop rates ranged from 63 to 98 mm, in compliance with the recognized requirements for high-strength concrete slump flow set by the American Society for Testing and Materials (ASTM-C143/C143M) [21]. The drop value shows a reduction when the proportion of SSP replacement increases, regardless of whether it is 2% or 3% NS content. This indicates a loss in workability. The drop in values is most significant when there is no SSP replacement, with a measurement of 98 mm for 2% NS and 80 mm for 3% NS, both of which are considered to be within the medium workability range. As the substitution of SSP increased to 6.5%, 7.5%, and 9%, the decline values dropped to the closest lower range of workability. When the SSP replacement level is increased to 3% NS, the values decrease to 76 mm, but with a replacement level of 2% NS, the values decrease to 63 mm. This pattern suggests that higher levels of NS and SSP substitution led to stiffer mixes, which might make it challenging to position the concrete. However, it could also improve some quality attributes like durability and strength.

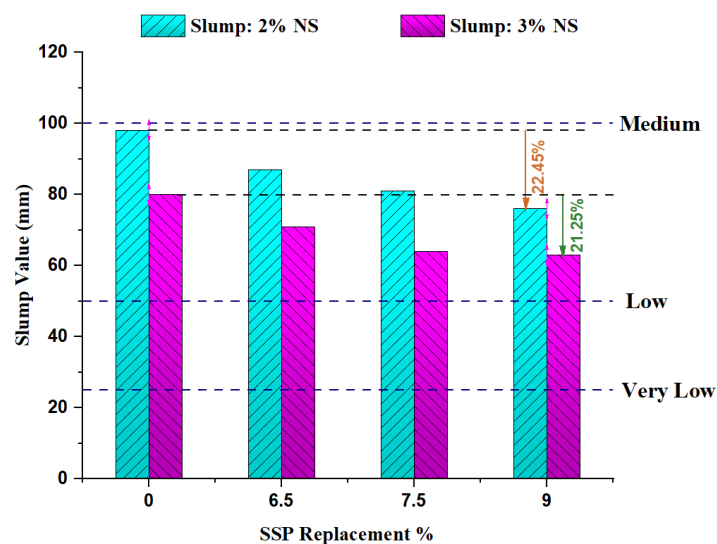


Figure 2: Slump Value with % SSP Replacement

The analysis of slump flow indicated that the mixture SSP9NS3 exhibited an ideal value of 63 mm, whereas the control mixture (SS0NS3) had a value of 80 mm. Upon closer analysis, it was discovered that the decrease in values of the different combinations, such as 0%, 6.5%, 7.5%, and 9% SSP, in addition to the constant 2% and 3% NS, were 11.22%, 17.35%, and 22.45% less than the control mixtures SSP0NS2 and SSP0NS3, respectively. The reduction in droop that was observed may be attributable to the material's increased surface area and decreased particle size, which facilitate water absorption but impede workability. The lowest slump rate was recorded at 9% substitution of SSP and 3% substitution of NS, as these findings are consistent with previous studies by [22], which observed a similar trend of decreasing slump with SSP incorporation. The addition of 0.5% steel fiber was found to reduce the workability in terms of increasing internal friction, surface area demand and mechanical interlocking among fibers, such that vertical deformation of fresh concrete is restricted, leading to lower slump values than traditional non-fiber high-strength concretes found within literature. Steel fibers develop a distributed reinforcement system in the fresh state, opposing slump-under influences against cohesive flow and mixture stiffness, particularly for low water-binder ratio concretes. This can also increase the demand for water around the fibers' surfaces and retain some of the mixing water in the fiber network, subsequently causing slump loss. Moreover, fiber interlocking hinders particle movement, retard fresh mix densification, and limits the freedom of concrete to deform freely under its own weight. Nevertheless, being the dosage of fibre used in all mixes was constant, it did not interfere with plotting the comparison of trend between mixes containing waste seashell powder and nano-silica. In addition, fibers also provided a positive effect on the stability of fresh mix, through which segregation potential was described as controlled, and early-age micro-crack initiation during casting and handling operation was restricted in the absolute value of slump but induced as well as stiffness.

3.2 Mechanical Properties

Figure 3(a) illustrates the test results for the compressive strengths of the concrete mixes at 7, 28, and 56 days. The control mix-1 (SSP0NS2) had a 28-day compressive strength of 47.34 MPa, whereas the control mix-2 (SSP0NS3) had a compressive strength of 47.27 MPa. This amounts to a decrease in strength of 0.15% compared to the concrete SSP0NS2. However, after a period of 28 days, the compressive strengths of the SSP7.5NS3 and SSP9NS3 combinations show an increase of 3.44% and 1.85% respectively, compared to the SSP7.5NS2 and SSP9NS2 mixtures. In addition, Figure 5 demonstrates that the compressive strengths of the SSP6.5NS2, SSP7.5NS2, and SSP9NS2 mixes at 7 days are 21.44%, 16.42%, and 28.04%, respectively, compared to the SSP0NS2 mix. The compressive strengths of the SSP6.5NS3, SSP7.5NS3, and SSP9NS3 mixes at 7 days are 5.68%, 21.18%, and 37.52% of the compressive strength of the SSP0NS3 concrete. The increment in the compressive strength with the percent replacement has similar patterns at 56 days, as the SSP particles generate greater cement matrix bonding, as which improves particle packing and greater pozzolanic reactions [23]. A higher percentage of ns helps in the process of improving the more delicate characteristics, as the inclusion of 3% ns resulted in better strength compared to the inclusion of 2% ns. The development of calcium silicate hydrate (C-S-H) gel arises from the chemical reaction between calcium carbonate present in seashell particles and the hydration byproducts of cement. In the end, the process of gelation improves the strength of concrete by helping to create a more uniform microstructure. Imran and zulkornain [24] also discovered a positive correlation between the quantity of seashell powder (SSP) added to the concrete mixture and the resulting improvement in compressive strength.

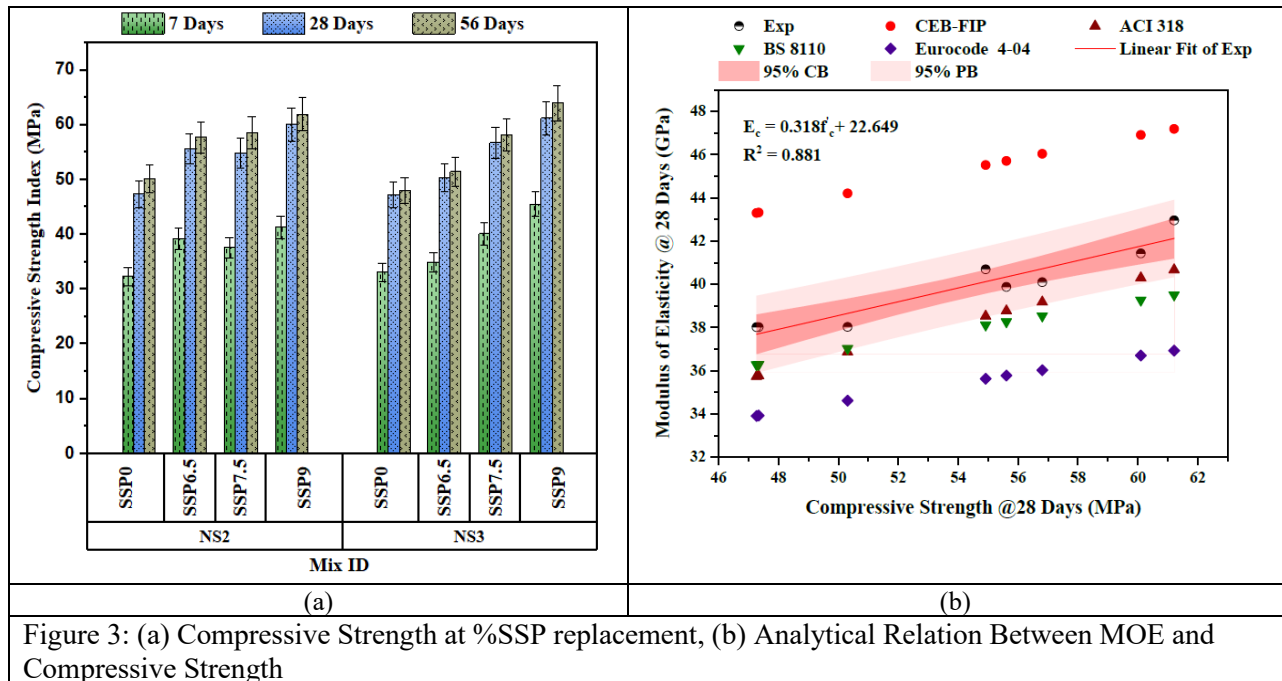


Figure 3: (a) Compressive Strength at %SSP replacement, (b) Analytical Relation Between MOE and Compressive Strength

Analytical models predict concrete properties when large-scale experiments are impractical due to cost, space, or time limitations. Figure 3(b) represents the analytical correlation of the current investigation with various code of practices for MOE and compressive strength of concrete. The relationship depends on the parameters of each other, where one strength can be quantified from the other. The different code of practices, such as CEB-FIP [25], ACI 318 [26], BS 8110 [27] and Eurocode 4-04 [28] recommend the following equations (1), (2), (3) and (4), respectively, for predicting the alternative strength, where f'_c and E_c represent the compressive strength in MPa and MOE in GPa, respectively.

Equations:

$$E_c = 21500\alpha E(f'_c/10)^{1/3} \quad (1)$$

$$E_c = 0.043 W_c^{1.5} \sqrt{f'_c} \quad (2)$$

$$E_c = 0.0017 W_c^2 f'_c^{0.33} \quad (3)$$

$$E_c = 9500 f'_c^{0.33} \quad (4)$$

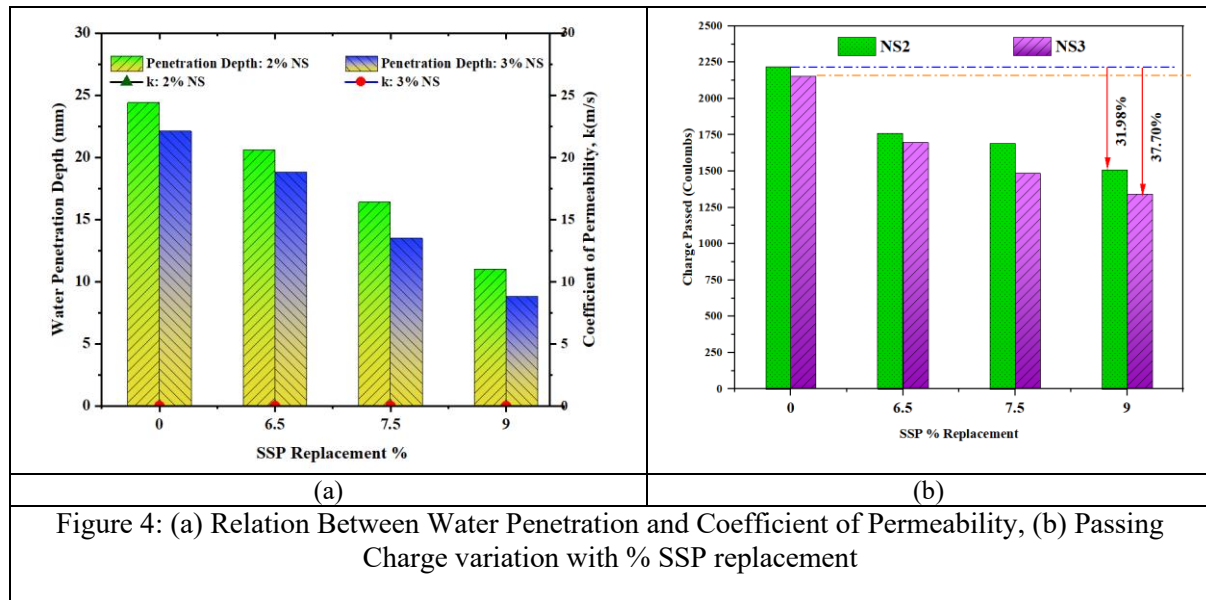
The projected strength data values from ACI 318 were closest to the tested findings of the four standards. CEB-FIP projected strength values were furthest from the tested results. The experimental relationship among strength values was predicted well with a moderate coefficient predictive correlation ($R^2 = 0.881$). Eurocode 4-04 underestimated MOE versus compressive strength experimental prediction line in all standards. MOE experimental data points slightly diverged from the standards' predicted line as compressive strength increased. The following correlation equation can be suggested from this experimental investigation:

$$E_c = 0.318f'_c + 22.649$$

3.3 Durability Properties Test

HSC penetration depth and water permeability coefficient (k) at 56 days are shown in Figure 4(a). The NDT examination of water permeability shows that concrete with 3% NS content has impermeable characteristics, blocking water entry with an increase of SSP. The SSP0%, SSP6.5%, SSP7.5% and SSP9% with 3% NS content mixes have 9.45%, 8.74%, 17.68% and 20% lower k values than the SSP0%, SSP6.5%, SSP7.5% and SSP9% with 2% NS mixes. Due to fewer capillary pores, concrete

with a higher % of NS content has lower k values. However, SSP, which is primarily composed of calcium carbonate and has a smaller particulate size than cement, despite being coarser than NS, contributes to the overall densification of the matrix by filling and reducing the size and connectivity of capillary openings within the concrete [29, 30]. Nguyen, Boutouil [31] [31] investigated the long-term effects of crushed seashells on pervious concrete and discovered that the addition of seashells increased the concrete's resistance to water penetration. Multiple investigation shows that seashell improves impermeability, densifies the matrix, and reduces water absorption in high-strength concrete [5, 32, 33].



In this study, the NSSM test was conducted to determine the chloride ion permeability of concrete in accordance with AASHTO T 277-86 [34]. The average results of the HSC specimens of all concrete samples at 56 days are presented in Figure 4(b). The amount of charge passed through the concrete specimen varied from 2217 to 1342 coulombs when SSP replacement increased from 0 to 9%. The results showed that the concrete with SSP9NS3 decreased by up to 37.70% compared to the control concrete. Meanwhile, it was found that the specimen with 2% NS the amount of charge passing tendency decreased about 20.52%, 23.68% and 31.98% for 6.5%, 7.5% and 9% replacement of SSP compared with control mixture whereas for 3% NS it had become 21.22%, 31.01% and 37.70% decrement which is approximately 4.59% lesser average decrement than 2% NS. The restriction of chloride ion transport by capillary pores is well acknowledged [35]. An abundance of capillary voids obstructed the movement of chloride ions in the HSC samples as the levels of SSP and NS rose. The control specimen may exhibit somewhat more chloride ion permeation compared to the modified concrete samples due to its greater porosity; however, the permeation process will ultimately be hindered mostly by SSP and NS.

4.CONCLUSIONS

This paper systematically investigated the influence of adding Waste Seashell Powder (SSP) and Nano-Silica (NS) to High Strength Concrete (HSC). It can be concluded (based on the results from key findings) that, though a combination of these materials involves a trade-off between workability

and performance, it serves to improve the mechanical and durability properties of HSC that exhibits synergistic behavior.

Key Findings:

- **Fresh Properties:** An evident negative trend was found between workability and the amounts of SSP and NS. Mix SSP9NS3 (9% of SSP and 3 % NS) showed the lowest slump (63 mm), which was ~35.7% lower than that of the control mix (SSP0NS2, 98 mm), signifying much stiffer concrete.
- **Mechanical properties:** The best properties were observed for a 7.5% SSP and 3% NS composition (SSP7.5 NS3) that attained a maximum 28-day compressive strength with a gain of 3.44% as compared to its 2% NS counterpart. This is due to increased particle packing and pozzolanic reactivity that result in a denser microstructure. The mechanical integrity was additionally confirmed, since the experimental modulus of Elasticity clearly matched that predicted by ACI 318 ($R^2 = 0.881$).
- **Durability Properties:** Impermeability SSP9NS3 mix reduced 20% water permeability coefficient more than the SSP9NS2 mix, NS of 3% in volume histograms is significantly improved pore refinement and closed water penetration. The optimum mix (SSP9NS3) showed the maximum resistance towards chloride ion penetration, 37.70% lower charge passed in the RCPT system compared to the control. In general, the average enhanced chloride resistance value due to 3% NS addition was found to be as high as 4.59% over that of 2% NS.

In conclusion, the combination of SSP with NS can produce denser, stronger, and higher durable concrete. The primary compromise is low workability that can be controlled by means of superplasticizers. The mix SSP7.5NS3 was identified to be a promising candidate with a great compromise between higher strength and better high-temperature long-term resistance.

The work was conducted at the laboratory level and within selected mix conditions; future work should include full-scale structural testing, long-term durability study in harsh environments, as well as an in-depth microstructural investigation for more quantitatively describing the synergistic actions between SSP and NS.

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DECLARATION OF USE OF AI

For writing this manuscript, the authors did not use any AI.

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