FUDMA Journal of Sciences (FJS)
ISSN online: 2616-1370
ISSN print: 2645 - 2944
Vol. 4 No. 1, March, 2020, pp 480 – 489

STRENGTH DEVELOPMENT CHARACTERISTICS AND MICROSTRUCTURAL PROPERTIES OF HIGH STRENGTH CONCRETE HAVING OPTIMAL NANOSILICA DOSAGE

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ABSTRACT

The use of Supplementary Cementitious Materials (SCM) to improve the performance of concrete is gaining popularity globally. This study investigated the tensile and compressive strengths development, microstructural properties and cement hydration reaction for High Strength Concrete (HSC) having optimal dosage of an SCM called Nanosilica (nS). The Optimal Nanosilica Dosage (ONSD) in HSC was determined to be 1 % by weight of cement using compressive strength test. The influence of ONSD on the properties of the HSC was investigated using compressive strength test, splitting tensile strength test, Scanning Electron Microscopy (SEM) and Energy Dispersion Spectroscopy (EDS). Results revealed that addition of ONSD led to 17.10 % and 20.52 % respective increase in compressive and tensile strengths of HSC at 7 days of curing. There was 15.41 % and 9.60 % respective increase in characteristic cylindrical compressive and axial tensile strengths of HSC determined according to Eurocodes on addition of ONSD. SEM micrographs show better packing density in the High Strength Nano-Concrete (HSNC) at 90days of curing. EDS shows that addition of ONSD in HSC led to formation of more C-S-H gels at 90days of curing, and a corresponding reduction in Ca/Si ratio of the Optimal High Strength Nano-Concrete (OHSNC) to 0.91, a ratio very close to 0.81; the Ca/Si ratio of 14Ǻ tobermorite C-S-H model reported in literature.

Keywords: Compressive strength, Tensile strength, Optimal high strength nano-concrete, SEM, EDS.

INTRODUCTION

Concrete is one of the most common and predominantly used materials in the construction of civil engineering infrastructure. It occupies nearly 70 % of the volume of concrete structures and shows significant impact (Venkat-Rao et al., 2015). With morethan 11billion metric tons consumed each year, Portland Cement (PC) concrete is the world's most widely used manufactured material, but it is also one of the most complex (Allen et al., 2007). High global warming potential and poor durability performance in aggressive environmental conditions are associated with PC concrete production and usage (Duxson et al., 2007).

High Strength Concrete (HSC) is one of the most significant new materials available to the public to utilize in new construction and in rehabilitation of buildings, highways and bridges (Ismeik, 2009). ACI 211.4R-93 (1998) defined HSC as concrete with compressive strength of 40 N/$mm^2$and more. HSC was developed as structural material of better quality when compared to normal strength concrete (Kovacevic and Dzidic, 2018). According to Kovacevic and Dzidic (2018), HSC has the advantage of reducing structural element size as a result of higher compressive strength and better performance, leading to the use of large spans and having increased floor area for utilization, furthermore, the use of structurally safe and better material enables idea and concepts of vertical cities and vertical living. However, the bond between cement and aggregate in HSC, which accounts for its tensile strength, does not improve significantly with increase in compressive strength, which may result in low tensile strength that can lead to crack formation and propagation with consequent effect of reinforcement corrosion (Kovacevic and Dzidic, 2018). As opined by Shariq et al. (2013), literature revealed that improvement in the tensile strength of HSC is important for better structural behavior of HSC as a construction material.

Corrosion of steel reinforcement is a major deterioration mechanism for concrete structures in cold, marine and industrial environment (Ababnah et al, 2009). Corrosion damage accelerates the aging of highway bridges, concrete pavements, parking structures, waterfront structures and water and waste water treatment structures, which in turn, shortens their service life and lead to additional expenditure commitment in repairs or replacement, endanger public safety and damages the environment (Ababnah et al, 2009). Therefore, a concrete with reduced permeability and reduced possibility of crack formation and propagation is essential to reduce corrosion and its consequential effect on reinforced concrete (RC) members.

Cement is a basic constituent of concrete and is the largest manufactured product on earth (Scrivener et al., 2016). The amount of CO_2 emitted from the worldwide production of PC corresponds to approximately 7 % of the total emissions into the earth's atmosphere (Mistry et al., 2014). The emission of CO_2 in cement and concrete industry can be controlled by incorporation of green concrete in the mix design, without reducing the quality of the final product (Mistry et al., 2014). According to (Scrivener et al., 2016) the major strategy towards improving sustainable use of PC is the use of mineral and chemical admixtures like ground granulated blast furnace slag (GGBS), pulverized fuel ash (PFA) and possibly nanosilica (nS) as SCM. Up to 50% replacement of PC with GGBS has proven to improve mechanical and durability properties of concrete, while slowing the early age strength development (Claisse, 2016). The use of nS is a promising approach for reducing the use of PC which can help reduce the CO_2 footprint of construction (Aly et al., 2018)

In recent years, the use of nS is receiving particular attention in the field of cement mortar and cement concrete. When ultra-fine particles are merged into PC, mortar, and concrete, materials with different features from predictable materials could obtained (Kumar and Singh, 2018). According to Aly et al. (2018), recent studies on the use of nS in concrete helped to improve our understanding of the role of nS in cementitious materials matrix; this include cement hydration, mechanical properties and microstructure of concrete; some of these effect are still not fully understood. Ayad and Said (2018) showed that the use of colloidal nS in cement mortar enhanced the compressive strength, reduced the total porosity and accelerates the pozzolanic reaction. In this study, certain percentages of nS were added in cement mortar to observe the effect on cement mortar strength development and microstructural properties improvement, but the optimal nS dosage was not determined.

Worldwide, resources are scarce and the demand for funds to be used for infrastructural development projects is always greater than supply, as a result, optimization in resource utilization in infrastructural development projects is gaining relevance across the globe. Jayaseelan et al. (2019) investigated the behavior of binary concrete containing nS and nanoferric (nF) oxide and observed that the addition of ONSD determined to be 1.5% by weight of cement improved the strength and durability characteristics of the concrete. The strength development characteristics and microstructural properties of HSC having ONSD was scarcely reported in literature as research efforts focused on normal strength concrete for a short-term curing period of 28days. Therefore, this study determined the strength development characteristics and microstructural properties of HSC having ONSD for a medium term curing period of 90days.

In Nigeria, concrete designs are done according British Standards. The withdrawal of the recent versions of British Standards by British Standards Institution in Britain and their replacement with Eurocodes released by European Committee for Standardization puts the fate of concrete design in Nigeria on Eurocodes. Therefore, this study generates OHSNC design data according to Eurocodes for use in civil engineering designs in Nigeria.

MATERIALS AND METHODS

Materials

Grade 42.5 N Portland Limestone Cement type II B-L produced according to Nigerian Industrial Standard (NIS444-1:2003) by Cement Company of Northern Nigeria was used in all mixes. The nS used has a commercial name VK-SP15 with size, nanosilica content, specific surface area and PH of $15\pm$ 5 nm, 99.8 %, $250\pm$ 30 m^2/g and 5-7 respectively as reported by the manufacturer. Glenium based Hydroplast 500 produced by Armosil ltd was used as superplastisizer. Sharp sand finer than 4.5 mm sieve and crushed aggregate of 25 mm maximum size obtained from local suppliers were used for all the concrete mixes. The fine aggregate has specific gravity (SSD), finess modulus, moisture content (SSD), absorption capacity and dry rodded unit weight of 2.67, 2.60, 3 %, 2 % and 1550 kg/ m^3 respectively. The coarse aggregate has specific gravity (SSD), moisture content (SSD), absorption capacity, flakiness, elongation, impact value and crushing value of 2.50, 0.90 %, 0.89 %, 20.4 %, 30.2 %, 17.4 % and 27.9 % respectively. The grading of the coarse and fine aggregates used conform to the requirements of ASTM C33/C33M (2018), BS EN933-1(2012) and BS EN12620(2002). Clean water conforming to the requirements of BS EN1008 (2002) was used in concrete sample production.

Concrete Mix Design and Validation

Grade 40 control mix was designed according to American Concrete Institute (ACI 211.1-98: 2004, and ACI 211.4R-93, 1998) method with target mean cylindrical compressive strength of 39.9 N/mm^2 derived from the target cube compressive strength of 49.8 N/mm^2 at 28 days. The target slump value was 80 mm using 25 mm maximum aggregate size. The design was implemented using MS Excel (2007). The mix proportions obtained were used to produce laboratory trial mixes for slump and compressive strength tests according to BS EN206 (2013). The fresh concrete was tested for slump in accordance with BS EN12350-2(2009). The concrete samples produced according to BS EN206 (2013) were subjected to compressive strength test at 28 days of curing in line with the provisions of BS EN12390-3(2009). Laboratory adjustments were made to the trial mixes to meet characteristic cube compressive strength and design slum values. The characteristic cube strength of the control mix was obtained using equation (1) utilizing the measures of dispersion (mean, standard deviation and coefficient of variation) obtained after statistical analysis of experimental data using MS Excel (2007). The trial and validated mix proportions are presented in Table 1. The validated mix containing varying proportions of nS is presented in Table 2.

$$f_{cu} = f_m - 1.64S_d \quad (1)$$

Where: f_{cu} is characteristic compressive strength, f_m is mean compressive strength and S_d is standard deviation.

Table 1: Trial and Validated Mix Proportions

Mix Type	Grade	W/C	Cement	Aggregates		Water	Superplastisizer	
				Coarse	Fine		%	Weight
			kg/m^3	kg/m^3	kg/m^3	kg/m^3		kg/m^3
Design (Trial Mix)	40	0.35	557	963	688	170	2.00	11.14
Validated Mix	40	0.30	650	963	606	174	2.00	13.00

Table 2: Validated Mix Containing Varied Proportions of Nano-Silica

Grade	Designation.	W/C	Cement	Nanosilica		Aggregate		Water	Superplastisizer	
			kg/m^3	%	kg/m^3	kg/m^3		kg/m^3	%	kg/m^3
						Fine	Coarse			
40	NS0	0.30	650	0.0	0.0	606	963	174	2.00	13.0
	NS0.5		647	0.5	3.3					
	NS1		644	1.0	6.5					
	NS1.5		640	1.5	9.8					
	NS2		637	2.0	13.0					
	NS2.5		634	2.5	16.3					
	NS3		631	3.0	19.5					
40	40NS0	0.30	650	0.0	0.0	606	963	174	2.00	13.0
	40NS1		644	1.0	6.5					

Concrete Samples Preparation

The process of preparation and casting of test samples for determination of ONSD, determination of tensile and compressive strength development of the OHSNC is presented in this section. NS1 stands for nano-concrete having 1 % nano-silica dosage, while NS0 is the control concrete mix for determination of ONSD. 40NS0 and 40NS1 stand for grade 40 control HSC mix and OHSNC mix having 1 % nano-silica dosage by weight of cement respectively, used in determining strength development characteristics of the OHSNC. The work was conducted at Concrete Laboratory, Civil Engineering Department, Ahmadu Bello University, Zaria, Nigeria. The test samples were prepared according to BS EN12390-1(2012) and BS EN12390-2(2009).

Determination of Optimal Nano-Silica Dosage (ONSD)

The weight of cement from laboratory validated mix proportions for control concrete was recorded. To determine ONSD, cement replacement by nano-silica of 0.5 % to 3.0 % at interval of 0.5 % by weight of cement was used. A mix was produced for the control samples without nS and with the varying percentages of nS for determination of ONSD. Hydroplast 500 superplastisizer having 2 % content by weight of cement was added to both the control HSC and OHSNC mixes. The control mix; having zero percentage of nS was produced by mixing cement and aggregate (coarse and fine aggregate) individually in the mixer. A homogeneous concrete mix was obtained with all the constituents mixed together with addition of potable water and superplastisizer; mixed uniformly with the constituents to enhance workability. Due to high surface area of the nS and the difficulty associated with its dispersal, the mixing was done by stirring nS with water and superplastisizer at a high speed for 5 minutes using Altrad Minimix 130 Concrete Mixer. The cement was added to the mixer and mixed at medium speed, fine aggregate was then gradually added followed by coarse aggregate. The concrete mix was placed in 100 mm x 100 mm x 100 mm oiled moulds and vibrated on a vibrating table. Demoulding of the test specimens was done after 24 hours of casting. The specimens were cured for a period of 7 and 28 days in water tanks under laboratory conditions. Slump test was conducted according to BS EN12350-2(2009) to assess the workability of concrete mixes.

Determination of Compressive and Tensile Strength Development

The weight of cement from validated mix proportions for the control concrete was used. The ONSD determined to be 1.0 % by weight of cement was added to produce OHSNC samples. The corresponding control concrete samples for tensile and compressive strength test were produced. The sample size, mixing and demoulding procedure for the compressive strength development investigation was as used for determining ONSD. The samples produced for determining splitting tensile strength were cylindrical having 150 mm diameter and 300 mm height. The mixing procedure for the concrete samples was as outlined above. The specimens were cured for a period of 3, 7, 14, 21, 28, 42, 56, 70 and 90 days in water tanks under laboratory conditions. Three samples were produced for each curing age and strength test type.

Strength Tests

The strength test was divided into compressive strength test and splitting tensile strength test. The tests were conducted to determine the ONSD, compressive and tensile strength development characteristic of the OHSNC mixes. The detailed test procedure for the two strength tests are presented below.

Compressive Strength Test

The compressive strength test for determining ONSD was conducted at 7 and 28 days of curing according to BS EN12390-3(2009). In determining the strength development characteristics of the OHSNC mix in comparison to the control concrete mix, the compressive strength test was conducted at 3, 7, 14, 21, 28, 42, 56, 70 and 90 days of curing. The tests were conducted using Avery Denison Universal Testing Machine. The load rate was kept at 0.6 ± 0.2 MPa/Sec according to BS EN12390-3(2009) for all test samples until the specimen failed. The failure loads were recorded. The compressive strength was calculated by dividing the failure load by cross-sectional area of the cube samples. The mean strength was obtained by taking average of the compressive strength of three concrete cube samples in accordance with BS EN12390-3(2009). The characteristic strength of the control mix was obtained using equation (1) utilizing the measures of dispersion (mean, standard deviation and coefficient of variation) obtained after statistical analysis of experimental data using MS Excel (2007).

To allow for concrete design according to EN1992-1-1(2004), the characteristic cube strength obtained were converted to characteristic cylindrical strength using equation (2) from Domone (2010).

$$f_{cyl} = 0.85f_{cu} - 1.6 \quad (2)$$

Where: f_{cyl} is characteristic cylindrical strength, f_{cube} is characteristic cube strength of test specimens respectively.

Splitting Tensile Strength Test

The splitting tensile strength test was conducted according to BS EN12390-6(2009) after 3, 7, 14, 21, 28, 42, 56, 70 and 90 days of curing. The test was conducted using Avery Denison Universal Testing Machine. The load rate was kept at 0.04 to 0.06 MPa/Sec according to BS EN12390-6 (2009) for all test samples until the specimen failed. The failure loads were recorded. The splitting tensile strength was calculated using equation (3) according to BS EN12390-6(2009).

$$f_{st} = \frac{2P_s}{\pi LD} \quad (3)$$

Where: f_{ct} is splitting tensile strength, P_s is failure load, L and D are length and diameter of the cylindrical specimen respectively.

For design purpose, the splitting tensile strength results were converted to axial tensile strength using equation (4) according to EN1992-1-1(2004).

$$f_{ct} = 0.9f_{st} \quad (4)$$

Where: f_{st} is axial tensile strength, and f_{st} is splitting tensile strength.

SEM and EDS Analysis

SEM was used to determine the surface morphology of the OHSNC and the corresponding control concrete samples at 90 days of curing. The rate of formation of C-S-H gel in the OHSNC was investigated using EDS at 90 days of curing. The weight concentration of Calcium (Ca) and Silicon (Si) in OHSNC and control concrete samples was determined using EDS. Samples not more than 10mm in size were collected from test samples after compressive strength test at the specified age for EDS and SEM analysis. The SEM and EDS analysis were done using Phenom ProX SEM machine. The collected samples were prepared and placed on the sample holder of the SEM machine. Thereafter, the samples were illuminated with X-ray beam of 15 kV magnitude. The proportion of the energy emitted which is unique to the morphology and chemistry of the samples was analyzed for the morphology, elemental composition, and weight concentration of the elements in the samples.

RESULTS AND DISCUSSION

Trial and Validated Concrete Mixes

The strength properties; mean compressive strength and characteristic strength, as well as slump values obtained when the trial and validated control concrete mixes were implemented in the laboratory are presented in Table 3. The trial mix characteristic cube compressive strength (fcu) obtained was 12.42 % short of the desired characteristic cube strength for grade 40 control concrete mix. The slump value obtained was 106.25 % more than the design slump. The excess slump value obtained was as a result of superplastizer addition which was designed taking into account the workability reduction effect of nS as observed in the preliminary concrete mixes. The failure of the designed concrete to meet the strength requirements of grade 40 concrete reinforces the assertion by Neville and Brooks (2010); that concrete mix design calculations provide an intelligent guess, not the exact mix proportions for a given concrete grade. Exact mix proportions are obtained from laboratory trial mixes and adjustments.

For the validated mix properties of the control concrete grade presented in Table 3, the characteristic cube compressive strength (fcu) obtained was 2.08 % more than the desired characteristic cube strength for grade 40 concrete, which is adequate. The slump value obtained was 62.50 % more than the design slump, but is within acceptable limits, especially for production of nano-concrete, whose nS finess reduce workability. This proved the assertion by Neville and Brooks (2010); that exact concrete mix proportions are obtained from laboratory trial mixes and adjustments.

Table 3: Properties of Trial and Validated Concrete Mixes

Concrete Mix Type	**Concrete Grade**	**Strength Parameters**		**Slump**		**Statistics**	
		Fcu N/mm^2	Fm N/mm^2	Design mm	Achieved mm	SD	COV
Design Mix (Trial Mix)	40	35.58	36.37	80	165	0.57	0.04
Validated Mix	40	40.83	43.33	80	130	0.58	0.02

Optimal Dosage of Nano-Silica in High Strength Concrete

There was an increase in compressive strength on addition of 0.5 % to 2.0 % (NS0.5 to NS2) nS by weight of cement at both 7 and 28days of curing as shown in Figure 1. Thereafter, a drop in compressive strength was observed up to 3 % nS addition (NS2.5 to NS3) at 7 and 28 days of curing. The highest and lowest compressive strengths of the nano-concrete mixes were 36.30 N/mm^2 and 33.33 N/mm^2 at 7 days, and 48.67 N/mm^2 and 41.33 N/mm^2 at 28 days respectively. The maximum gain in compressive strength of the nano-concrete was recorded on mix NS1 having 1.0 % nS dosage at both 7 and 28 days of curing. This means that optimal compressive strength gain was recorded on nano-concrete cubes with NS1 designation having 1.0 % nano-silica dosage, signifying that the ONSD in grade 40 concrete mix is 1.0 % by weight of cement, which is less than ONSD value of 1.5 % by weight of cement reported by Jayaseelan et al. (2019) for normal strength concrete. The observed reduction of ONSD in grade 40 concrete could be as a result of an increase in cement content due to lower water-cement ratio requirement of HSC when compared with normal strength concrete. Therefore, ONSD greater than 1.0 % by weight of cement led to agglomeration and reduction in compressive strength of the HSNC.

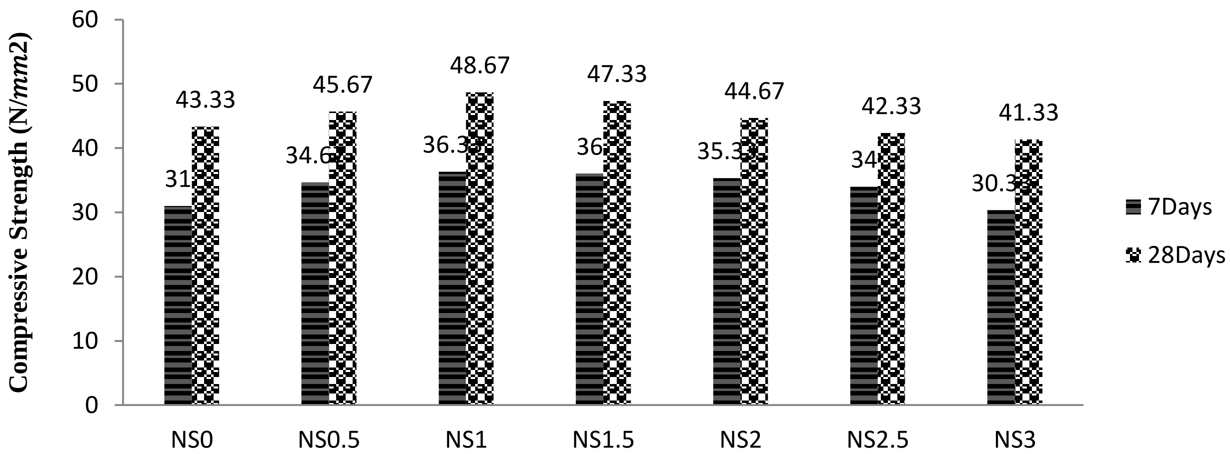


Fig. 1: Compressive Strength of High Strength Nano-Concrete Mixes at 7 and 28days of Curing

Compressive Strength Development of Optimal High Strength Nano-Concrete

The highest and lowest compressive strength values obtained for the OHSNC mix (40NS1) were 49.7 N/mm^2 and 32.3 N/mm^2 at 90 days and 3 days of curing respectively, as shown in Figure 2. The mix containing ONSD (40NS1) showed higher compressive strength than control concrete mix (40NS0) at all curing ages. There was 11.38 %, 17.10 %, 12.93 %, 10.49 %, 12.47 %, 6.67 %, 7.51 %, 7.88 % and 8.04 % increase in compressive strength of the OHSNC mix at 3, 7, 14, 21, 28, 42, 56, 70 and 90 days respectively in comparison with the control HSC mix. This shows that OHSNC has higher compressive strength than HSC of the same grade. Furthermore, the improvement in compressive strength of the OHSNC mix (40NS1) was more pronounced at 7days of curing than at the other curing ages, as concluded by (Behzadian and Shahrajabian, 2019; Jayaseelan et al., 2019). The early age compressive strength gain of OHSNC mix might be due to accelerated hydration reaction on addition of ONSD.

There was 50.77 % increase in compressive strength of OHSNC mix between 3 and 28 days of curing, whereas 2.05 % compressive strength gain was recorded between 28 and 90 days of curing. This shows that the most significant increase in compressive strength of the OHSNC mix was between 3 and 28 days of curing, which is in line with the conclusions of (Kaura et al., 2014; Behzadian and Shahrajabian, 2019; Jayaseelan et al., 2019), whose study considered a curing period of 3 to 28 days. This pattern of strength development in the OHSNC mix could be attributed to accelerated hydration of the mix leading to early consumption of portlandite and lime in the presence of nS.

The results show that the highest percentage of hydration for the OHSNC mix was complete at 28 days; the remaining negligible hydration was very slow up to 90 days of curing. Therefore, it could be concluded that the accelerated compressive strength gain of the OHSNC mix at early age is an indication that nS does not only serve as filler to increase the density of the micro and nano structure of HSC, but also work as an activator in the process of hydration.

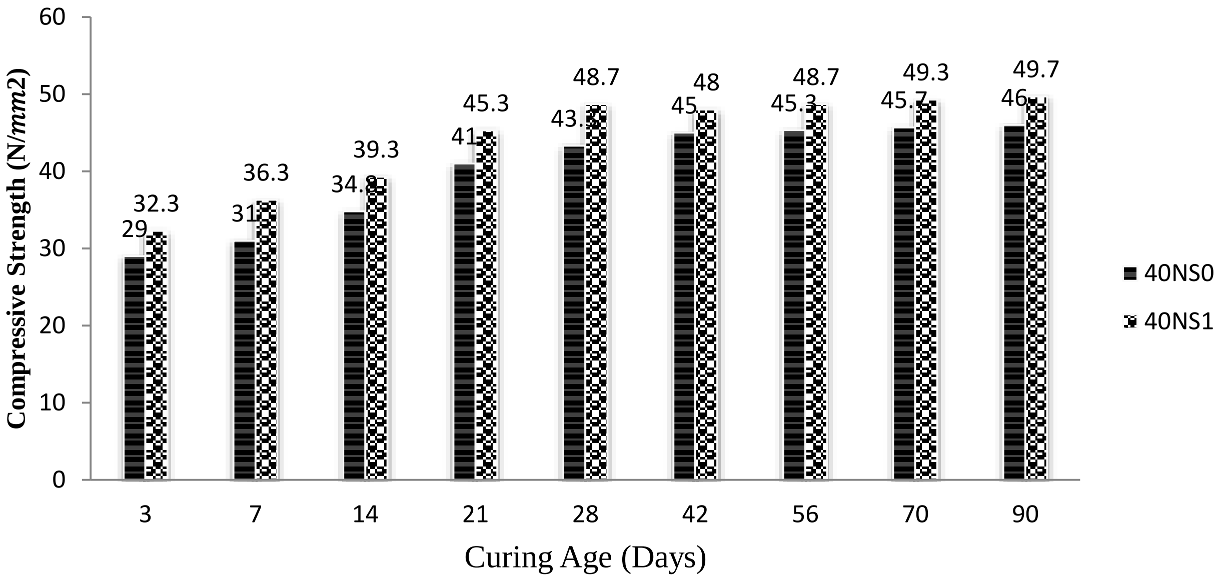


Fig. 2: Compressive Strength Development of OHSNC Mix

Tensile Strength Development of Optimal High Strength Nano-Concrete

The respective lowest and highest values of splitting tensile strength of the OHSNC mix (40NS1) were 2.26 N/mm^2 and 3.91 N/mm^2 at 3 and 90 days of curing, as presented in Figure 3. The splitting tensile strength of the OHSNC mix (40NS1) at 3, 7, 14, 21, 28, 42, 56, 70 and 90 days was improved by 10.24 %, 20.52 %, 12.30 %, 5.69 %, 9.85 %, 6.74 %, 4.03 %, 2.89 % and 2.89 % respectively in comparison with the control HSC mix (40NS0). This shows that OHSNC has higher tensile strength than an equivalent HSC. Moreover, the improvement in splitting tensile strength of the OHSNC mix was more pronounced at 7 days of curing than at the other curing ages as concluded by Behzadian and Shahrajabian (2019). The early age splitting tensile strength gain of the OHSNC mix might be due to accelerated hydration reaction on addition of ONSD.

There was 62.83 % increase in splitting tensile strength of OHSNC mix between 3 and 28 days of curing, whereas 6.25 % splitting tensile strength gain was recorded between 28 and 90 days of curing. This shows that the most significant increase in splitting tensile strength of the OHSNC mix was between 3 and 28 days of curing, in line with the conclusions of Behzadian and Shahrajabian (2019). This could be due to accelerated hydration of the OHSNC mix, leading to the formation of more C-S-H gels.

The results show that maximum percentage of hydration of the OHSNC mix was complete at 28 days; the remaining negligible hydration was very slow up to 90 days of curing. The increase in tensile strength of the OHSNC mix might be due to improved properties of the concrete mix and the strong inter-phase bond between the binders (cement and nS) and the aggregates used. The tensile strength gain in OHSNC mix could also be as a result of improvement in the interfacial transition zone bonding of the concrete.

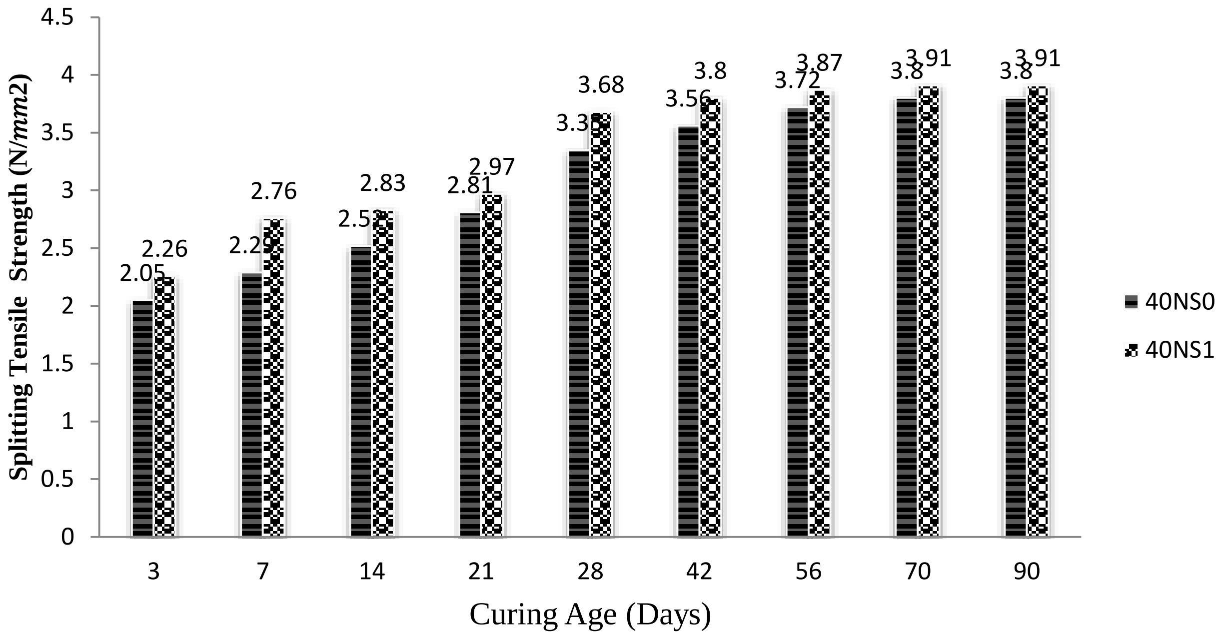


Fig. 3: Tensile Strength Development of OHSNC Mix

Compressive and Tensile Strengths of Concrete according to EN1992-1-1(2004)

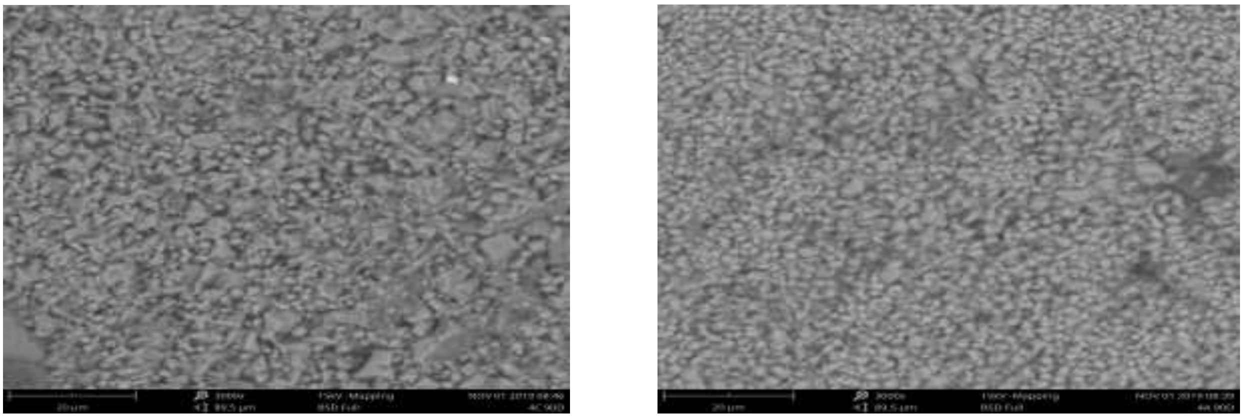
To allow for OHSNC design according to EN1992-1-1(2004) and its reference standards, and also for the purpose of strength comparison with the control HSC, the calculated characteristic compressive and tensile strengths of the control HSC (40NS0) and OHSNC (40NS1) mixes at 28 days reference curing period according to the European Standard are presented in Table 4. The splitting tensile strength value obtained at the reference curing period was converted to axial tensile strength, while the characteristic cube compressive strength was converted to cylindrical characteristic strength. The conversion of cube compressive strength to cylindrical strength, as well as splitting tensile strength to axial tensile strength led to reduction in compressive and tensile strengths for all the HSC mixes. There was 15.41 % and 9.60 % respective increase in characteristic cylindrical compressive strength and axial tensile strength at 28 days of curing on additional of ONSD in grade 40 concrete.

Table 4: Concrete Characteristic Strength Parameters according to EN1992-1-1 (2004)

Concrete Mixes	**Strength Parameters**		**Strength Parameters (EN1992-1-1(2004)**	
	Compressive Cube f_{cu} N/mm^2	Splitting Tensile Cylindrical f_{st} N/mm^2	Compressive Cylindrical f_{cyl} N/mm^2	Axial Tensile Cylindrical f_{ct} N/mm^2
40NS0	40.8	3.35	33.1	3.02
40NS1	46.5	3.68	38.2	3.31

Relationship between Nano-Concrete Strength Properties and Microstructure

SEM examination was performed on control HSC and OHSNC samples at 90days of curing to allow for verification of the mechanism predicted by compressive and splitting tensile strength tests. The SEM images of the control HSC and OHSNC mixes are presented in Figure 4((a) and (b)) respectively. A dense and compact formation of hydration products was observed for the OHSNC unlike a more porous structure of the HSC mix. Moreover, a dense interfacial layer between aggregates and cement paste was observed for the OHSNC mix. The high quantity of C-S-H gel formed in the OHSNC was confirmed, as high content of calcium (Ca) and Silica (SiO_2) was found in the EDS spectrum of the OHSNC, as presented in Figure 5. Thus, it could be concluded that the improvement in the tensile and compressive strengths of the OHSNC mix was as a result of densification and pore refinement, which could reduce ingress of water and harmful gases into the concrete structure, leading to reduction in reinforcement corrosion.



(a) (b)

Fig. 4: SEM Images of Concrete at 90days of Curing. (a) HSC Mix (b) OHSNC Mix

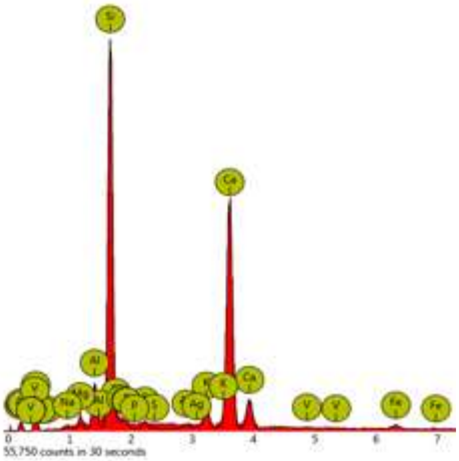


Fig. 5: EDS Spectrum of OHSNC Mix at 90days of Curing

Relationship between High Strength Nano-Concrete Properties and Ca/Si ratio

In order to provide a correlation between compressive and tensile strengths development of OHSNC and Ca/Si ratio, the weight concentration of the two elements in both the control HSC mix and OHSNC mix was determined using EDS. The OHSNC mix (40NS1), which has higher compressive and tensile strengths, has lower Ca/Si ratio than the control HSC mix (40NS0) at 90days of curing, as shown in Table 5. The Ca/Si ratio of the OHSNC was calculated as 0.91 from weight concentration of the two elements which is very close to 0.81; the Ca/Si ratio of 14Ǻ tobermorite C-S-H model reported by Li (2011). This shows that the compressive and tensile strengths of OHSNC increase with decrease in Ca/Si ratio. Furthermore, it could be said that the addition of ONSD in HSC makes the internal structure and bond assembly of OHSNC to approach that of 14Ǻ tobermorite C-S-H model reported in literature.

Table 5: Ca/Si Ratio of Grade 40 Concrete at 90days of Curing

Concrete Mix	Element	Weight Concentration (%)	Ca/Si ratio
40NS0	Calcium (Ca)	60.48	2.40
	Silicon (Si)	25.20	
40NS1	Calcium (Ca)	30.10	0.91
	Silicon (Si)	33.07	

CONCLUSIONS

The results of this study revealed that the ONSD in grade 40 HSC is 1.0 % by weight of cement. The study showed that the addition of ONSD in HSC led to improvement in compressive and tensile strengths of HSC with increase in curing age. Also, the use of ONSD in HSC mixes improved the microstructural properties of the matured OHSNC at 90days of curing through densification and pore refinement, thereby reducing permeability and void content, which could lead to reduction in reinforcement corrosion caused by ingress of water and harmful gases into the HSC structure. Furthermore, the addition of ONSD in HSC reduced Ca/Si ratio at 90days of curing to a value very close to that of 14Å tobermorite C-S-H model reported in literature, thereby, resulting in improved bond assembly, improved hydration reaction in OHSNC, and a corresponding increase in the tensile and compressive strengths of the OHSNC mix. Moreover, the use of ONSD in HSC could overcome the shortcomings in early age strength development of GGBS used in the production of HSC. The characteristic compressive and axial tensile strength values obtained for OHSNC can be used in concrete designs according to Eurocodes. OHSNC could be applied where strength improvement, especially at early age and reduction in permeability are requirements.

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