Nigerian Journal of Technology (NIJOTECH)
Vol. 39, No. 3, July 2020, pp. **710 – 720**
Copyright© Faculty of Engineering, University of Nigeria, Nsukka,
Print ISSN: 0331-8443, Electronic ISSN: 2467-8821
www.nijotech.com
http://dx.doi.org/10.4314/njt.v39i3.9

EFFECT OF NANOSILICA ON THE MECHANICAL AND MICROSTRUCTURAL PROPERTIES OF A NORMAL STRENGTH CONCRETE PRODUCED IN NIGERIA

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ABSTRACT

The failure of conventional concrete to have classical mechanical properties, reduced permeability and lead to sustainability in concrete production called for the use of supplementary Cementitious Materials (SCM) in concrete to improve its performance. This study investigates the effect of adding optimal dosage of an SCM called nanosilica (nS) on the tensile and compressive strengths, microstructural properties and cement hydration reaction for grade 30 concrete. The optimal dosage of the nS was determined to be 1.5% by weight of cement using compressive strength test. The influence of optimal nS dosage on the concrete properties was investigated using compressive strength test, splitting tensile strength test, Scanning Electron Microscopy (SEM) and Energy Dispersion Spectroscopy (EDS). Results revealed that optimal nS addition led to 30% and 23.3% respective increase in compressive and tensile strengths of conventional concrete at 7days of curing. SEM micrographs show better packing density in the nano-concrete at 90days of curing. EDS shows that addition of optimal nS dosage in concrete led to formation of more C-S-H gels at 90days curing period, and a corresponding reduction in Ca/Si ratio of the nano-concrete to 0.89; a ratio that is very close to that of 14Å tobermorite reported in literature. The optimal nano-concrete can be used where strength improvement, especially at early age and reduction in concrete permeability are requirements.

Keywords: *Compressive strength, Tensile strength, Normal strength nano-concrete, SEM, EDS.*

1. INTRODUCTION

The world faces unprecedented global challenges related to depleting natural resources, pollution, climate change, clean water and poverty. These problems are directly linked to the physical characteristic of our current technology base for producing energy and materials products [1]. Concrete is one of the most common and predominantly used construction material in the construction of civil engineering infrastructure. It occupies nearly 70% of the volume of concrete structures and shows significant impact [2]. With morethan 11billion metric tons consumed each year, Portland cement concrete is the world's most widely used manufactured material, but it is also one of the most complex [3]. High global warming potential and poor durability performance in aggressive environment conditions are associated with Ordinary Portland cement (OPC) concrete production and usage [4]. According to [5] the appropriate use of mineral and chemical admixtures in concrete can improve its long-term strength and durability to aggressive conditions.

Cement is a basic constituent of concrete and is the largest manufactured product on earth [6]. The amount of CO_2 emitted from the worldwide production of OPC corresponds to approximately 7% of the total emissions into the earth's atmosphere [7]. 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 [7]. According to [6] the major strategy

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towards improving sustainable use of OPC is the use of mineral and chemical admixtures like ground granulated blast furnace slag (GGBS), pulverized fuel ash (PFA) and possibly nanosilica (nS) as Supplementary Cementitious Material (SCM). Up to 50% replacement of OPC with Ground Granulated Blast Furnace Slag (GGBS) have proven to improve mechanical and durability properties of concrete, while slowing the early age strength development [8].

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 Portland cement, mortar, and concrete, materials with different features from predictable materials could be obtained [9]. According to [10] 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 [10]. Ayad and Said [11] showed that the use of colloidal nS in cement mortar enhanced the compressive strength, reduces the total porosity and accelerates the pozzolanic reaction. The use of nS in cement mortar was reported in [12], the study also showed that the addition of nS in cement mortar led to improvement in mechanical and microstructural properties of the mortar, moreover, the study reported that the improvement in strength and microstructural properties of the nS modified mortar was as a result of an increase in the quantity of Calcium Silicate Hydrate (C-S-H) gel in the nS modified mortar. In these studies, certain percentages of nS were added 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. Moreover, optimal performance of hardened concrete is obtained by using optimal not the highest or lowest nS dosage. It is therefore necessary to determine the nS dosage that can guarantee optimal performance of hardened concrete so as to avoid wastage in material usage, which can result to unnecessary increase in the cost of concrete production without a corresponding improvement in the performance of the hardened concrete. [13] investigated the behavior of binary concrete containing nS and nanoferric (nF) oxide and observed that the addition of optimal dosage of nS determined to be 1.5% by weight of cement improved the strength and durability characteristics of the concrete. In another study conducted and reported in [14] for Polyethylene Terephthalate (PET) bottle waste nano-concrete, it was found that the addition of optimal nS dosage determined to be 3% by weight of cement improved the compressive, tensile and flexural strengths of the PET-nS concrete, the study also showed an improvement in microstructural properties of the PET-nS concrete caused by pore reduction in the interfacial transition zone between PET and cement in the concrete, resulting in dense microstructure. The improvement in mechanical and microstructural properties of the nano-concrete obtained in the studies presented was determined on a short-term curing period of 28days, whereas, a better understanding of the strength development characteristic and microstructural properties improvement of the nano-concrete could be achieved when a medium or long term concrete curing period is considered. Furthermore, different optimal dosage of nS were obtained in the studies presented, therefore, a need arise for determining the actual optimal dosage of nS in normal strength concrete; its effect on strength development, and microstructural properties improvement for a medium term curing period of at least 90days. Therefore, this study determined the mechanical and microstructural properties improvement of a normal strength nano-concrete produced in Nigeria with optimal nS dosage, cured for a period of 90days, and provide the reasons for the improvements.

In Nigeria, concrete design 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 nano-concrete design data according to Eurocodes for use in civil engineering designs in Nigeria.

2. MATERIALS AND METHODS

2.1 Material

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. Glenium based Hydroplast 500 produced by Armosil ltd was used as superplastisizer. Sharp sand finer than 4.5mm sieve and crushed aggregate of 25mm 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 1550kg/m^3 respectively. The coarse aggregate has specific gravity (SSD), moisture content (SSD), absorption capacity, flakiness, elongation, impact value and crushing value of 2.5, 0.90%, 0.89%, 20.4%, 30.2%, 17.4% and 27.9% respectively. The grading of the coarse and fine aggregates used conformed 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.

2.2 Concrete Mix Design and Validation

Grade 30 control mix was designed according to American Concrete Institute (ACI 211.1-98: 2004) method for normal concrete mixes with target mean cylindrical compressive strength of 31.87N/mm^2 derived from the target cube compressive strength of 39.4N/mm^2 at 28days. The target slump value was 80mm using 25mm maximum aggregate size. The design was implemented using MS Excel (2007). The mix proportions obtained was 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 28days 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 slump 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.

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

Where: f_{cu} is characteristic strength, f_m is mean strength, 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)	30	0.50	390	963	835	163	2.00	7.80
Validated Mix	30	0.45	433	963	797	165	2.00	8.66

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			
30	NS0	0.45	433	0.0	0.0	797	963	165	2.00	8.70
	NS0.5		431	0.5	2.2					
	NS1		429	1.0	4.3					
	NS1.5		427	1.5	6.5					
	NS2		425	2.0	8.7					
	NS2.5		423	2.5	10.8					
	NS3		420	3.0	13.0					
30	30NS0	0.45	433	0.0	0.0	797	963	165	2.00	8.66
	30NS1.5		427	1.5	6.5					

2.3 Preparation of Concrete Samples

The process of preparation and casting of test samples for determination of optimal nano-silica dosage, determination of tensile and compressive strength development of the nano-concrete is presented in this section. NS1.5 stands for nano-concrete having 1.5% nano-silica dosage, while NS0 is the control concrete mix for determination of optimal nano-silica dosage. 30NS0 and 30NS1.5 stand for grade 30 control concrete mix and nano-concrete mix having 1.5% nano-silica dosage by weight of cement respectively for determining strength development characteristics of the nano-concrete. 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.

2.3.1 Determination of Optimal Nano-Silica Dosage

The weight of cement from laboratory validated mix proportions for control concrete was recorded. To determine the optimal nanosilica dosage, 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 nano-silica and with the varying percentages of nano-silica for determination of optimal nano-silica dosage. Hydroplast 500 superplastisizer having 2% content by weight of cement was added to both the control and nano-concrete mixes. The control mix; having zero percentage of nano-silica 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 nano-silica and the difficulty associated with its dispersal, the mixing was done by stirring nano-silica 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 100mm x 100mm x100mm 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 28days in water tanks under laboratory conditions. Slump test was conducted according to BS EN12350-2:2009 to assess the workability of concrete mixes.

2.3.2 Determination of Compressive and Tensile Strength Development

The weight of cement from validated mix proportions for the control concrete was used. The optimal nano-silica dosage determined to be 1.5% by weight of cement was added to produce nano-concrete 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 optimal nano-silica dosage. The samples produced for determining splitting tensile strength were cylindrical having 150mm diameter and 300mm 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 90days in water tanks under laboratory conditions. Three samples were produced for each curing age and strength test type.

2.4 Strength Tests

The strength test done was divided into compressive strength test and splitting tensile strength test. The tests were conducted to determine the optimal nano-silica dosage, compressive and tensile strength development characteristic of the nano-concrete mixes. The detailed test procedure for the two strength tests are presented below.

2.4.1 Compressive Strength Test

The compressive strength test for determining optimal nS dosage was conducted at 7 and 28days of curing according to BS EN12390-3:2009. In order determine the strength development characteristics of the nano-concrete mixes in comparison to the control concrete mixes, the compressive strength test was conducted at 3, 7, 14, 21, 28, 42, 56, 70 and 90days of curing. The tests were conducted on Avery Denison Universal Testing Machine. The load rate was kept at 0.6 ± 0.2MPa/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 sample. 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 [15].

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

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

2.4.2 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 90days of curing. The test was conducted on Avery Denison Universal Testing Machine. The load rate was kept at 0.04 to 0.06MPa/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 EN12390-6:2009.

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

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

2.5 SEM and EDS Analysis for Concrete Samples

The surface morphology of the nano-concrete test samples containing optimal nano-silica dosage and the corresponding control samples without nano-silica at 28 and 90days of curing was determined using Scanning Electron Microscope (SEM). The rate of formation of C-S-H gel in the nano and control concrete was investigated using Energy Dispersion Spectroscopy (EDS) at 90days of curing. 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 15kV 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 percentage of the elements in the samples.

3. RESULTS AND DISCUSSION

3.1 Properties of 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 concrete control mixes were implemented in the laboratory are presented in Table 3. The trial mix characteristic cube compressive strength (fcu) obtained was 23.71% short of the desired characteristic cube strength for the grade 30 control concrete mix. The slump value obtained was 93.75% 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 nano-silica as observed in the preliminary concrete mixes. The failure of the designed concrete to meet the strength requirements of grade 30 concrete reinforces the assertion by [16] 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 1.47% more than the desired characteristic cube strength for grade 30 concrete, which is adequate. The slump value obtained was 68.75% more than the design slump, but is within acceptable limits, especially for production of nano-concrete, whose nS finess reduces workability. This proved the assertion by [16]; that exact concrete mix proportions are obtained from laboratory trial mixes and adjustments.

3.2 Optimal Dosage of Nano-Silica in Grade 30 Concrete

There was an increase in compressive strength on addition of 0.5% to 1.5% (NS0.5 to NS1.5) 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 to NS3) at 7 and 28days of curing. The highest and lowest compressive strengths of the nano-concrete mixes were 27.3N/mm^2 and 19.6 N/mm^2 at 7days, and 37N/mm^2 and 27.67N/mm^2 at 28days respectively. The maximum gain in compressive strength of the nano-concrete was recorded on mix NS1.5 having 1.5% nS dosage at both 7 and 28days of curing. This means that optimal compressive strength gain was recorded on nano-concrete cubes with NS1.5 designation having 1.5% nano-silica dosage, signifying that the optimal nS dosage in grade 30 concrete mix is 1.5% by weight of cement, as concluded by [17].

3.3 Compressive Strength Development of Grade 30 Nano-Concrete Mix

The highest and lowest compressive strength values obtained for the optimal nano-concrete mix (30NS1.5) were 41N/mm^2 and 20N/mm^2 at 90 and 3days of curing respectively, as shown in figure 2. The mix containing optimal nano-silica dosage (30NS1.5) showed higher compressive strength than control concrete mix (30NS0) at all curing ages. There was 11.11%, 30%, 17.41%, 11.24%, 14.55%, 8.65%, 12.04%, 8.53% and 8.75% increase in compressive strength of the nano-concrete mix at 3, 7, 14, 21, 28, 42, 56, 70 and 90days respectively in comparison with the conventional concrete mix. This shows that nano-concrete has higher compressive strength than conventional concrete of the same grade. Furthermore, the improvement in compressive strength of the optimal nano-concrete mix (30NS1.5) was more pronounced at 7days of curing than at the other curing ages, as concluded by [14] and [17]; whose study considered curing period of 3 to 28 days. The early age compressive strength gain of nano-concrete mix might be due to accelerated hydration reaction on addition of optimal dosage of nano-silica.

There was 85% increase in compressive strength of nano-concrete mix between 3 and 28 days of curing, whereas 10.81% compressive strength gain was recorded between 28 and 90 days of curing. This shows that the most significant increase in compressive strength of the nano-concrete mix was between 3 and 28 days of curing, which is in line with the conclusions of [12], [14] and [17] whose study considered a curing period of 3 to 28 days. This pattern of strength development in the optimal nano-concrete 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 optimal nano-concrete 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 nano-concrete mix at early age is an indication that nano-silica does not only serve as filler to increase the density of the micro and nano structure of concrete, but also work as an activator in the process of hydration.

3.4 Tensile Strength Development of Grade 30 Nano-Concrete Mix

The respective lowest and highest values of splitting tensile strength of the optimal nano-concrete mix (30NS1.5) were 2.13N/mm^2 and 4.15N/mm^2 at 3 and 90 days of curing, as presented in figure 3. The splitting tensile strength of the optimal nano-concrete mix (30NS1.5) at 3, 7, 14, 21, 28, 42, 56, 70 and 90 days was improved by 7.04%, 23.3%, 16.47%, 19.19%, 13.47%, 7.71%, 8.58%, 8.12% and 8.64% respectively in comparison with the control concrete mix (30NS0). This shows that nano-concrete has higher tensile strength than an equivalent conventional concrete. Moreover, the improvement in splitting tensile strength of the nano-concrete mix was more pronounced at 7 days of curing than at the other curing ages as concluded by [14]. The early age splitting tensile strength gain of the nano-concrete mix might be due to accelerated hydration reaction on addition of optimal dosage of nS.

There was 85.92% increase in splitting tensile strength of nano-concrete mix between 3 and 28 days of curing, whereas 4.80% 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 nano-concrete mix was between 3 and 28 days of curing, in line with the conclusions of [14]. This could be due to accelerated hydration of the nano-concrete mix, leading to the formation of more C-S-H gels.

The results show that maximum percentage of hydration of the nano-concrete mix was complete at 28 days; the remaining negligible hydration was very slow up to 90days of curing. The increase in tensile strength of the nano-concrete 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 nano-concrete mix could also be as a result of improvement in the interfacial transition zone bonding of the concrete.

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

To allow for nano-concrete design according to EN1992-1-1 (2004) and its reference standards, and also for the purpose of strength comparison with the control concrete, the calculated characteristic compressive and tensile strengths of the control (30NS0) and optimal nano-concrete (30NS1.5) mixes at 28days reference curing period according to the European standard are presented in Table 4. The splitting tensile strength values obtained at the reference curing period were converted to axial tensile strength, while the characteristic cube compressive strengths were 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 concrete mixes. There was 17.36% and 13.38% increase in characteristic cylindrical compressive strength and axial tensile strength on additional of optimal nS dosage in grade 30 concrete.

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)	30	24.25	27.67	80	155	2.08	0.08
Validated Mix	30	30.44	32.33	80	135	1.16	0.04

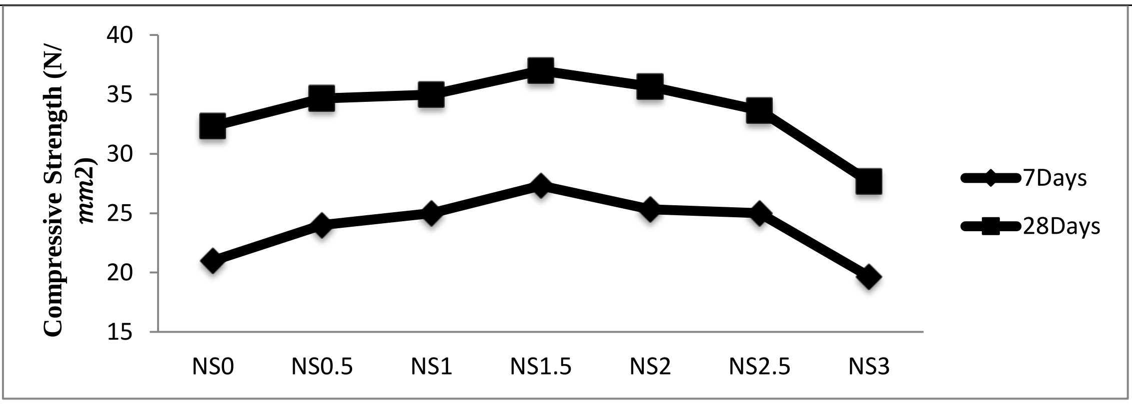


Figure 1: Compressive Strength of Grade 30 Mixes at 7 and 28days of Curing

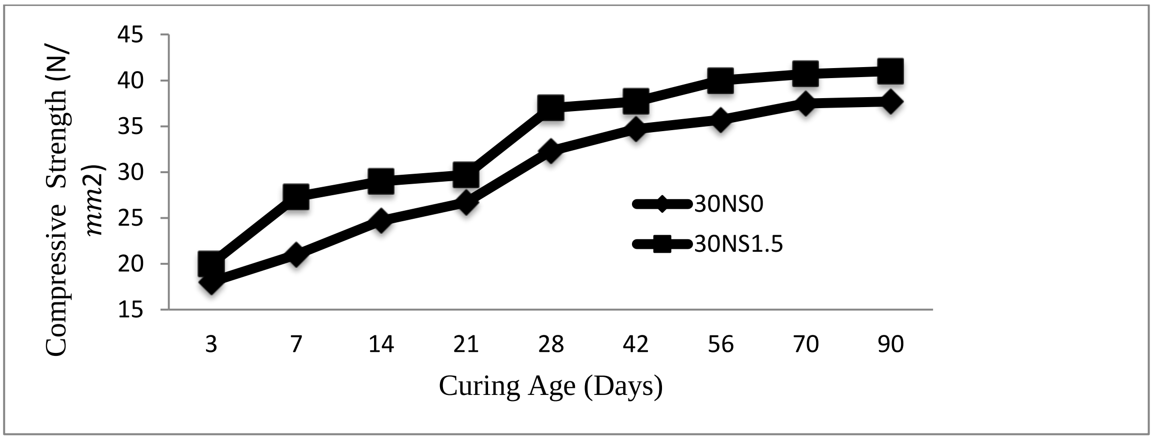


Figure 2: Compressive Strength Development of Grade 30 Control and Nano-Concrete Mixes

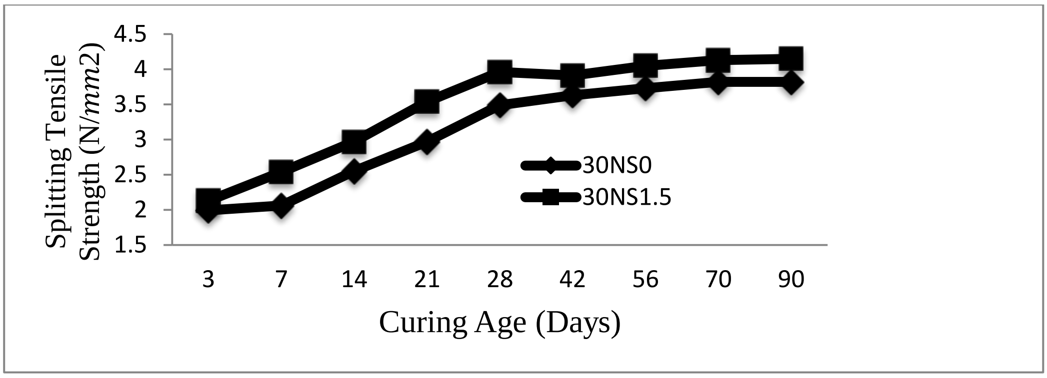


Figure 3: Tensile Strength Development of Grade 30 Control and Nano-Concrete Mixes

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
30NS0	30.4	3.49	24.2	3.14
30NS1.5	35.3	3.96	28.4	3.56

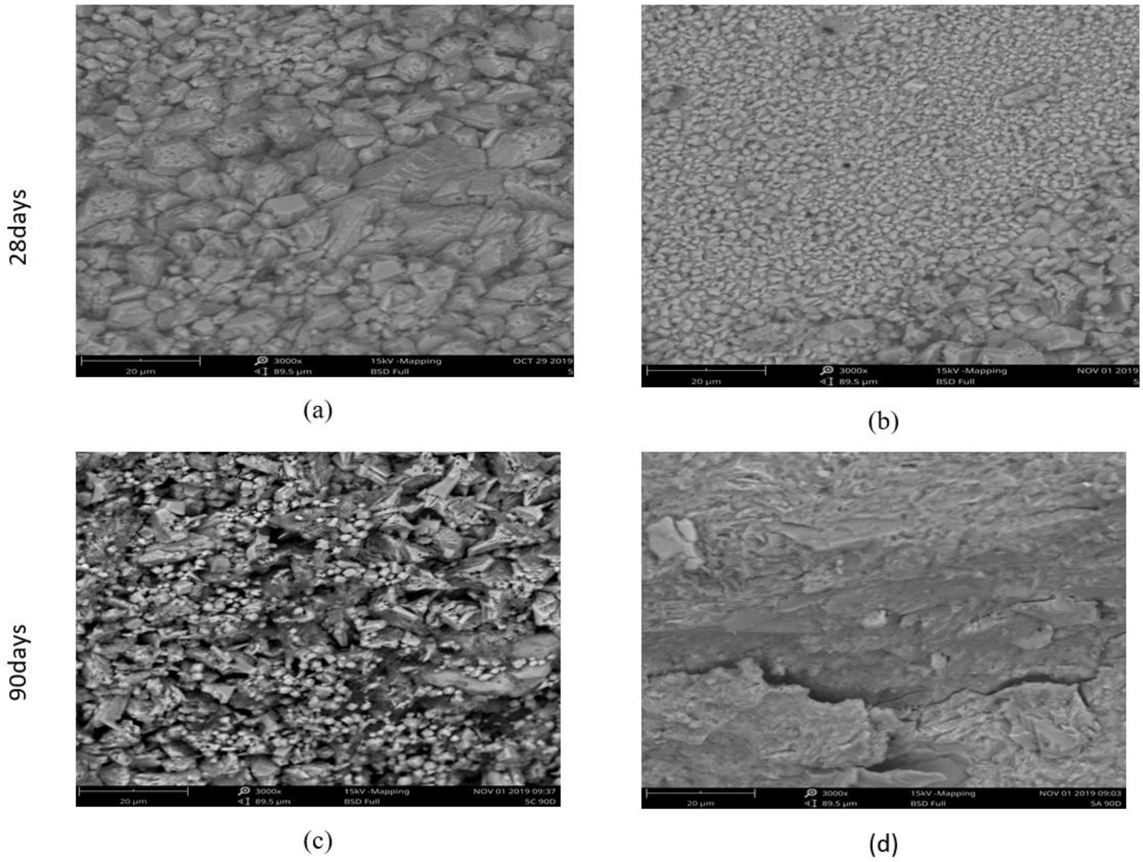
3.6 Relationship between Nano-Concrete Strength Properties and Microstructure

SEM examination was performed on control and nano-concrete samples at 28 and 90days of curing to allow for verification of the mechanism predicted by compressive and splitting tensile strength tests. The SEM images of the control concrete mix at 28 and 90days curing period are presented in Figure 4(a) and (c) respectively. The corresponding SEM images for the optimal nano-concrete mix at 28 and 90days curing period are presented in Figure 4(b) and (d) respectively. A dense and compact formation of hydration products was observed for the nano-concrete at 90days of curing unlike porous plate like structure of the control concrete at the same curing age. Moreover, a dense interfacial layer between aggregates and cement paste was observed for the nano-concrete at 90days of curing. The crack which appear on the surface of the nano-concrete SEM image at 90days of curing could be attributed to the load applied to the cube to obtain the 10mm fractured size sample for the analysis. Furthermore, the improvement in the packing density of the normal strength nano-concrete was more pronounced at 90days of curing (Figure 4(d)) than at 28days of curing (Figure 4(b)). Therefore, it could be said that the microstructural properties of a normal strength nano-concrete could be better assessed at 90days of curing than at 28days reference curing period.

The high quantity of C-S-H gel formed in the nano-concrete was confirmed, as high content of calcium (Ca) and Silica (SiO_2) was found in the EDS spectrum of the nano-concrete, as presented in Figure 5. Thus, it could be concluded that the improvement in the tensile and compressive strengths of the nano-concrete was as a result of densification and pore refinement.

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

In order to provide a correlation between compressive and tensile strengths development of nano-concrete and Ca/Si ratio, the weight concentrations of the two elements in both the control and optimal nano-concrete mix was determined using EDS. The optimal nano-concrete mix (30NS1.5), which has higher compressive and tensile strengths, has lower Ca/Si ratio than the control concrete mix (30NS0) at 90days of curing, as shown in Table 5. The Ca/Si ratio of the nano-concrete was calculated as 0.89 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 in [18]. This shows that the compressive and tensile strengths of nano-concrete increase with decrease in Ca/Si ratio.



(a) (b)

(c) (d)

Figure 4: SEM images of concrete at 28 and 90days of curing. (a) control concrete at 28days, (b) nano-concrete at 28days, (c) control concrete at 90days, (d) nano-concrete at 90days.

Table 5: Ca/Si ratios of the grade 30 concrete at 90days of curing

Concrete Mix	Element	Weight Concentration (%)	Ca/Si ratio
30NS0	Calcium (Ca)	37.05	1.90
	Silicon (Si)	19.50	
30NS1.5	Calcium (Ca)	34.31	0.89
	Silicon (Si)	38.55	

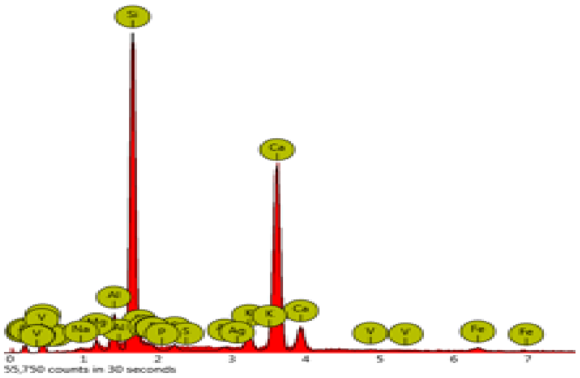


Figure 5: EDS spectrum of nano-concrete at 90 days of curing

Furthermore, it could be said that the addition of optimal nS in concrete makes its internal structure and bond assembly to approach that of 14Ǻ tobermorite reported in literature.

4 CONCLUSION

The effect of optimal nS dosage on strength and microstructural properties of a normal strength concrete reported in this study showed that addition of optimal nS dosage improves the strength and microstructural properties of concrete. From the results, the following conclusions were drawn:

1. The optimal nS dosage in grade 30 normal strength concrete was determined to be 1.5% by weight of cement.
2. The addition of optimal nS dosage in normal strength concrete led to improvement in compressive and tensile strengths of nano-concrete mixes with increase in curing age. The addition of optimal nS led to 30% and 23.3% respective increase in compressive and tensile strengths of conventional concrete at 7days of curing.

3. The most significant improvement in the tensile and compressive strengths of normal strength nano-concrete was between 3 and 28days of curing, whereas, a negligible increase in compressive and tensile strengths of the nano-concrete exist between 28 and 90days of curing. Therefore, the practice of using 28days reference curing period to determine characteristic strength in concrete is actually a good one and could be extended to normal strength nano-concrete.
4. The use of optimal nS in normal strength concrete could overcome the shortcomings in early age strength development of Ground Granulated Blast Furnace Slag (GGBS) in the production of high strength concrete.
5. Addition of optimal dosage of nS in normal strength concrete mixes improved the microstructural properties of the matured concrete at 28 and 90days of curing through densification and pore refinement, thereby reducing permeability and void content.
6. The effect of optimal nS dosage on the packing density of normal strength nano-concrete was more pronounced at 90days of curing than at 28days curing period. Therefore, the microstructural properties of a normal strength nano-concrete could be better assessed at 90days of curing.
7. Optimal nS addition in normal strength nano-concrete reduced Ca/Si ratio at 90days of curing to 0.89, a value very close 0.81; the Ca/Si ratio of 14Å tobermorite C-S-H model reported in literature, thereby, resulting in improved hydration reaction and corresponding increase in tensile and compressive strengths of the normal strength nano-concrete.
8. Addition of optimal nS dosage in grade 30 normal strength concrete led to 17.36% and 13.38% respective increase in characteristic cylindrical compressive and axial tensile strengths determined according to Eurocodes.

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