COMPRESSIVE STRENGTH OF ULTRA HIGHPERFORMANCE FIBER-REINFORCED CONCRETE USING NANO-SILICA

Ngekpe, Barisua Ebenezer[1], Rivers State University of Science and Technology, Port Harcourt, ebenezer.ngekpe@ust.edu.ng
Akobo, Iboroma Seddon[1], Rivers State University of Science and Technology, Port Harcourt, izsakobs@yahoo.com.
Briggs, Ma-awogberiye Opuda[2], Rivers State University of Science and Technology, Port Harcourt, opuda.briggs@yahoo.com
Georgewill, Victor Adokiye[2], Rivers State University of Science and Technology, Port Harcourt, victor.georgewill@ust.edu.ng

Abstract: Ultra High Performance Fiber Reinforced Concrete (UHPFRC) was developed to meet the tripartite requirement of strength, durability and ductility. To achieve this, Nano-silica was used to replace cement partially and also glass fiber was incorporated at various inclusion levels. The Particle Packing Method of mix design was adopted for the design of UHPFRC in order to reduce void volume. The popular use of steel fibers in Reinforce concrete structure situated hostile environment causes corrosion. However, other corrosion resistant fibers such as glass fibers was adopted. To evaluate workability, slump test was conducted on fresh concrete while compressive and tensile strength tests were carried out on hardened concrete specimens at water-cement ratios of 0.2 and 0.22 and the inclusion of glass fibers at varying percentages (0.5, 1.0, 1.5 %). was investigated. The results showed increase in compressive and split tensile strength of the concrete as the incorporation of Nanosilica (5%, 10%, and 15%) and glass fiber (0.5%, 1.0%, and 1.5%) increases. Maximum compressive strength of **152.3 MPa** was measured at 15% replacement of cement with Nanosilica and 1.5% inclusion of glass fiber. Results showed that nanosilica, a superior supplementary cementitious material can be used to produce UHPFRC.

INTRODUCTION

According to ACI 239R-18, Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) is a concrete that exhibits compressive strength of 150 MPa and above. For proper structural application, its material and mechanical properties have been investigated. The following material properties such as; hydration process, permeability, fibres role, mix design, fibre-matrix bond properties, workability, mixing procedure and curing have been addressed. The advantages of the mechanical properties such as high ductility, low permeability, very high strength capacity in compression and higher toughness, have been proven to be economically and technically more efficient in rehabilitating and strengthening bridge deck slabs subjected to significant fatigue loading in reinforced concrete with or without steel rebars on top of the existing slab than the conventional methods. [1][2][3][4]. Concrete with compressive strength of 150 MPa and above, also has a relational increase between tensile strength and Modulus of

Elasticity. For a better tensile response, particularly in the post-cracking regime, fibres are incorporated in the concrete mix. UHPFRC being a new kind of concrete, the principles of application, is not captured in the current design codes and the review of those design codes to include its application is of importance. Presently, UHPFRC can be prepared with a relatively low costly material and energy consumption by replacing part of the cement with environmentally friendly cementitious materials like fly ash, slag, silica fume etc.

RELATED STUDIES

The concept of UHPFRC was developed by [5] developed the concept of UHPFRC. In their study, they investigated high strength cement pastes with water cement (w/c) ratio between 0.2-0.3. These low w/c ratios gave concrete with low porosities leading to compressive strengths up to 200 MPa and low dimensional changes.

[6] conducted a research using silica fume and nanosilica. Nanosilica and fine steel fibres to produce Ultra High Performance Concrete (UHPC) and Reactive Powder Concrete (RPC). The result of the Compressive strengths test confirms that 150 MPa was achieved and further shows that UHPC and RPC can be produced using standard concrete mixing system without the use of activating mixing and without a special treatment regime during curing of the concrete. Concrete aging took place in a normal environment without elevated pressure or temperature. The aging process at 20 °C allowed the use of UHPC and RPC for the ready-mixed concrete when working on high volume construction projects. When the process excluded thermal treatment, application of solidification pressure and autoclaving, RPC reached a compressive strength of more than 180 MPa and a flexural tensile strength after 60 days greater than 22 MPa. The study further recommended that high tensile bending strength be considered as the main advantage of RPC, as the RPC parameters allow for the use of pre-stressed structural elements where a high initial strength is also needed.

[7] examined the effect of steel fiber geometry on the mechanical properties of ultra-high-performance fiber-reinforced concrete (UHPFRC) under cryogenic conditions (approximately −162 °C). The compressive and tensile tests were performed using UHPFRCs containing three types of straight steel fibers and one type of twisted steel fiber. To investigate the mechanical properties of UHPFRCs under various temperatures, mechanical tests were performed in three different conditions: ambient temperature, cryogenic temperature, and recovered ambient temperature. The test results demonstrated considerable increases in both the compressive strength and tensile performance, including strength and fracture energy, for UHPFRCs with straight fibers at the cryogenic temperature, whereas that containing the twisted fibers demonstrated the poorest energy absorption capacity at the cryogenic temperature, due to the fiber fracturing. Finally, UHPFRCs containing longer straight fibers most effectively achieved excellent mechanical properties at the cryogenic temperature, compared to those with short straight and twisted fibers.

[8] investigated the effects of replacing a portion of Portland cement with slag cement by mass on the properties of plain ultra-high performance concrete (UHPC). It was observed that slag

cement appreciably enhanced the flowability of the UHPC and reduced the dosage the water reducing agent. Mechanical properties were evaluated for mixes with similar air void characteristics and result obtained showed that initial strength of the concrete reduced but increased more at the later curing age. The initial age strength reduction was consistent with semi-adiabatic hydration heat evolution. The presence of slag cement reduces the maximum temperature rise. Linear deformation measurement on duplicate sealed specimens reveals four distinct stages for the shrinkage development and slag cement increases the shrinkage strain in the steady state associated with the pozzolanic reaction. Simultaneous measurement of moisture uptake, mass loss and relative dynamic modulus of elasticity (RDM) on UHPC mixes for F-T durability shows that the cumulative moisture uptake and mass loss, when normalized with respect to the paste content, are almost negligible compared with a regular concrete mix. This reconciles the capillary suction dominated surface scaling mechanism. No internal bulk cracking is detected due to the dense matrix restricting the ingress of external moisture and the amount of freezable pore water.

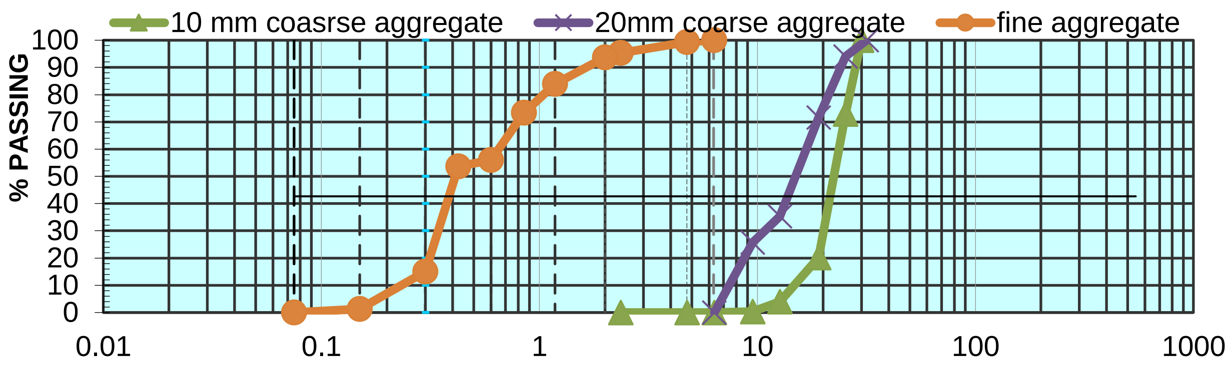
MATERIALS AND METHODS

Materials

Limestone Cement grade 42.5R produced by Dangote Group of Company PLC conforming to NIS 444 obtained from Mile 3 Diobu Port-Harcourt was used together with crushed granite stones of maximum size 20mm from quarry in Akamkpa, Cross Rivers State. Fine aggregate (River Sand) conforming to EN 12620 was obtained from the River bed in Choba, Obio/Akpor Local Government Area of Rivers State. Water used for this study was obtained from the Civil Engineering Laboratory and Nanosilica used for this study was obtained from Lagos State. The Alkali resistant glass fiber in compliance with EN 15422 was incorporated. Super plasticizer used was Forsroc Auracast 200 obtained from Aba, Abia State.

Particle Size Distribution (PSD)

The results obtained from the sieve analysis test carried out on the aggregates are presented in the plot presented in **Fig. 1**



CLAY	*SILT*			*SAND*			*GRAVEL*		
	FINE	*MED*	*COARSE*	*FINE*	*MED*	*COARSE*	*FINE*	*MED*	*COARSE*

Fig. 1 Particle size distribution

Mix design method

Particle Packing Method

Determination of aggregate fractions and packing density: In the Particle Packing Method (PPM) the optimal combination of aggregate is determined experimentally. In this study, the different sized coarse aggregates are selected, their gradation in different size zones from coarser to finer, such as CA_1, CA_2 and CA_3 was carried out. The compacted bulk density and specific gravity of aggregates were determined separately for each size category.

The basic concept of the packing density is to minimize the void content. The objective of PPM is to obtain maximum possible packing density which leads to the minimization of void. In each mixture, the bulk density is determined experimentally and packing density (PD) and void content (CV) are calculated using Eqn (1) and Eqn (2) accordingly to EN1097-3:1998

$$\text{Packing Density} = \frac{\text{BulkDensityxWeightfraction}}{\text{SpecificGravity}} \tag{1}$$

$$\text{Void Content} = 1 - \frac{BulkDensityxWeightfraction}{SpecificGravity} \tag{2}$$

Determination of Paste Content

The total packing density (PD) determined by mixing different sized coarse aggregates and fine aggregate is used to determine the void content (VC) of the mixture using Eqn (3)

$$\text{Void content (VC)} = 1 - PD \tag{3}$$

Aggregate Fractions and Packing Density

The present study incorporates 20mm, 10mm sized with zone 2 fine aggregate to optimize the combination of aggregates. To achieve maximum packing density, the proportion of aggregates used is 40:60 for fine and coarse aggregates respectively and 70:30 for 10mm and 20mm coarse aggregate respectively, making the final proportion 18:42:40 for fine, 10mm coarse and 20mm coarse aggregates respectively. Various aggregate combinations were examined and the aggregate combination that gives the maximum packing density was selected.

Bulk Density

(a) Bulk density of combined coarse aggregate 20mm, 10mm in the proportion 18:40.

$$\text{Bulk density} = \frac{W_1 - W_2}{Volumeofmould}$$

Where, W_1 = Empty weight of mould

W_2 = Weight of mould + aggregate filled

(b) Bulk density of three aggregates i.e 20mm coarse aggregate, 10mm coarse aggregate and fine aggregate calculated are 1744 kg/m^3, 1524 kg/m^3 and 1940 kg/m^3.

The maximum bulk density is selected.

The void content in percentage volume of aggregate of mixture of three aggregate is determined from its bulk density from the following relations.

Void content in percentage volume $= \frac{SpecificGravity - BulkDensity}{SpecificGravity}$

Packing Density (max) = $\frac{BulkDensity x WeightFraction}{SpecificGravity}$

Bulk density of 20mm CA = 1744 kg/m^3

Bulk density of 10mm CA = 1524 kg/m^3

Bulk density of FA = 1940 kg/m^3

Packing Density (max) $= \frac{Bulk\ Density x Weight\ Fraction}{Specific\ Gravity}$

PD 20mm = $\frac{1{,}744\ x\ 0.42}{2.56}$ = 0.2861

PD 10mm = $\frac{1{,}524\ x\ 0.18}{2.61}$ = 0.1051

PD FA = $\frac{1{,}940\ x\ 0.40}{2.63}$ = 0.2951

Packing density of 20mm as calculated = 0.2861

Packing density of 10mm as calculated = 0.1051

Packing density of FA as calculated = 0.2951

Total packing density = 0.6863

Void content = $1 - PD$ = 0.3137

Paste content 10% in excess of void content

Allowable 10% for excess paste volume = 10% of void content = 0.03137

Total void content (Vp) = 0.3451

Volume of aggregate = $1 - Vp$ = 1 - 0.3451 = 0.6549m^3

Total volume ratio of solid aggregate = $\frac{0.42}{2.56} + \frac{0.18}{2.61} + \frac{0.40}{2.63}$ = 0.3851

Weight of 20mm Aggregate = $\frac{0.6549}{0.3851}\ x\ 0.42\ x\ 1000$ = 714.25 kg/m^3

Weight of 10mm Aggregate = $\frac{0.6549}{0.3851}\ x\ 0.18\ x\ 1000$ = 306.11 kg/m^3

Weight of Fine Aggregate = $\frac{0.6549}{0.3851}\ x\ 0.40\ x\ 1000$ = 680.24 kg/m^3

For w/c ratio of 0.20, S.P = 1.0% of cement weight

Total paste = C + W + S.P

$= \frac{C}{3.10} + \frac{0.2C}{1.0} + \frac{0.01}{1.06} = 0.5324C$

Cement content = $\frac{0.3541}{0.5324} X \frac{1000}{1}$ = 648.20 kg/m^3

For inclusion Fibre

For volume of Fibre = 0.5%

Volume of Aggregate = $1 - Vp - 0.5\%$ of fiber volume

= 1 - 0.3451 - 0.005 = 0.6499m^3

Weight of 20mm Aggregate = $\frac{0.6449}{0.3851} x\ 0.42\ x\ 1000$ = 708.79 kg/m^3

Weight of 10mm Aggregate = $\frac{0.6449}{0.3851} x\ 0.18\ x\ 1000$ = 303.77 kg/m^3

Weight of Fine Aggregate = = $\frac{0.6449}{0.3851} x\ 0.40\ x\ 1000$ = 675.05 kg/m^3

For volume of Fiber = 1 %

Volume of Aggregate = 1 - Vp - 1.0 % of fiber volume

= 1 - 0.3451 - 0.01 = 0.6449m^3

Weight of 20mm Aggregate = $\frac{0.6449}{0.3851} x\ 0.42\ x\ 1000$ = 703.35 kg/m^3

Weight of 10mm Aggregate = = $\frac{0.6449}{0.3851} x\ 0.18\ x\ 1000$ = 301.43 kg/m^3

Weight of Fine Aggregate = = $\frac{0.6449}{0.3851} x\ 0.40\ x\ 1000$ = 669.85 kg/m^3

For volume of Fiber = 1.5%

Volume of Aggregate = 1 - Vp - 0.015 % of fiber volume

= 1 - 0.3451 - 0.015 = 0.6399m^3

Weight of 20mm Aggregate = $\frac{0.6399}{0.3851}$ x 0.42 x 1000 = 697.89 kg/m^3

Weight of 10mm Aggregate = $\frac{0.6399}{0.3851} x\ 0.18\ x\ 1000$ = 697.89 kg/m^3

Weight of Fine Aggregate = $\frac{0.6399}{0.3851} x\ 0.40\ x\ 1000$ = 664.66 kg/m^3

The summary of mix proportion is presented in Table 1

Table-1 Mix Proportion

% NS	% GF	20mm CA	10mm CA (kg/m^3)	FA (kg/m3)	Cement Content (kg/m^3)	NS Content (kg/m^3)	GF Content (kg/m^3)
0	0	714.25	306.11	680.21	648.20	0	0
	0.5	708.79	303.77	675.05	648.20	0	12
	1.0	703.35	301.43	669.85	648.20	0	24
	1.5	697.89	299.10	664.66	648.20	0	36
5	0	714.25	306.11	680.24	615.79	32.41	0
	0.5	708.79	303.77	675.05	615.79	32.41	12
	1.0	703.35	301.43	669.85	615.79	32.41	24
	1.5	697.89	299.10	664.66	615.79	32.41	36
10	0	714.25	306.11	680.24	583.38	64.82	0
	0.5	708.79	303.77	675.05	583.38	64.82	12
	1.0	703.35	301.43	669.85	583.38	64.82	24
	1.5	697.89	299.10	664.66	583.38	64.82	36
15	0	714.25	306.11	680.24	550.97	97.23	0
	0.5	708.79	303.77	675.05	550.97	97.23	12
	1.0	703.35	301.43	669.85	550.97	97.23	24
	1.5	697.89	299.10	664.66	550.97	97.23	36

using a table compacting machine. The tensile 36 was calculated using the formula as obtained from BS1881-117 section 3.3.2.

$$\mathbf{f}_{\tau} = \frac{2f}{\pi l d} \quad \text{.........} 3.5$$

RESULTS AND DISCUSSION

Compressive Strength

The concrete prepared for the experiment at 0.20 water/cement ratio were subjected to compressive test after curing it for 7, 14 and 28 days. The results obtained are presented in **Table 2**

Table-2 Compressive Strength Results of Control and Nanosilica blended UHPFRC at various ages.

% Replacement With Nanosilica	% Inclusion of Glass Fiber	Compressive Strength (MPa)		
		7Days	14Days	28Days
0	0.0	76.00	95.41	102.64
	0.5	81.72	101.35	114.51
	1.0	83.11	103.73	117.72
	1.5	86.34	107.00	122.35
5	0.0	78.67	99.12	109.14
	0.5	83.00	105.91	122.27
	1.0	85.71	106.25	125.37
	1.5	88.30	110.56	130.70
10	0.0	83.21	102.17	118.79
	0.5	89.72	107.41	131.21
	1.0	90.43	110.39	137.23
	1.5	92.70	115.23	142.73
15	0.0	90.13	110.17	124.82
	0.5	96.00	116.92	137.84
	1.0	98.36	119.36	145.04
	1.5	101.30	125.70	152.30

From Table-2 above, the maximum compressive strength value of 152.3 MPa was achieved for a mix with 15% replacement of ordinary cement with Nanosilica and 1.5% by volume incorporation of fiber, it was observed that the strength of the concrete at different amount of Nanosilica increases steadily with the inclusion of glass fiber from 0.5 to 1.5%.

Partial replacement of cement with Nanosilica significantly affected the compressive strength of the concrete mix. Increasing the amount of Nanosilica in the concretes increased the compressive strength of the concrete. In essence, the increase in compressive strength is as a result of reduction of voids in the concrete through the introduction of finer particles of Nanosilica (NS). Thus, for all curing ages, the maximum strength values were observed for concretes with 15% replacement of cement with Nanosilica and 1.5% by volume inclusion of glass fiber. Therefore, the compressive strength of UHPFRC was obtained at 15% Nanosilica content and 1.5% glass fiber content.

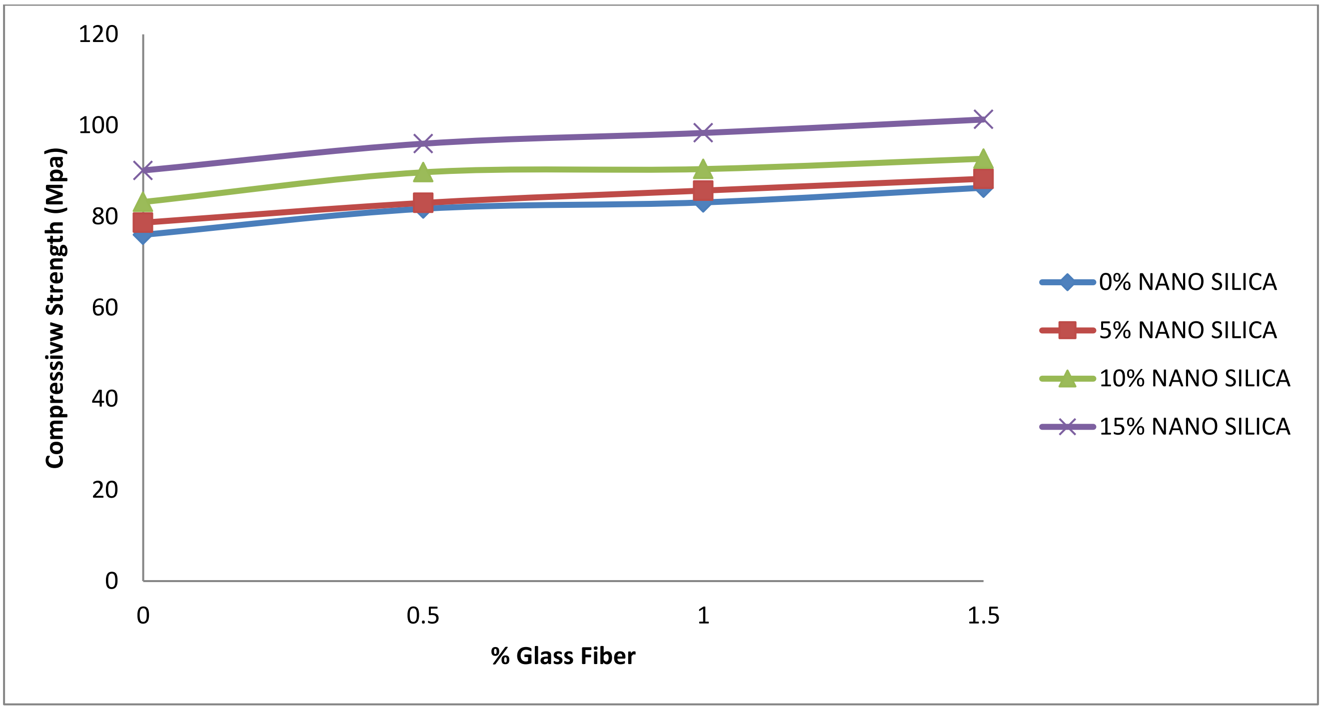


Fig. 2 Compressive strength of UHPFRC for 7 DAYS

From Fig. 2, it was observed that the compressive strength of the concrete after 7 days of curing increases on increasing amount of glass fiber up to 1.5% with the introduction of Nanosilica content. At 0% Nanosilica content, the compressive strength is observed to increase by 7.5%, 9.2% and 11.45% at 0.5%, 1.0% and 1.5% by volume inclusion of glass fiber. At 5% Nanosilica content, the compressive strength is observed to increase by 5.51%, 8.78% and 11.81% at 0.5%, 1.0% and 1.5% by volume inclusion of glass fiber. At 15% Nanosilica content, the compressive strength is observed to increase by 6.42%, 9.32% and 11.92% at 0.5%, 1.0% and 1.5% inclusion of glass fiber.

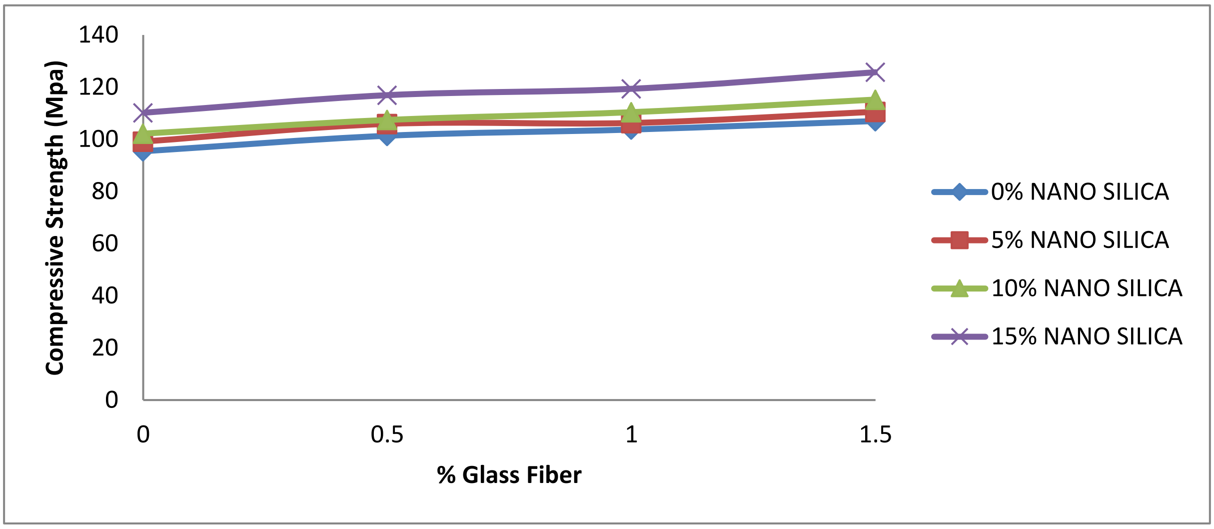


Fig. 3 Compressive strength of UHPFRC for 14 DAYS

Fig. 3, it was observed that the compressive strength of concrete after 14 days increases on increasing amount of glass fiber up to 1.5% with the introduction of Nanosilica content. At 0% Nanosilica content, the compressive strength is observed to increase by 6%, 8.55% and 11.65% at 0.5%,1.0% and 1.5% by volume inclusion of glass fiber. At 5% Nanosilica content, the compressive strength is observed to increase by 6.85%, 7.18% and 10.7% at 0.5%, 1.0% and 1.5% by volume inclusion of glass fiber. At 10% Nanosilica content, the compressive strength is observed to increase by 5.12%, 7.9% and 12.29% at 0.5%, 1.0% and 1.5% inclusion of glass fiber content. At 15% Nanosilica content, the compressive strength is observed to increase by 6.1%, 8.2% and 13.51% at 0.5%, 1.0% and 1.5% inclusion of glass fiber content.

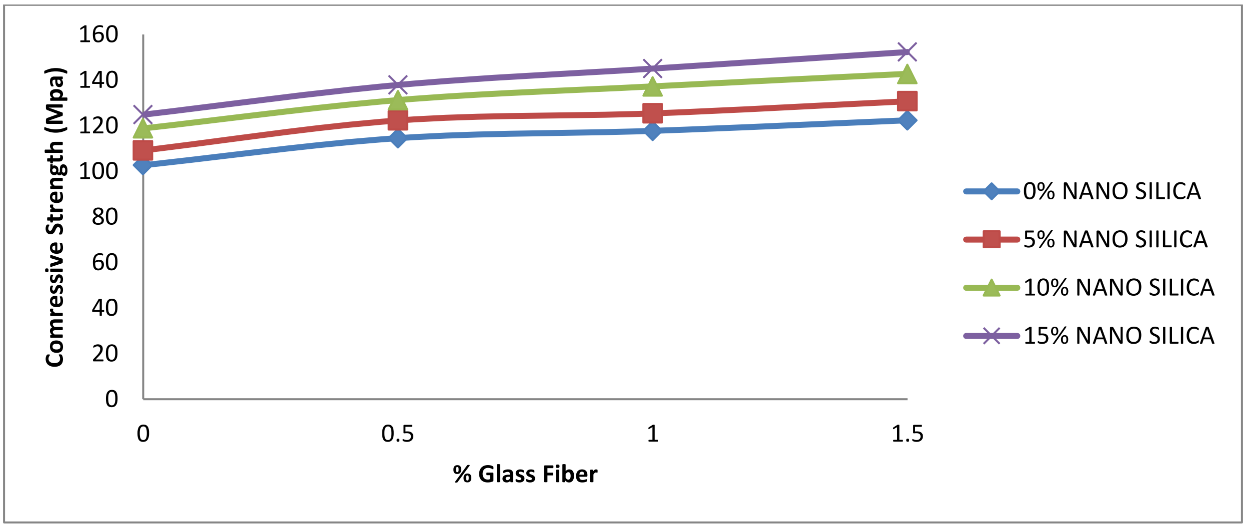


Fig. 4 Compressive strength of UHPFRC for 28 Days

From Fig. 4, it is observed that the compressive strength of concrete after 28 days increases on increasing amount of glass fiber up to 1.5% with the introduction of Nanosilica content. At 0% Nanosilica content, the compressive strength is observed to increase by 11.5%, 14.3% and

18.25% at 0.5%, 1.0% and 1.5% by volume inclusion of glass fiber. At 5% Nanosilica content, the compressive strength is observed to increase by 12.2%, 14.8% and 19.05% at 0.5%, 1.0% and 1.5% by volume inclusion of glass fiber. At 10% Nanosilica content, the compressive strength is observed to increase by 11.3%, 15.8% and 20.19% at 0.5%, 1.0% and 1.5% inclusion of glass fiber content. At 15% Nanosilica content, the compressive strength is observed to increase by 9.4%, 15.6% and 22.6% at 0.5%, 1.0% and 1.5% inclusion of glass fiber content

CONCLUSION

This study aimed at developing an appropriate Mix Design method for the production of Ultra High Performance Fiber-Reinforced Concrete (UHPFRC). The aim was achieved by harnessing the cementitious capability of Nanosilica and the ductile capability of glass fiber. The salient findings are highlighted as follows;

- The adopted Particle Parking Method (PPM) of mix design, provided an acceptable results for the fresh and hardened state properties of the Ultra High Performance Fiber-Reinforced concrete. Thus, this mix design method is proposed for the production of Ultra High Performance Fiber-Reinforced Concrete (UHPFRC) because the compressive strength above 150MPa.
- At 15% Nanosilica content, the compressive strength is observed to increase by 9.4%, 15.6% and 22.6% at 0.5%, 1.0% and 1.5% inclusion of glass fiber content.
- As the inclusion of glass fiber increases to 1.5%, maximum value of split tensile strength of 3.84 Mpa was observed.
- The incorporation of glass fiber increased the ductility of UHPFRC and thereby increased the compressive strength of the concrete.

Acknowledgement
The authors wish to acknowledge Technical Staff at the Structural Engineering, Rivers State University, Nigeria.

REFERENCES

[1] E. Denarie & E. Bruhwiler, Structural rehabilitations with ultra high performance fibre reinforced concretes. *Int J Restor Build Monum* **2006** 12(5,6), 453–465.
[2] E. Bruhwiler, Rehabilitaion of concrete structures using ultra-high performance fibre sreinforced concerete, *In: Fehling E, Schmidt M, Sturwald S eds Proceedings of UHPC: the second international symposium on ultra high performance concrete, Kassel*, **2008,** 3, 895-902.
[3] E. Bruhwiler, Rehabilitation of bridges using ultrahigh performance fiber reinforced concrete. *In: Proceedings of 5th New York City Bridge Conference, New York 4*. **2009**

[4] E. Bruhwiler, Ultra-high performance fiber reinforced concrete improves concrete structures. *Structural concrete in Switzerland, Swiss national group of the international federation for structural concrete*, **2010**, 145–149.

[5] M. Yudenfreund, I. Odler, & S. Brunauer, Hardened portland cement pastes of low porosity I, *Materials and experimental methods. Cement and Concrete Research*, **1972**, *2(3)*, 313 - 330.

[6] R. Hela, L. Bodnarova & L. Rundt, Development of ultra high performance concrete and reactive powder concrete with nanosilica. *In IOP Conference Series: Materials Science and Engineering (Vol. 371, No. 1, p. 012017). IOP Publishing.* **2018.**

[7] M. J. Kim, D. Y. Yoo, S. Kim, M. Shin & N. Banthia, Effects of fiber geometry and cryogenic condition on mechanical properties of ultra-high-performance fiber-reinforced concrete, *Cement and Concrete Research,* **2018,** 107, 30-40.

[8] Z. Liu, S. El-Tawil, W. Hansen & F. Wang, Effect of slag cement on the properties of ultra-high performance concrete, *Construction and Building Materials,* **2018**, 190, 830-837.