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Hardened State Properties of Glass Fiber Reinforced High Strength Concrete

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Abstract
Plain high strength concrete is more brittle as the compressive strength increases and therefore susceptible to cracking. To overcome this, concretes are reinforced with fibers to improve their ductility, toughness and reduce cracks possibility. This study was carried out to investigate the hardened state properties of high strength concrete reinforced with alkaline resistant glass fiber at varying percentages (0.5, 1.0, 1.5, and 2.0%). In order to reduce autogenous shrinkages resulting from excess cement volume, microsilica, a cementitious material, was used as a partial replacement for cement. The Particle Packing Method mix design was adopted to design specimens to reduce the mixes' void volume. A compressive strength test was carried out on hardened concrete specimens. Results showed that the compressive strength of the concrete increase as the incorporation level of microsilica and glass fiber increase. However, a slight drop in strength was observed at 2% glass fiber inclusion. The maximum compressive strength of 130MPa was measured at 10% replacement of cement with microsilica and 1.5% inclusion of glass fiber.

Keywords - *High Strength Concrete, Compressive Strength, Glass fiber, Microsilica, Particle Packing Method*

I. INTRODUCTION

Concrete is one of the most universally used construction materials based on its versatility. However, the deficiencies of low tensile strength and lack of ductility (brittleness) may limit its applicability. According to ACI/ASCE 441R-2018, high strength concrete (HSC) is defined as concrete with compressive strength higher than 55 MPa.

It is a concrete block with lower permeability, lower water content, higher strength, and durability. The wide range of applications of high-strength concrete (HSC) resulted in its promotion and development. High-strength concrete offers higher compressive strength and more durable concrete. A significant advantage of high-strength concrete is that it allows for smaller cross-sectional areas to be used to design concrete structures (Salah-Eldin, 2019).

In the recent development of fiber-reinforced high-strength concretes, reinforced polymer fibers such as glass fiber have been used as an alternative to the highly corrosion-susceptible conventional steel fibers. Glass fibers have high corrosion resistance, high tensile strength, lightweight, and speed of application resulting in lower production cost compared to steel fiber-reinforced concrete (Saleh et al., 2019). Glass fiber has a comparative advantage over other types of fiber because of high surface area to weight ratio and high strength properties to unit cost ratio. However, the alkaline nature of cement effect glass fiber when used in a combined form. To overcome this, alkaline resistant glass fibers have been developed (Grzymski et al., 2019).

Rasheed and Zeedan (2011) noted that gases that cause the greenhouse effect are emitted during cement production and lead to severe environmental hazards. Other cementitious materials such as microsilica with less environmental impact could be applied to mitigate this adverse effect.

Fiber-reinforced high-strength concrete found its application in the following areas; building long-span bridges, building high-rise buildings, applying relatively small column sizes, and precast concrete (Mayer et al., 2002).

II. LITERATURE REVIEW

This chapter presents a comprehensive review of the mechanical properties of fiber-reinforced concrete. The review is carried out by reporting objectives, methodologies, and results of published research studies. Existing kinds of literature are reviewed and criticized to identify gaps for further investigation.

Tassew and Lubell (2014) carried out an experimental investigation to examine chopped glass fibers' influence on the mechanical and rheological properties of concrete prepared with ceramics. The concrete matrices were made with either sand or lightweight expanded clay aggregates. The volume of fiber introduced into the mixes varied from 0 to 2%.

From the test carried out, the following was observed;

1. Fiber does not exhibit any significant influence on the densities of the ceramic concrete. However, the inclusion of glass fibers reduced the flow of the concrete.
2. The increase in the fiber content increased the compressive strength of ceramic concrete containing clay aggregates. However, there was a negligible effect on the elastic modulus. The concrete containing sand aggregate decreased in both the compressive strength and elastic modulus at higher volume content of glass fiber.

3. The inclusion of glass fiber into both concrete types increased the compression toughness, sheer toughness, and flexural toughness. This showed that the failure was predominantly caused by fracture rather than pullout.
4. The flexural strength of the concrete was observed to have increased on the increase in the fiber content.

Mastali et al. (2016) examined the impact resistance and mechanical properties of glass fiber reinforced self-compacting concrete. Three volume fractions of glass fiber (0.25%, 0.75%, and 1.25% were incorporated into the self-compacting concrete. A scanning electron microscope was employed to investigate recycled glass fiber's failure mechanism in the mix design. Results obtained from the experimental tests were used as input parameters in the statistical and analytical analyses.

The mechanical properties and impact resistance of the glass fiber reinforced concrete were improved from the experimental result. Statistical analysis showed that the flexural strength, impact resistance correlated linearly to compressive strength with the coefficient of correlation, R^2 more than 0.86. The compressive strength and flexural strength showed normal distribution while the first and the ultimate crack-partner resistance scarcely followed a normal distribution.

Hasan et al. (2017) carried out an experimental study to evaluate the performance of high-strength concrete (HSC) and steel-fiber high strength concrete (SFHSC) reinforced longitudinally and transversely with glass fibers and helices, respectively. The column specimens were subjected to concentric, eccentric, and four-point loading to test for the reinforced concrete columns' performance. A total of 16 specimens were tested; four under four-point loading, four under concentric axial load, and eight under eccentric axial load.

From the test carried out, the following observations and conclusions were made;

1. The high strength concrete's axial load bearing capacity was observed not to be influenced by the direct replacement of the transverse and longitudinal steel reinforcement with glass fiber reinforced polymer under concentric axial load. However, upon changing the loading condition from concentric loading to 25 and 50 mm eccentric axial loading, the glass fiber reinforced high strength concrete showed about 10% and 12% lower axial load-bearing capacity, respectively.
2. Under concentric loading, the 60% glass fiber reinforced concrete's axial load-bearing capacity was observed to be similar or slightly greater than the 60% steel fiber reinforced concrete for the steel fiber high strength concrete. However, under eccentric loading, the glass fiber concrete's axial load bearing capacity was greater than that of the steel fibers.
3. There was about a 30% reduction in concrete ductility when the same amount of steel fiber was replaced with glass fiber under concentric loading. The ductility of SFHSC reinforced with glass fiber reinforced polymer was observed to be similar to the normal steel fiber high strength concrete specimen.

The oxygen plasma etching of glass fibers on lime-based mortar was examined by Trejbal (2018). Mechanical destructive tests were carried out on prismatic fiber-reinforced mortar samples to reveal the interaction between fibers and mortar matrix. Bending tests carried out on the samples revealed that slightly reinforced samples with glass fibers exhibited significantly better bending toughness than those with treated fibers. The samples reinforced with strong reinforcement showed that the maximum elastic limit approximately 25% higher than the samples with treated reinforcement.

Hilles and Ziara (2019) investigated high strength concrete's mechanical behavior reinforced with alkali-resistant glass fiber. Concrete mixes were prepared with 0.3, 0.6, 0.9, and 1.2% by weight of cement, and the compressive strength, splitting tensile strength, and flexural strengths were tested after 7 and 28 days in accordance with ASTM standards.

From the experiment carried out, the following results were obtained;

1. The compressive strength of the concrete was observed to have increased on an increasing amount of glass fiber. Maximum compressive strength was achieved at 1.2% of glass fiber content.
2. The splitting tensile strength, flexural strength, and density were also observed to be greater than that of compressive strength. Therefore, it was concluded that the glass fiber was more significant in enhancing splitting tensile strength than the compressive strength.

Grzymski et al. (2019) studied the effectiveness of recycled steel fibers on the increase of concrete ductility. The steel fiber was obtained from the machining process discard. Three concrete mixes were examined; plain concrete without steel fiber was used as a reference, concrete with hook-end steel fiber, and concrete with the proposed recycled steel fiber. Tests were carried out on the mixes to determine the compressive strength, splitting tensile strength, flexural strength, and equivalent flexural strength. Also, the distribution of strains in the middle cross-section of the beams reinforced with recycled steel fibers was obtained.

Concrete mixes reinforced with recycled steel fiber compared with concrete reinforced with hook-end steel fiber showed energy absorption efficiency six times lower after concrete matrix cracking. Due to this low efficiency and difficulties in producing the proposed recycled steel fiber, the fiber was considered not viable for the structural reinforcement of concrete.

Salah-Eldin et al. (2019) investigated high-strength-concrete columns' structural performance reinforced with glass fiber reinforced polymers bars and ties under eccentric loads. Eight concrete columns (400 × 400 × 200mm) reinforced with glass fiber reinforced polymers were tested under axial monotonic loading. Eccentricity-to-width ratio concrete strength, reinforcement type (glass and steel) ties were used as test variables.

From the test, the following observations and conclusions were drawn;

1. At eccentricity-to-depth ratio 0.2h and 0.6h, the axial resistance of glass fiber reinforced polymer high strength concrete achieved similar axial resistance.
2. The ductility, lateral and axial deformation of glass fiber reinforced polymer columns were more than those of steel-reinforced columns under the same eccentricity.
3. The concrete reinforced with glass fiber was observed to have failed due to crushing under loading with low to moderate eccentricity (0.2 to 0.4h). At high eccentricity (0.6h), the glass fiber reinforced columns had deep and wide cracks and a 30% increase in lateral deformation than the steel-reinforced columns at peak load.

Tigiri et al. (2019) carried out a study on A New Mix Design Method for Self-Compacting Concrete Based on Close Aggregate Packing Method; they established that the close aggregate packing method is suitable for the production of concrete, they had a 28 days maximum compressive strength of 81 MPa with a water-cement ratio of 0.25.

The literature reviewed above shows the different applications of glass fiber and other fibers in improving the mechanical properties of concretes through varying mix design methodologies. The review revealed that glass fiber is significant in improving concrete strength at certain percentages of inclusion into concrete mixes.

However, there exists a significant shortage in the incorporation of cementitious materials with less environmental impacts, such as microsilica, in the design of fiber-reinforced high strength concretes.

Therefore, in this research, these gaps were addressed. Firstly, control specimens were prepared with a water-cement ratio of 0.25 and specimens prepared with partial replacement level of cement of 5%, 10%, and 15% with microsilica and glass fiber inclusion at 0.5%, 1.0%, 1.5%, and 2.0%. Secondly, a comprehensive assessment of principal input variables that influence compressive strength was carried out.

III. MATERIALS AND METHODS

The following materials were used in this study;

- Ordinary Portland cement manufactured by Dangote Cement Company (Conforming to EN 196 – 1:1987)
- Natural fine aggregates of 5mm maximum size conforming (conforming to BS 882:1992).
- Crushed granites of two sizes, 12.5-6.70mm and 20-12.5mm obtained from a quarry in Akampa, Cross River State, Nigeria.
- Clean potable water, which satisfies drinking standards and conforming to BS EN 1008: 2002, was used to mix and cure concrete samples.
- Elkem Microsilica 920 D ASTM was used as a partial replacement for cement in this study.
- Alkali Resistant Glass Fiber produced by Nippon Electrical Company Limited in collaboration with Kanebo Limited.
- Fosroc Auracast 200, a low viscosity, high-performance water reducer, and advanced high early-age strength superplasticizer conforming to EN 934-2, was used in this experiment.

The sample preparation, fresh and hardened state tests were carried out in the Structural Laboratory, Department of Civil Engineering, Rivers State University.

IV.MIX DESIGN PROCEDURE

A. *Particle Packing Method*

Determination of aggregate fractions and packing density:

In the Particle Packing Method (PPM), the optimal combination of aggregates 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 the 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 the maximum possible packing density leading to the minimization of voids.

Two important steps involved in the PPM design are:

1. Determination of aggregate fractions and packing density
2. Determination of paste content.

In each mixture, the bulk density is determined experimentally, and packing density (PD) and voids content (VC) is calculated using Eqn (1) and (2) according to EN 1097 -3; 1998.

$$Packing\ density = \frac{Bulk\ Density\ x\ weight\ Fraction}{Speicific\ Gravity}$$ 3.1

$$Voids\ Content = 1 - \sum \frac{Bulk\ Density\ x\ weight\ Fraction}{Speicific\ Gravity}$$ 3.2

B. *Determination of Paste Content*

The total packing density (PD) determined by mixing different sized coarse aggregates and fine aggregate is used to determine the voids content (VC) of the mixture using Eqn (3.3).

Voids Content (VC) = 1 - PD 3.3

C. *Aggregate Fractions and Packing Density*

Various aggregate combinations were examined. The aggregate combination that gives the maximum packing density was selected. This study incorporates 20-12.5mm, 12.5-6.70mm sized with zone 2 fine aggregate to optimize the combination of aggregates. To achieve maximum packing density, the fraction of aggregates used is 18: 42: 40.

D. *Bulk Density*

a. Bulk density of combined coarse aggregate 20 – 12.5mm, 12.5 - 6.70mm in the proportion 18:40.

$$Bulk\ Density = \frac{W2 - W1}{Volume\ of\ Mould}$$

Where W_1 = empty weight of Mould

W_2 = weight of mould + aggregate filled

b. The bulk density of three aggregates, i.e., 20mm coarse aggregate, 12.5mm coarse aggregate, and fine aggregate as calculated, are 1608 kg/m^3, 1744 kg/m^{3,} and 1940 kg/m^3.

The maximum bulk density is selected.
The voids content in percentage volume of aggregate for the mixture of three aggregate was determined from its bulk density using the following relations.

$$VC\ in\ percent\ volume = \frac{Specific\ Gravity - Bulk\ density}{Specific\ Gravity}\ x\ 100$$

$$PD\ (max) = \frac{Bulk\ density\ x\ weight\ fraction}{Specific\ Gravity}$$

TABLE I
Summary of Mix Proportions

% MS	% GF	20mm CA (kg/m^3)	12.5mm CA (kg/m^3)	FA (kg/m^3)	Cement Content (kg/m^3)	MS Content (kg/m^3)	GF content (kg/m^3)
	0	260.96	608.92	579.92	576.60	0	0
	0.5	258.68	603.59	258.68	576.60	0	12
0	1.0	256.40	598.27	569.78	576.60	0	24
	1.5	254.12	592.94	564.71	576.60	0	36
	2.0	251.83	587.61	559.63	576.60	0	48
	0	260.96	608.92	579.92	547.77	28.83	0
	0.5	258.68	603.59	258.68	547.77	28.83	12
5	1.0	256.40	598.27	569.78	547.77	28.83	24
	1.5	254.12	592.94	564.71	547.77	28.83	36
	2.0	251.83	587.61	559.63	547.77	28.83	48
	0	260.96	608.92	579.92	518.94	57.66	0
	0.5	258.68	603.59	258.68	518.94	57.66	12
10	1.0	256.40	598.27	569.78	518.94	57.66	24
	1.5	254.12	592.94	564.71	518.94	57.66	36
	2.0	251.83	587.61	559.63	518.94	57.66	48
	0	260.96	608.92	579.92	490.11	86.49	0
	0.5	258.68	603.59	258.68	490.11	86.49	12
15	1.0	256.40	598.27	569.78	490.11	86.49	24
	1.5	254.12	592.94	564.71	490.11	86.49	36
	2.0	251.83	587.61	559.63	490.11	86.49	48

V. RESULTS AND DISCUSSION

A. Compressive Strength

The concrete prepared at 0.25 water-cement were subjected to compressive test after curing for 7, 14, and 28 days. The results obtained are presented in table 2. These results are further plotted against glass fiber inclusion at the different amounts of microsilica contents.

TABLE 2: Compressive Strength Result for Concrete Mixtures under Different curing ages

% Replacement with Microsilica	% Inclusion of Glass Fiber	Compressive Strength (MPa)		
		7 Days	14 Days	28 Days
0	0.0	75.48	90.15	91.33
	0.5	79.67	97	103.33
	1.0	81.67	99.67	107.33
	1.5	83.67	102.67	109.33
	2.0	76.67	91	92.33
5	0.0	76.82	96.22	99.78
	0.5	80.67	102.67	111.67
	1.0	82.67	106.67	118.67
	1.5	84.67	108.33	120.67
	2.0	77.67	99.67	102
10	0.0	82.44	101.11	105.85
	0.5	87	108.67	121.67
	1.0	88	112	129
	1.5	91	114.67	130
	2.0	83	101.67	108
15	0.0	76.22	96.08	103.04
	0.5	80	103	117
	1.0	82	107	125
	1.5	84	109	125
	2.0	77.67	97	105

From Table 2, the maximum compressive strength value of 130 MPa is achieved for a mix with 10% replacement of ordinary cement with microsilica and 1.5% by volume incorporation of glass fiber. Also, from the table, it is observed that the strength of the concrete with the different amount of microsilica increased steadily from 0.5 to 1.5% inclusion of glass fiber but decreased significantly at 2% incorporation of glass fiber. This sharp decrease of compressive strength at 2% glass fiber content is due to the increase in the concrete's ductility at 2% glass fiber content. This is because compressive strength is inversely proportional to the ductility of concrete.

Also, it is observed that the partial replacement of cement with microsilica significantly affect the compressive strength of the concrete mix. An increasing amount of microsilica in the concretes increased the

Compressive strength of the concrete. This increase in compressive strength results from the reduction of voids in concrete through the introduction of finer particles of microsilica.

However, under all curing ages, the maximum strength values are observed for concretes with 10% replacement of cement with microsilica and 1.5% by volume of glass fiber inclusion. Therefore, High Strength Concrete's optimum design for this work is obtained at 10% microsilica content and 1.5% glass fiber content.

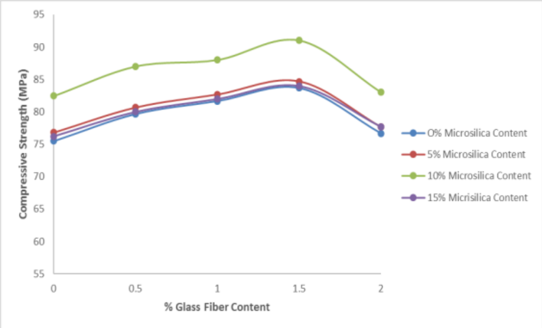

Figure 1: Compressive Strength of Concrete after 7 Days Curing

From Figure 1, it is observed that the compressive strength of the concrete increases on increasing amount of glass fiber to 1.5% and drops significantly at 2% of glass fiber for all amount of microsilica content. At 0% microsilica content, the compressive strength is observed to increase by 5.55%, 8.2%, 10.85% and 1.58% at 0.5%, 1.0%, 1.5% and 2.0% by volume inclusion of glass fiber respectively. At 5% microsilica content, 3.85%, 7.62%, 11.67% 2.44% increment in strength are observed for 0.5%, 1.0%, 1.5% and 2.0% glass fiber content respectively. At 10% microsilica content, 5.53%, 6.74%, 10.38% and 0.68% strength increment are recorded for 0.5%, 1.0%, 1.5% and 2.0% glass fiber inclusion respectively. Also at 15% microsilica content, 4.96%, 7.58%, 10.21% 1.90% increment in strength are observed for 0.5%, 1.0%, 1.5% and 2.0% glass fiber content respectively.

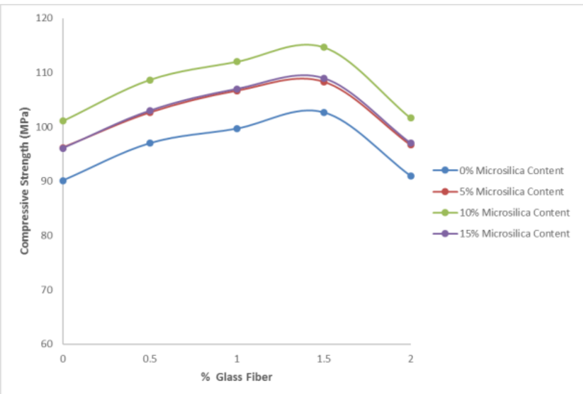

Figure 2: Compressive Strength of Concrete after 14 Days Curing

Figure 2 shows that the compressive strength of the concrete increases as the amount of glass fiber increases to 1.5% and drops significantly at 2% of glass fiber for all amount of microsilica content. At 0% microsilica content, the compressive strength is observed to increase by 7.60%, 10.56%, 13.89% and 0.94% at 0.5%, 1.0%, 1.5% and 2.0% by volume inclusion of glass fiber respectively. At 5% microsilica content, 6.7%, 10.86%, 12.59% 3.59% increment in strength are observed for 0.5%, 1.0%, 1.5% and 2.0% glass fiber content respectively. At 10% microsilica content, 7.48%, 10.77%, 13.41% and 0.55% strength increment are recorded for 0.5%, 1.0%, 1.5% and 2.0% glass fiber inclusion respectively. Also at 15% microsilica content, 7.2%, 11.37%, 13.45%, 0.96% increment in strength are observed for 0.5%, 1.0%, 1.5% and 2.0% glass fiber content respectively.

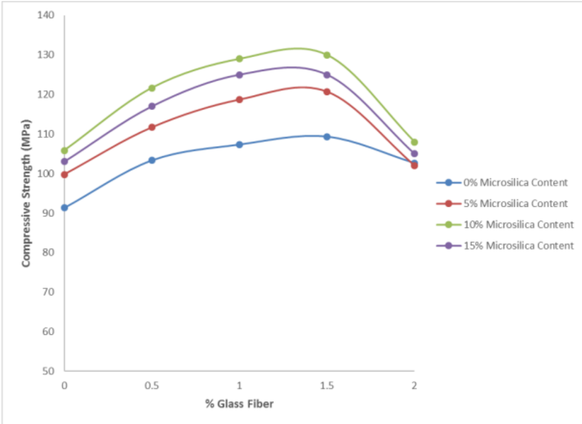

Figure 3: Compressive Strength of Concrete after 28 Days Curing

From Figure 3, it is observed that for all amount of microsilica content, the compressive strength of the concrete increases on increasing amount of glass fiber to 1.5% and drops significantly at 2% of glass fiber. At 0% microsilica content, the compressive strength is observed to increase by 13.14%, 17.52%, 19.70% and 1.09% at 0.5%, 1.0%, 1.5% and 2.0% by volume inclusion of glass fiber respectively. At 5% microsilica content, 11.92%, 18.93%, 20.94% 2.22% increment in strength are observed for 0.5%, 1.0%, 1.5% and 2.0% glass fiber content respectively. At 10% microsilica content, 14.98%, 21.87%, 22.82% and 2.03% strength increment are recorded for 0.5%, 1.0%, 1.5% and 2.0% glass fiber inclusion respectively. Also at 15% microsilica content, 13.55%, 21.31%, 21.31% 1.90% increment in strength are observed for 0.5%, 1.0%, 1.5% and 2.0% glass fiber content respectively.

VI. FINDINGS AND CONCLUSION

This study aimed to develop an appropriate mixed design method for Fiber Reinforced High Strength Concrete (FRHSC). This was achieved via harnessing the cementitious ability of microsilica and the ductile ability of glass fiber on the compressive strength of HSC at 7, 14, and 28 days curing ages. The salient findings are highlighted as follows;

A. Particle Packing Method (PPM), the adopted mix design method, provided acceptable results for the concrete's fresh and hardened state properties. Hence, this mixed design method can be adapted to produce Fiber Reinforced High Strength Concrete (FRHSC) of 90MPa to 130MPa. High strength was achieved as a result of the significant reduction in the pore volume of the mixture.

B. Maximum Compressive strength of 130 MPa was achieved for concrete with 10% replacement of cement with microsilica and 1.5% inclusion of glass fiber. The inclusion of microsilica reduced voids in the concrete, thereby increasing the strength.

C. Comparing the strength of the concrete mixtures revealed that at all amounts of microsilica content, the strengths increased significantly by the inclusion of glass fiber from 0.5% to 1.5% but declined significantly at 2%. This decline in strength at 2% inclusion of glass fiber was due to an increase in the concrete's ductility by 2% inclusion of glass fiber.

D. The compressive strength of FRHSC was greatly improved by the replacement of cement with microsilica and the inclusion of glass fiber at the range of 0.5 – 1.5%.

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