

Evaluation of First-Crack Strength of Waste Copper Wire Fiber Reinforced Concrete

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DOI: <https://doi.org/10.62154/ajastr.2025.019.01025>

Abstract

Cracks in concrete are paths for external agents that resulted in corrosion of steel reinforcement. Corrosion of steel is one of the main and expensive deterioration mechanisms affecting reinforced concrete structures. Adding fibres to concretes arrest the propagation of cracks. Copper wire has very slow corrosion process, better mechanical properties and ductility than most of the steel fibres. This research studied the first-crack strengths of waste copper wire fibre reinforced concrete (WCWFRC). The first-crack strength parameters tested on beam specimens (100 x 100 x 500 mm) were the deflection, load-deflection relationship, flexural strength and toughness of samples containing 0, 0.5, 1.0 and 1.5% waste copper wire fibre (WCWF). Models for the relationship between the first-crack strength parameters and the WCWF contents were developed using regression analysis, and the models' adequacy were determined using coefficient of determination (R^2). The results revealed that the resistance to deformation, deflection, flexural strength and toughness increased with increase in WCWF contents at first-crack. The initial stiffness of the samples increased from 26.75 kN/mm at 0.5% WCWF content to 38.33 kN/mm at 1.5% WCWF content. The model equations for the relationships between the first crack properties and WCWF contents have R^2 values greater than 93% which indicates good response predictive ability. The increments in the first-crack strengths with increase in WCWF contents proved that WCWF improves energy absorption capacity of the concrete.

Keywords: First-Crack, Load-Deflection Relationship, Stiffness, Toughness, Waste Copper Wire Fibre.

Introduction

Concrete is relatively brittle and it has low tensile strength, typically only around 1/10th of its compressive strength (Tiwari, 2018). Therefore, steel reinforcements are normally used to reinforce the regular concrete, but these reinforcements do not normally take care of cracks caused by thermal and drying shrinkages. At present, steel fibre reinforced concrete (SFRC) is widely used to cater for these cracks in many applications such as concrete pavements, patching repair of hydraulic structures, overlays and precast concrete. The mechanism of randomly distributed discrete short fibres is to make a bridge across the cracks which provide some ductility after cracking. If the fibres are strong enough and

sufficiently bonded to the material, then they allow fibre reinforced concrete (FRC) to carry notable number of stresses over a relatively great rupture strain capacity in the post-cracking stage (Shariful-Islam & Al-Amin, 2017).

Fibre is described as any natural or synthetic material whose length is significantly longer than its width. Fibres can be classified as either natural or artificial fibres according to their origin. Natural fibres are obtained from either organic or inorganic sources and processed using small amount of energy before use. The organic fibres are normally processed from pine trees. The organic fibres include cellulose, sisal, bamboo, cotton and jute fibres (Deegoda *et al.*, 2023).

The inorganic fibres include asbestos, wollastonite, rock wool etc. (Naaman, 2003). Natural fibres are not much popular because they are vulnerable to alkali attack (Gopal, 2018). Artificial fibres are factory produced fibres produced from materials such as steel, glass, carbon, nylon, polyester, polyethylene, polypropylene, polyvinyl acetate aramid, acrylic, plastic, etc. Artificial fibres have good mechanical and thermal properties which make them suitable for use in concrete and mortar (Gopal, 2018). Carbon fibres have been recently used due to their very high modulus of elasticity and flexural strength (Mohajerani, 2019).

The use of fibres in brittle materials started far back as 3500 years when sunbaked bricks reinforced with straw were used to construct the 57 m high hill of Aqar Quf near Baghdad (Ali, 2017). In recent times, asbestos fibres were used to reinforce cement products for almost up to 100 years, cellulose fibres for at least 50 years, and steel, polypropylene and glass fibres were used for the same purpose for the past 30 years (Adewuyi & Thibedi, 2021). Fibres in the cement-based matrix acts as cracks arrester, which restricts the growth of flaws in the matrix, preventing these from enlarging under load, into cracks, which eventually cause failure. Prevention of propagation of cracks originating from internal flaws can result in improvements in static and dynamic properties of the matrix (Prahallada & Prakash, 2011).

SFRC is increasingly being used to produce in-situ and precast concrete elements such as:

- a) Auxiliary reinforcement for temporary load cases, e.g., arresting shrinkage cracks, limiting cracks encountered during transportation or installation of precast members,
- b) Partial substitution of the conventional reinforcement, i.e., combined reinforcement systems, and
- c) Total replacement of the conventional reinforcement in elements in overall compression, e.g., ground supported slabs, tunnel linings, foundations, thin-shell structures (Marcos-Meson *et al.*, 2018).

Copper is a highly durable material that will continue to function throughout its lifetime without a significant loss in performance. Because copper develops its own adherent protective coating, it has an excellent resistance to corrosion in all kinds of common environments including atmospheric air, potable water, soil, and even sea water and a wide variety of chemicals (Abubakar *et al.*, 2022a). Copper belongs to group of transition elements (element found between group 2 and 3 in the periodic table). Transition elements

are metals with properties such as high tensile strength and high melting point (Ababio *et al.*, 2016). It is estimated that Nigeria has 10 million tons of copper ore deposits existing in many forms (Foraminifera, 2018). According to Orazulike (2002) there are between 150 and 180 copper minerals in Nigeria. Among these, the commonest and the most important form mined are native copper (Cu); oxides of copper: cuprite (Cu_2O); tenorite (CuO); and a variety of copper sulphides such as bornite (Cu_5FeS_4); chalcocite (Cu_2S); tetrahedrite [$(\text{CuFe})_{12}\text{Sb}_4\text{S}_{13}$] and chalcopyrite (Cu_2FeS_4). These deposits are found in Plateau, Bauchi, Zamfara, Kogi, Gombe and Sokoto states.

Incorporating waste copper wire as fibre reinforcement in concrete would reduce the cost of maintenance of structures by arresting uncontrolled shrinkage and thermal cracks. It would also improve post cracking behaviour of the structure under bending due to its good mechanical and ductility properties (Mujalli *et al.*, 2022). Chemical attack on the structure would be reduced because copper wire has excellent corrosion resistance. These properties of WCWF would be beneficial in the construction of structures such as thin shells, hydraulic structures, pressure vessels, concrete pavement and structures susceptible to severe environments. In light of the foregoing, this research used waste copper wire as fibre reinforcement in concrete in order to address the problems associated with corrosion of fibre reinforcement and arrest cracks in the concrete. The research determined the strength properties of the WCWFRC after crack has initiated.

Literature Review

Fibre reinforced concrete is the composite material containing fibres in the cement matrix in an orderly manner or randomly distributed manner. Its properties depend upon the effective transfer of stress between the concrete and the fibres, which is largely dependent on the type of fibre, fibre volume, fibre geometry, orientation and distribution of the fibres, mixing and compaction techniques of concrete, and size and shape of the aggregate (Vikrant *et al.*, 2012). The main benefits of the inclusion of fibres in hardened concrete relate to the post-cracking state. If it is assumed that any load-bearing capacity greater than zero is described as reinforcement, then all types of fibres at any volume addition will reinforce hardened concrete (Hannant, 2003).

For long term, strength and toughness and high stress resistance, SFRC is increasingly being used in structures such as flooring, housing, precast, tunnelling, heavy duty pavement and mining. Generally, aspect ratios of steel fibres used in concrete mix are varied between 50 and 100. The most suitable volume fraction (volume of fibre per unit volume of concrete) values for concrete mixes are between 0.5% and 1.5% by volume of concrete (Yazici *et al.*, 2007). In the hardened state, when fibres are properly bonded, they interact with the matrix at the level of micro-cracks and effectively bridge these cracks thereby providing stress transfer media that delays their coalescence and unstable growth (Biswar, 2022).

Fibre reinforced concrete specimens, unlike ordinary concrete, which fail at the point of ultimate flexural strength or the first crack, do not fail immediately after the initiation of the first crack. After the first crack, the load is transferred from the concrete matrix to the

fibres (Hameen *et al.*, 2010). The fibre reinforced concrete beams exhibit a greater number of cracks with lesser widths at all load levels when compared to the reference beam. The maximum reduction in crack width at ultimate load level was found to be 56.90% when compared to the reference beam and 50% when compared to specimens consisting of 100% steel fibres. The high fibre reinforced concrete beams exhibit enhanced ductility than the reference beam. The increase in deflection and energy ductility was found to be 1.74 & 2.91 times than that of reference beam and 1.09 & 2.15 times than that of specimens consisting of 100% steel fibres (Natarajan, 2017).

Ding *et al.* (2022) investigated the flexural behaviour of high-ductility fibre-reinforced concrete (HDC) and proposed a suitable method for evaluating flexural toughness. The results indicated that the flexural failure modes, ultimate strength, and toughness of HDC improved with an increase in PVA fibre content, especially for deformation. The ultimate flexural strength of HDC with 2% PVA fibres of about 15.32 MPa showed an increase of up to 221%. The deformation and flexural toughness ratios were 23 times and 1.43 times higher than the specimens without fibres, respectively. The post-cracking ductility of conventional concrete was significantly improved due to the stress redistribution effect of the fibres. With an increase in PVA fibres, the HDC specimens exhibited better deflection-hardening behaviour, characterized by multiple cracks and crack width gradually decreasing.

Noushini *et al.* (2013) studied the flexural toughness and ductility characteristics of polyvinyl-alcohol fibre reinforced concrete (PVA-FRC). The flexural toughness of concrete is improved by introducing PVA fibres to the mix. The toughness value is further increased by adding more fibres. FRCs showed higher load bearing capacity compared to the control. This results in a higher ultimate deflection for FRCs where the peak load values remained constant. Furthermore, from the flexural tensile test results, it has been observed that prior to peak response of all concrete series was almost similar, however, a subtle improvement has occurred in post-peak flexural response of FRCs compared to control. In terms of structural properties, it has been observed that, PVA fibre addition to the mix has significantly improved the ductile behaviour of the beam. 30% higher value of ductility factor is calculated for the beam incorporating 0.5% volume fraction of 12 mm PVA fibres.

Shobana and Bright (2017) investigated the mechanical properties of high-performance electric wire fibre (EWF) reinforced concrete. Grade M40 concretes with EWF contents of 0.5%, 1%, 1.5% and 2% were tested. From the results revealed that the compressive, split tensile and flexural strengths of concrete were maximum when the fibre contents were at 2.0 %. Ramakrishnan *et al.* (2021) conducted research on flexural behaviour and toughness of fibre reinforced concrete. They found that the maximum quantity of hooked-end fibres that could be added without causing balling was limited to 1 percent by volume. Higher quantities (2 percent by volume) of straight steel fibres caused balling, and higher quantities of polypropylene fibres (2 percent by volume) entrapped a considerable amount of air. Compared with plain concrete, the addition of fibres increased the first-crack strength (15 percent to 90 percent), static flexural strength (15 percent to 129 percent), toughness index, post-crack load-carrying capacity, and energy absorption capacity.

Sofi and Gopu (2019) (as cited in Abubakar *et al.*, (2022b)) studied the influence of steel fibre (SF), electrical waste copper wire fibre (EWCWF) and electrical waste glass fibre (EWGF) on mechanical properties of concrete. They found that compressive strength of concrete by using SF, EWCWF and EWGF were increased by 42.6%, 23.76% and 15.35% when compared to normal concrete. Splitting tensile strength of concrete by using SF, EWCWF and EWGF were increased by 81.6%, 46.4% and 90.1% when compared to normal concrete. Flexural strength of concrete by using SF, EWCWF and EWGF were increased at 46.1%, 38.8% and 31.7% when compared to normal concrete. They concluded that the addition of SF, EWCWF and EWGF improve the compressive strength, splitting tensile strength, flexural strength and modulus of elasticity of the concrete and also reduced the crack width under different loading conditions.

The waste copper wire fibre changes the behavior of the concrete from brittle material to ductile material which resulted in increase in flexural strength and elastic modulus of the concrete, but from the literature consulted there is no study conducted on the behavior of WCWFRC within plastic limit (after the first crack). This paper evaluates the strength properties of WCWFRC immediately after the first crack.

Materials and Methods

A. Materials

Ashaka brand of Ordinary Portland cement was used throughout the research. The cement was grade 42.5 obtained in 50 kg bags from a vendor in Bauchi. The coarse aggregate used was normal weight, crushed igneous rock aggregate with maximum size of 20 mm. It was obtained from a quarry site in Bauchi. The fine aggregate was obtained from a stream at Bayara village along Bauchi – Dass road. Clean pipe borne water was used for preparation of the test specimens. CONPLAST SP 430 brand of sulphonated naphthalene polymers superplasticizer was used throughout the study. This superplasticizer is a factory product compatible with grade 42.5 ordinary Portland cement. The copper wire used was offcuts obtained from Alind Nigeria Limited, Bauchi. It was cut into 60 mm long fibres as shown in Plate I (a) and (b). The volume of fibre was varied from 0 to 1.5% at the interval of 0.5% by weight of concrete.



(a)



(b)

Plate I: Waste Copper Wire Fibre (a) Cutting length of the WCWF, (b) Prepared WCWF.

B. Methods

- 1) *Concrete mix design*: Grade M-25 concrete was used throughout the study. The mix was designed using Building Research Establishment (BRE) mix design method (formerly DOE mix design method). The minimum compressive strength is 25 N/mm². Moderate exposure was chosen for durability requirement. Also, moderate workability ranging from 30 – 60 mm and aggregate with 30% passing 600 microns were used. The summary of the mix design is presented in Table (1).

Table 1: Summary of Mix Design for the M-25 Concrete

	Cement	Fine aggregate	Coarse aggregate	Water
Weight (kgm-3)	380	789.6	1090.4	190
Ratio	1	2	3	0.50

- 2) *Concrete production*: The process of concrete production was strictly followed which involved batching, mixing, compaction and curing. The concretes were produced using 0, 0.5, 1.0 and 1.5% WCWF contents in accordance with BS EN 12390 Part 1 & 2 (2000) specifications. The concrete samples were removed from the moulds 24 hours after casting and cured for 28 days in water.
- 3) *Determination of first-crack strengths of WCWFRC*: The presence of WCWF in the concrete changes its behaviour from brittle to ductile material. Flexural strength test was carried out on the hardened concrete beams of size 100 x 100 mm x 500 mm. The specimens were tested using third-point loading arrangement in accordance with ASTM C 78 (2002) and ASTM C 1018 (1997) specifications. Three (3) beams were tested for each WCWF content at 28 days curing periods. The deflections of the WCWFRC beams were measured using Linear Variable Displacement transducer (LVDT). The loads and the corresponding deflections of the beam were measured using Automatic Digital Readout (ADR). The loading arrangement for testing the load-deflection relationship is shown in Plate II.

The first-crack strength properties were measured from the load-deflection curves of WCWFRC in accordance with ASTM C 1018 (1997) specifications. The strength parameters measured were the first-crack deflection, σ_i , first-crack load, P_i , first-crack flexural strength, f_i and first-crack toughness, T_i . The P_i is the maximum load at which the crack initiated (point on load-deflection curve above the form of the curve become nonlinear) while the σ_i is the corresponding value on the load-deflection curve at first crack. The f_i was determined by inserting the value of P_i in Equation (1). T_i is the energy equivalent to the area under the load-deflection curve up to the first crack.



Plate II: Loading arrangement for testing load-deflection relationship.

$$\text{Modulus of rupture, } M_{bt} = \frac{PL}{bd^2} \quad (1)$$

- 4) *Determination of adequacy of the models:* The models for the relationship between the first-crack strengths and WCWF contents were developed using regression analysis. The adequacy of the models was determined using coefficient of determination (R^2).

Results and Discussion

A. Load-Deflection Relationship of WCWFRC

Figures 1, 2 & 3 show the plots of load-deflection relationship of WCWFRC. The initial load-deflection responses of all the samples were linear up to first crack, which indicated that the concrete samples were elastic before cracks were initiated. Beyond the first crack the loads decreased in polynomial form indicating plastic behaviour of the samples. There is increase in resistance to deformation of the concrete with increase in WCWF contents as shown in the overlay plot in Figure 4. The stiffness of the WCWFRC samples decreased with increase in deflection as shown in Table 2. The stiffness decreased from 27.0 kN/mm at initial load to 7.24 kN/mm at failure and from 26.75 kN/mm to 0.21 kN/mm for samples containing 0 % and 0.5% WCWF respectively. Also, the stiffness of samples containing 1.0% WCWF decreased from 27.92 kN/mm to 0.3 kN/mm, while for samples containing 1.5% WCWF the stiffness decreased from 38.33 kN/mm to 0.3 kN/mm. The results agreed with the findings of Bakhshi *et al.* (2014) that the increase in crack width of FRC resulted in significant drop in flexural stiffness of the concrete.

Also, it was observed that the stiffness of the samples increased with increase in WCWF contents as shown in Figure 5. The initial stiffness increased from 27.0 kN/mm at 0% WCWF content to 38.33 kN/mm at 1.5% WCWF content. After cracking of the samples, the loads were largely supported by fibres bridging the crack, which resulted in abrupt decrease in the stiffness of the samples as shown in Table 2 for samples containing 0.5, 1.0 and 1.5%

WCWF respectively. The relationship between the stiffness and deflection (σ) of the WCWFRC is presented graphically in Figure 5.

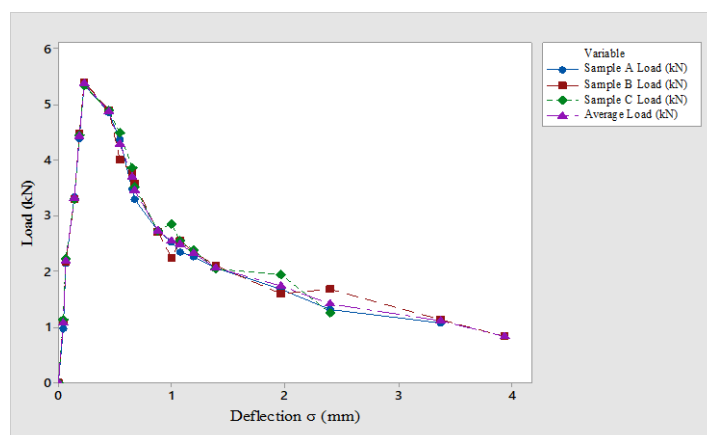


Figure 1: Load - Deflection Relationship of Concrete Containing 0.5% WCWF.

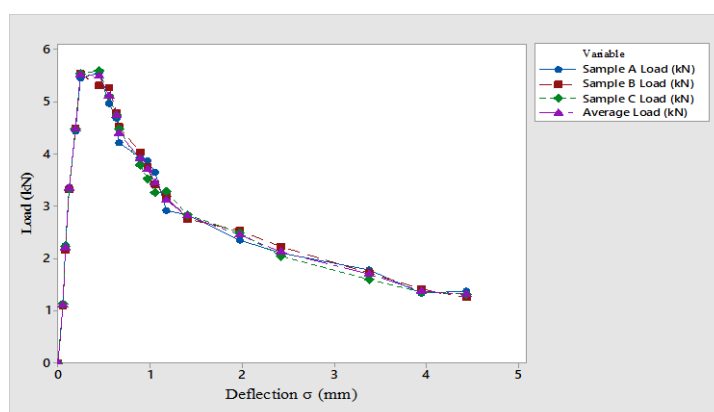


Figure 2: Load - Deflection Relationship of Concrete Containing 1.0 % WCWF.

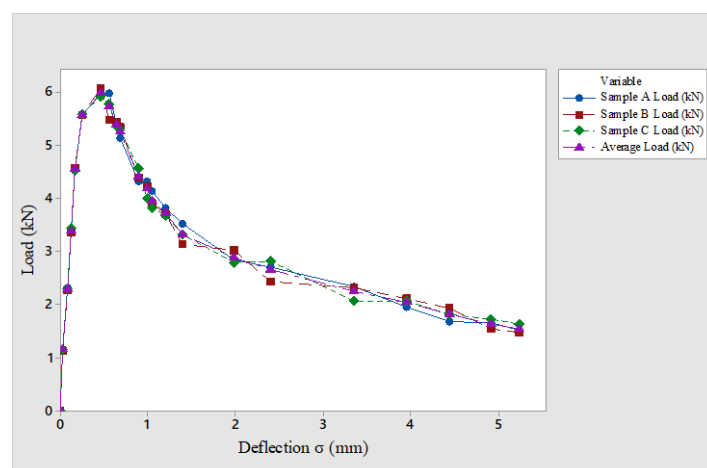


Figure 3: Load - Deflection Relationship of Concrete Containing 1.5% WCWF.

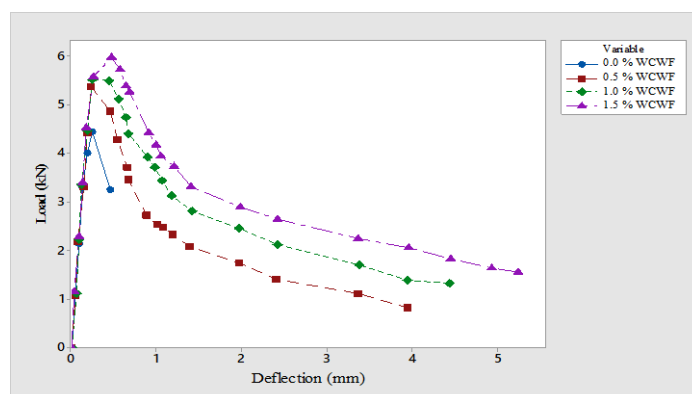


Figure 4: Overlay Plot of Load-Deflection showing Resistance in Deformation of WCWFR.

Table 2: Stiffness on concrete containing WCWF

0.0 %			0.5 %			1.0%			1.5%		
Load (kN)	σ (mm)	Stiffness (kN/mm)	Load (kN)	σ (mm)	Stiffness (kN/mm)	Load (kN)	σ (mm)	Stiffness (kN/mm)	Load (kN)	σ (mm)	Stiffness (kN/mm)
0.00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.08	0.04	27.00	1.07	0.04	26.75	1.12	0.05	22.40	1.15	0.03	38.33
2.15	0.08	26.87	2.18	0.07	31.14	2.22	0.08	27.75	2.29	0.09	25.44
3.29	0.13	25.31	3.31	0.14	23.64	3.35	0.12	27.92	3.39	0.13	26.08
4.01	0.18	22.28	4.43	0.18	24.61	4.48	0.19	23.58	4.54	0.17	26.71
4.45	0.24	18.54	5.37	0.23	23.35	5.52	0.24	23.00	5.58	0.25	22.32
3.26	0.45	7.24	4.88	0.45	10.84	5.5	0.44	12.50	5.98	0.46	13.00
-	-	-	4.29	0.54	7.94	5.12	0.55	9.31	5.74	0.56	10.25
-	-	-	3.71	0.65	5.71	4.75	0.63	7.54	5.39	0.64	8.42
-	-	-	3.46	0.67	5.16	4.41	0.66	6.68	5.26	0.68	7.74
-	-	-	2.73	0.88	3.10	3.92	0.89	4.40	4.42	0.90	4.91
-	-	-	2.54	1.00	2.54	3.72	0.98	3.80	4.18	0.99	4.22
-	-	-	2.48	1.07	2.32	3.45	1.06	3.25	3.95	1.05	3.76
-	-	-	2.33	1.19	1.96	3.13	1.18	2.65	3.73	1.20	3.11
-	-	-	2.07	1.39	1.49	2.82	1.41	2.00	3.32	1.40	2.37
-	-	-	1.74	1.96	0.89	2.46	1.97	1.25	2.89	1.98	1.46
-	-	-	1.41	2.40	0.59	2.13	2.42	0.88	2.65	2.41	1.10
-	-	-	1.11	3.37	0.33	1.71	3.38	0.51	2.24	3.36	0.67
-	-	-	0.82	3.94	0.21	1.38	3.95	0.35	2.05	3.96	0.52
-	-	-	-	-	-	1.32	4.44	0.30	1.82	4.45	0.41
-	-	-	-	-	-	-	-	-	1.64	4.93	0.33
-	-	-	-	-	-	-	-	-	1.55	5.24	0.30

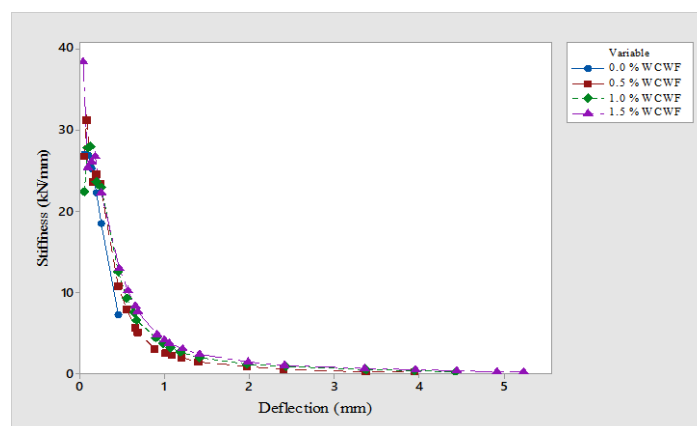


Figure 5: Stiffness-Deflection Relationship of WCWFRC.

B. First-Crack Strength Properties of WCWFRC

Table 3 shows the first-crack strength properties of concrete containing 0 to 1.5% WCWF. The properties of WCWFRC measured at first-crack are deflection, load, flexural strength and toughness. The deflection increased from 0.23mm at 0% WCWF content to 0.25 mm at 1.5% WCWF content. This indicates that the fibre improves resistance to deformation of the concrete. The relationship between the first crack deflection and WCWF content is presented graphically in Figure 6. The model equation for the relationship between the first crack deflection and WCWF content is shown in Equation 2. The coefficient of determination, R^2 for the model is 0.9818 (98.18%) which indicates good predictive ability of the model. Also, the first crack load increased with increase in fibre contents. Loads of 4.45, 5.37, 5.52 and 5.58 kN were obtained for 0, 0.5, 1.0 and 1.5% WCWF contents respectively. The load increased by 25.4% of the control at 1.5% fibre content. This also reaffirms that WCWF improves stiffness of concrete as larger load is needed to crack the concrete at higher WCWF contents. The relationship between first crack load and volume of fibre is shown in Figure 7 and Equation 3. The model's R^2 of 0.9723 (97.23%) shows good response predictive ability.

The first-crack flexural strength of the concrete increased with increase in WCWF contents. The strength increased from 2.0 N/mm² at 0% WCWF content to 2.51 N/mm² at 1.5% WCWF content. The relationship between the first crack flexural strength and WCWF content is presented graphically in Figure 8. Equation 4 is the model for predicting first crack flexural strength of WCWFRC with R^2 value of 96.79%, which also shows good prediction ability. Also, the first crack toughness increases with increase in WCWF contents. First crack toughness values of 1.46, 1.79, 1.82 and 2.01J were obtained for concrete containing 0, 0.5, 1.0 and 1.5% WCWF content respectively. This agrees with findings of Ding *et al.* (2022) that increase in fibre content has great effect on the flexural strength and toughness of concrete. The relationship between fibre volume and toughness of concrete is presented in Figure 9 and the model is presented Equation 5 with R^2 value of 0.9324 (93.24%).

Table 3: First crack strength properties of WCWFRC

Fibre content (%)	First crack			
	Deflection, σ (mm)	Load (N)	Flexural strength (N/mm ²)	Toughness (J)
0	0.23	4450	2.00	1.46
0.5	0.23	5370	2.42	1.79
1.0	0.24	5520	2.48	1.82
1.5	0.25	5580	2.51	2.01

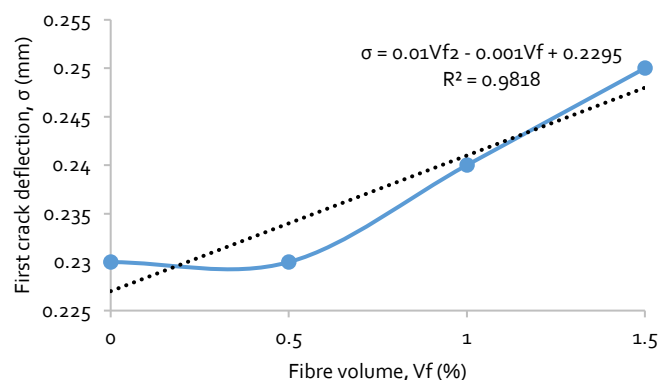


Figure 6: Relationship between First Crack Deflection and WCWF contents

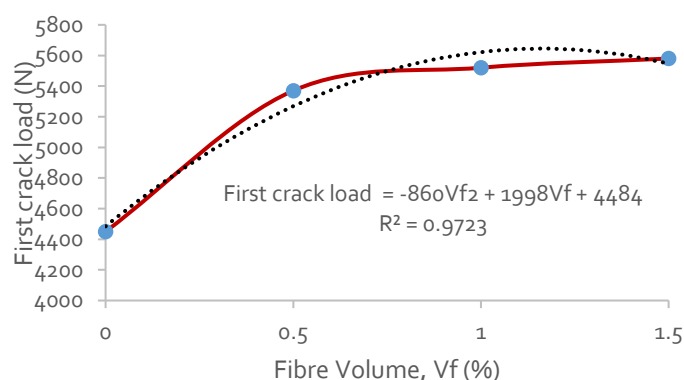


Figure 7: Relationship between First Crack Load and WCWF contents

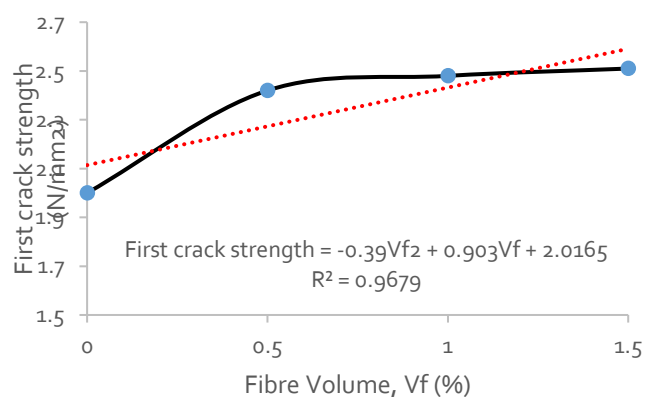


Figure 8: Relationship between First Crack Flexural Strength and WCWF contents

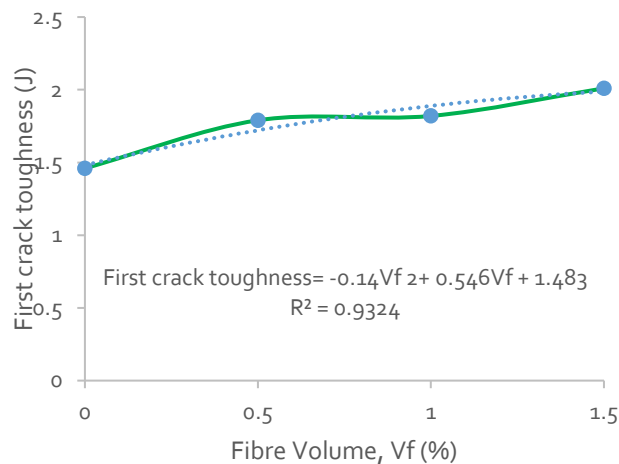


Figure 9: Relationship between First Crack Toughness and WCWF contents.

$$\text{First crack deflection, } \sigma = 0.01V_f^2 - 0.001V_f + 0.2295 \quad (2)$$

$$\text{First crack load} = -860V_f^2 + 1998V_f + 4484 \quad (3)$$

$$\text{First crack flexural strength} = -0.39V_f^2 + 0.903V_f + 2.0165 \quad (4)$$

$$\text{First crack toughness} = -0.14V_f^2 + 0.546V_f + 1.483 \quad (5)$$

C. Practical Applications and Limitations of WCWFRC

The results of the study indicated that WCWF increased the first-crack strength properties of the concrete. Due to high corrosion resistance of waste copper wire fibre, the WCWFRC can be used in water retaining structures and marine environment where steel fibers have limitation of low corrosion resistance. In order to avoid balling of the fibre in concrete, not more than 1.5% of the WCWF is recommended for liquid retaining structures.

Summary, Conclusion and Recommendations

Summary

Effect of WCWF on the first-crack strength properties of concrete was investigated. The properties tested were the load-deflection relationship, first-crack load, deflection, flexural strength and toughness. The results were analyzed and models that predict the first-crack strength parameters of concrete containing WCWF were determined.

Conclusions

The following conclusions were drawn from the results:

- The relationship between the applied load and deflection of the WCWFRC beams revealed that the resistance to deformation of the concrete increase with increase in WCWF contents. The initial stiffness of the samples increased from 27.0 kN/mm at 0% WCWF content to 38.33 kN/mm at 1.5% WCWF content.
- The first-crack deflection, load, flexural strength and toughness increased with increase in WCWF contents. The first-crack deflection increased from 0.23mm at

0% WCWF content to 0.25 mm at 1.5% WCWF content. The first-crack load increased by 25.4% of the control at 1.5% fibre content. The first-crack flexural strength increased from 2.0 N/mm² at 0% WCWF content to 2.51 N/mm² at 1.5% WCWF content. First crack toughness values of 1.46, 1.79, 1.82 and 2.01J were obtained for concrete containing 0, 0.5, 1.0 and 1.5% WCWF contents respectively. These indicated that the WCWF improves resistance to deformation of the concrete.

- iii. The model equations for the relationship between the first crack properties and WCWF contents have R² values greater than 93% which indicates good response predictive ability.

Recommendations

The following are recommended for further studies:

- i. Effect of WCWF on the relationship between the post-cracking strength parameters and crack-mouth displacement (CMOD).
- ii. Effect of WCWF on the stress-CMOD relationship.

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