Relationship between Compressive, Flexural and Split Tensile Strengths of Waste Copper Wire Fiber Reinforced Concrete

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Abstract. Concrete has low tensile strength, narrow ductile range and low crack resistance. Micro cracks in the concrete propagate quickly under loading, leading to brittle behaviour of the concrete. These cracks expose steel reinforcement to agents of corrosion. Adding steel fibres reduces the damage, but over a long period, the steel fibres corrode. This study used waste copper wire as fibre reinforcement in concrete to investigate the relationship between compressive, flexural and split tensile strengths. Grade 25 concrete was produced and cured for 7, 14 and 28 days before testing. One millimetre in diameter copper wire was used in the study. The fibre volume used was 0.5, 1.0 and 1.5%, respectively. The samples were tested for compressive, flexural and split tensile strengths. The results indicated a general increase in compressive, flexural and split tensile strengths of the concrete with an increase in waste copper wire fibre contents. Maximum compressive strength of 34.58 N/mm^2 was obtained at 1.5% fibre content and 28 days of curing. Flexural strength increases from 4.36 N/mm^2 at 0% fibre content and seven days curing to 6.68 N/mm^2 at 1.5% fibre content and 28 days curing. The split tensile strength increased fibre content from 2.72 N/mm^2 at seven days to 4.39 N/mm^2 at 28 days of curing. Mathematical models were produced for the relationships between compressive, flexural and split tensile strengths. The models have R^2 values greater than 70%, and the higher the value of R^2, the better the model fits the data. This indicates that the model's predictors influenced the variations in the responses.

Keywords: compressive strength; flexural strength; fiber reinforced concrete; split tensile strength; waste copper wire.

INTRODUCTION

Concrete experiences a nearly complete loss of loading capacity once failure is initiated. In structural applications, brittleness can be prevented through confinement with transverse reinforcement [1]. This property of concrete, which limits its applications, can also be overcome by including a small amount of short, randomly distributed fibres [2]. Threads in the cement-based matrix act as cracks arresters, which prevents the cracks from enlarging under load into gaps, which eventually cause failure. Prevention of propagation of cracks originating from internal flaws can result in improvements in the static and dynamic properties of the matrix [3].

The low tensile strength of concrete is being compensated in several ways, which has been achieved by using reinforcing bars and applying pre-stressing force. Though these methods provide tensile strength to concrete, they do not increase the inherent tensile strength of the concrete itself. These deficiencies have led researchers to investigate and develop a material which could perform better in areas where conventional concrete has several limitations. One such development is fibre-reinforced concrete, in which a cement-based matrix is reinforced with an ordered or random distribution of fibres [3].

It is known that Portland cement concrete is a brittle material. Concrete has a meagre tensile strength, narrow ductile range and low crack resistance. Micro cracks exist in the concrete, and these cracks propagate quickly because of their low tensile strength, leading to the brittle behaviour of the concrete. Corrosion of steel reinforcement is one of the primary and most expensive deterioration mechanisms affecting reinforced concrete structures. The addition of steel fibres reduces micro and macro cracks. Still, the steel fibres corrode over a long period, and the corrosion action affects the primary reinforcement [4].

Copper is an electrical conductor in many categories of electrical wiring. Roughly half of all copper mined is used to manufacture electrical wire and cable conductors [5]. It is a highly durable material that functions throughout its lifetime without significantly losing performance. Copper wire has better mechanical properties and flexibility than most steel fibres. It has excellent corrosion resistance in everyday environments, including atmospheric air, potable water, soil, seawater, and various chemicals. Also, copper is very insensitive to galvanic corrosion. As a result, it retains its excellent electrical and thermal conductivity throughout its lifespan, which is why copper is highly durable [6]. The corrosion resistance of copper is based on its ability to form stable compounds that provide some protection from corrosive attack when exposed to the atmosphere. Therefore, it is relatively inert against chemicals attack [7]. The copper has density of 8960 kg/m^3 and tensile strength range from 200 to 250 N/mm^2. Copper has higher elasticity than alternate metal conductors, except gold and silver. Because of copper's high flexibility, it is easy to draw down to diameters with very close tolerances [8]. These properties encourage the use of copper wire as fibre reinforcement in this study.

In light of the preceding, this research used waste copper wire as fibre reinforcement in concrete to determine the relationship between compressive, flexural and split tensile strength of waste copper wire fibre reinforced concrete.

Fibre Reinforcement. Fibre-reinforced concrete is the composite material containing fibres in the cement matrix in an orderly manner or randomly distributed form. Its properties depend upon the efficient transfer of stress between the matrix and the fibres, which is mainly dependent on the type of fibre, fibre geometry, fibre content, orientation and distribution of the fibres, mixing and compaction techniques of concrete, and size and shape of the aggregate [9].

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. If the fibre volume fraction is sufficiently high, this may increase the tensile strength of the matrix. Once the tensile capacity of the composite is reached and coalescence and conversion of micro-cracks to macro-cracks has occurred, fibres, depending on their length and bonding characteristics, continue to restrain crack opening and crack growth by effectively bridging across macro-cracks [10].

Waste copper wire as fibre reinforcement in concrete. Author [11] studied the behaviour of regular concrete with the partial addition of copper wire as fibre. Concrete cubes were cast with various percentages of copper wire (0, 0.5, 1, 1.5 and 2 %) by weight of cement and tested for mechanical properties. It showed that 1.5 % of the addition of copper wire had given more strength than the standard concrete. The results also indicated that copper wire incorporation in concrete significantly improves compressive strength.

Also, [12] investigated the mechanical properties of high-performance electric wire fibre (EWF) reinforced concrete. Grade M40 concretes with EWF contents of 5, 1, 1.5 and 2 % were tested. They observed variation in compressive, split tensile and flexural strengths for changes in the fibre contents. They found that concrete's compressive, split tensile and flexural strengths were maximum when the fibre content was 2.0 %.

The influence of steel fibre (SF), electrical waste copper wire fibre (EWCWF) and electrical waste glass fibre (EWGF) on mechanical properties of concrete with volume fractions of 0.25, 0.5, 0.75, 1.0 and 1.25 % were studied by [13]. They tested mechanical properties such as compressive strength, splitting tensile strength and flexural on regular and fibre-reinforced concrete for seven days, 14 days and 28 days. They found that the compressive strength of concrete using SF, EWCWF and EWGF were increased by 42.6, 23.76 and 15.35 % compared to standard concrete. Splitting tensile strength of concrete using SF, EWCWF and EWGF was increased by 81.6%, 46.4% and 90.1% compared to ordinary concrete. The flexural strength of concrete using SF, EWCWF and EWGF was increased by 46.1, 38.8 and 31.7 % compared to standard concrete. They concluded that adding SF, EWCWF, and EWGF improved the compressive strength, splitting tensile strength and flexural strength of the concrete and reduced the crack width under different loading conditions.

MATERIALS AND METHODS

The materials used for the study are cement, coarse aggregate, fine aggregate, water, superplasticizer and WCWF.

Ashaka brand of ordinary Portland cement (OPC) was used throughout the research.

The cement properties tested include consistency, initial and final setting times, soundness, specific gravity, bulk density and oxides composition. The tests were conducted by [14, 15] specifications.

The coarse aggregate used is an average-weight crushed igneous rock aggregate with a maximum size of 20 mm. It was obtained from a quarry site in Bauchi and tested in Abubakar Tafawa Balewa University's structures laboratory. Tests carried out on the aggregate are specific gravity, bulk density, aggregate crushing value, and aggregate impact value and particle size distribution. The tests were conducted by [16, 17, 18, 19] specifications.

The fine aggregate (sand) used was obtained from a stream at Bayara village along Bauchi – Dass road. It was tested for specific gravity, bulk density and particle size distribution. The tests were conducted by [16, 17, 19] specifications.

Clean pipe-borne water was used for the preparation of the test specimens.

CONPLAST SP 430 brand of sulfonated naphthalene polymers superplasticizer was used throughout the study. This superplasticizer is a factory product compatible with the type of cement selected for the study. No test was conducted on the superplasticizer. It was used in line with the manufacturer's specifications.

The copper wire used was factory offcuts obtained from Alind Nigeria Limited, Bauchi. A single size of one millimetre (1 mm) diameter wire was used and cut into 60 mm long fibres according to [20] recommendations. Fibre Volumes of 0.5, 1.0 and 1.5 % by weight of concrete were used.

METHODOLOGY

Concrete mix design. Grade M-25 concrete was used throughout this study. The mix was designed using Building Research Establishment (BRE) mix design method. The minimum compressive strength is 25 N/mm^2. Moderate exposure was chosen for durability requirements. Also, moderate workability ranging from 30–60 mm and 30 % passing 600 microns was used. The summary of the mixed 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

Concrete Production. The concrete production processes were strictly followed, involving batching, mixing, transportation, compaction and curing. The concretes were produced by [21, 22] specifications. The concrete cubes were removed from the moulds 24 hours after casting and cured for 7, 14 and 28 days in water, respectively.

Mechanical Properties of WCWFRC. A compressive strength test was carried out on hardened concrete cubes of 100 mm x 100 mm x 100 mm. The specimens were tested by [23, 24] specifications. Three cubes were tested for each curing period and WCWF contents. The compressive strengths were determined using equation (1).

$$compressive\ strength, f_c =$$

$$= \frac{Failure\ load, F_c\ (KN)}{Cross\ sectional\ area\ of\ contact, A_c\ (mm^2)} \qquad (1)$$

The mean value of compressive strength for the three cubes would be determined.

A flexural strength test was carried out on the hardened concrete beams of 100 x 100 mm x 500 mm. The specimens were tested by BS [25] specifications. The loading arrangement for the determination of flexural strength is shown in Figure 1. Three beams were tested for each WCWF content and curing period. The modulus of rupture (flexural strength) was determined using equation (2).

$$Modulus\ of\ rupture,\ M_r = \frac{3PL}{2bd^2}, \qquad (2)$$

where P – Maximum load (N), L – Span of the beam (mm), d – Depth of the beam (mm), b – Breadth of the beam (mm).

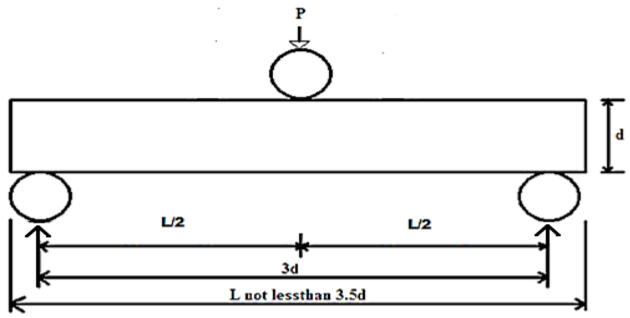

Figure 1 – Loading Arrangement for Flexural Strength Test Specimen (Three Point Bending)

Split-tensile strength test was carried out on the hardened concrete cylinders of diameter 150 mm and length of 300 mm. The specimens were tested by [26] specifications. Three cylinders were tested for each WCWF contents and curing period. The Split-tensile strengths were determined using equation (3).

$$Split - tensile\ Strength,\ F_{st} = \frac{2P}{\pi LD}, \quad (3)$$

where P – Maximum load (N), L – Length of the cylinder (mm), d – Diameter of the cylinder (mm).

RESULTS AND DISCUSSION

Physical and Chemical Properties of Cement. The results of the physical and chemical properties of the cement are presented in Tables 2–3, respectively.

The tests were conducted by [15]. A consistency of 28 % was obtained, within the range of 25–35% specified by [15]. The initial setting time was 53 minutes which is greater than the minimum value of 45 minutes set by [15], while the final setting time was 475 minutes which is less than the maximum value of 600 minutes specified by the code.

Table 2 – Physical Properties of Cement

Tests	Results
Consistency (%)	28
Initial setting time (min)	53
Final setting time (min)	475
Soundness (mm)	3.5
Specific Gravity	3.14
Loose Bulk Density (Kg/m^3)	1550

Table 3 – Chemical Properties of Cement

Oxides	Percentage by weight
SiO_2	20.7
Al_2O_3	6.1
Fe_2O_3	2.3
CaO	62.1
MgO	1.2
Na_2O	0.9
K_2O	1.0
SO_2	1.6
Ignition loss (%)	1.4

The soundness of the cement paste was found to be 3.5 mm, which is less than the total value of 10 mm specified by [15]. The specific gravity was 3.14, which agrees with the value of 3.15 specified for OPC, while the loose bulk density was 1550 kg/m^3, within the range of 850–1650 kg/m^3 set by [27].

Physical properties of Fine Aggregate. The results of the fine aggregate's physical properties and particle size distributions were presented in Table 4.

Table 4 – Physical Properties of Fine Aggregate

Tests	Results
Specific Gravity	2.42
Moisture Content (%)	1.72
Bulk Density (kg/m^3)	1611

The particle size distribution was determined using the method specified by [19]. The specific gravity of the fine aggregate was 2.42, which falls within the range of 2.4–2.9 set by the code. The moisture content was 1.72 %, within the scope of 0.2–2.0 % specified by [28] for saturated surface dry fine aggregate. The bulk density of the total was 1611 kg/m^3, which falls within the range of 1520–1680 kg/m^3 specified by the code. The result of particle size distribution is presented graphically in Figure 2. The aggregate falls within zone III by [29].

Physical Properties of Coarse aggregate. The results of the physical properties of the coarse aggregate are summarized in Table 5. The specific gravity of the coarse aggregate was 2.75, which falls within the range of 2.4–2.9 specified by the code. The moisture content was 1.1%, within the scope of 0.2–4 % defined by [28] for saturated surface dry, coarse aggregate.

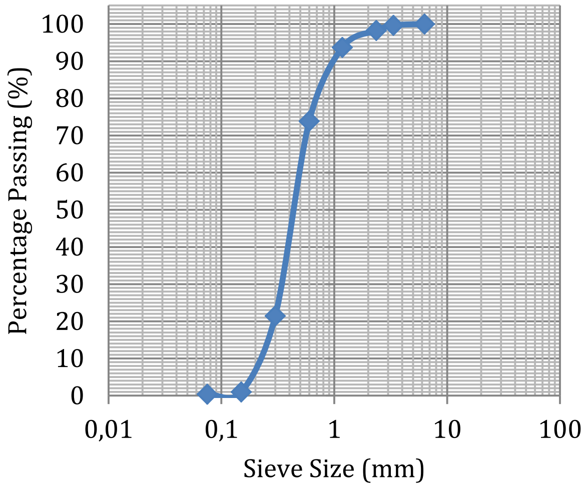

Figure 2 – Grading curve for fine aggregate

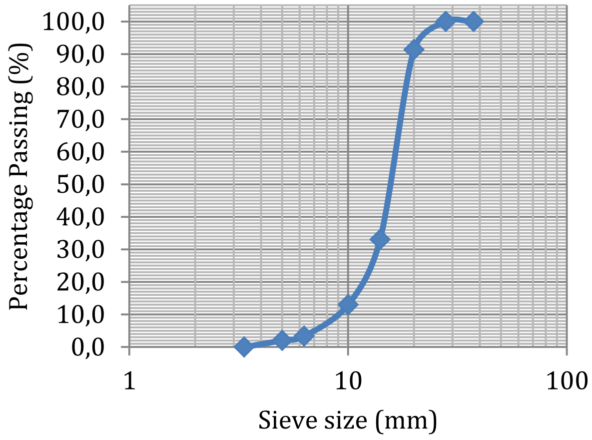

Figure 3 – Grading Curve for Coarse Aggregate

Table 5 – Physical Properties of Coarse Aggregates

Tests	Results
Specific Gravity	2.75
Moisture content (%)	1.1
Bulk Density (kg/m³)	1586
Aggregate Impact Value (%)	14.65
Aggregate Crushing value (%)	26.84

The bulk density of the total was 1586 kg/m³, which falls within the range of 1200–1750 kg/m³ specified by the code. The aggregate impact value was 14.65 %, which is less than the maximum value of 20 % defined for solid aggregates. The aggregate crushing value was 26.84 %, less than 30 % specified for concrete pavement. The result of particle size distribution is presented graphically in Figure 3. The aggregate falls within zone III by [29].

Variation of Strengths with Fibre Contents. Figure 4 shows the variation of compressive strength with fibre contents at different curing periods.

The compressive strength increases with an increase in both fibre contents and curing periods. Maximum compressive strength of 34.58 N/mm² was obtained at 1.5% fibre content and 28 days of curing. Flexural strength also increases with an increase in both fibre contents and curing periods, as shown in Figure 5.

It grows from 4.36 N/mm² at 0 % fibre content and seven days of healing to 6.68 N/mm² at 1.5 % fibre content and 28 days of curing. There is also an increase in split tensile strength with an increase in fibre content from 2.72 N/mm² at seven days to 4.39 N/mm² at 28 days of curing, as shown graphically in Figure 6. All the results agree with the findings of other researchers [13].

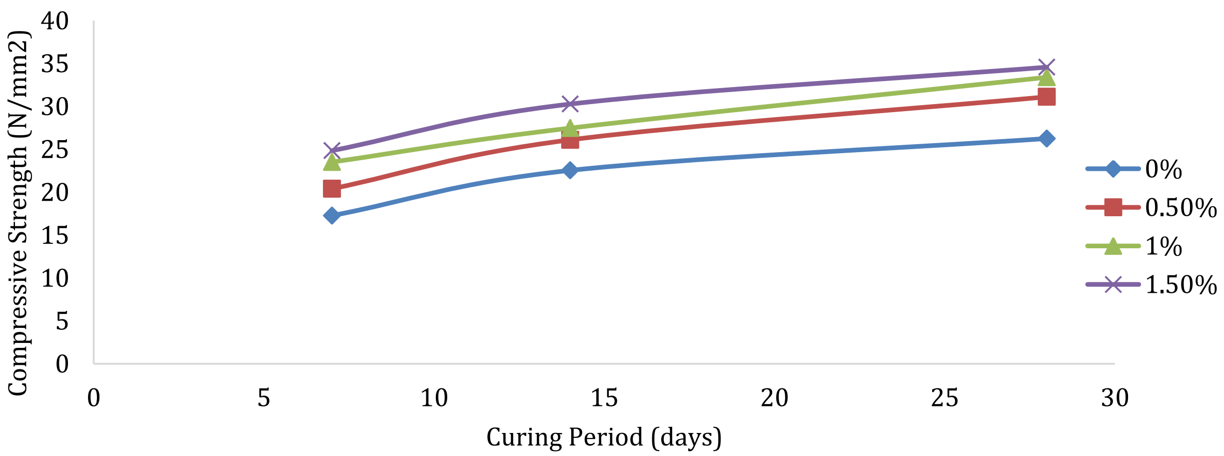

Figure 4 – Compressive Strength of Concrete Containing WCWF

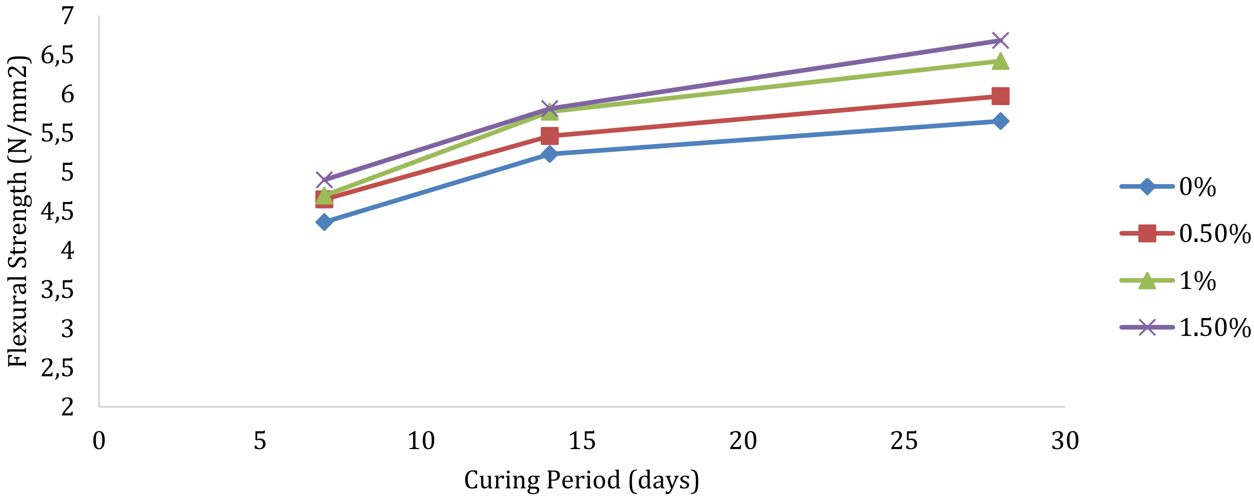

Figure 5 – Flexural Strength of Concrete Containing WCWF

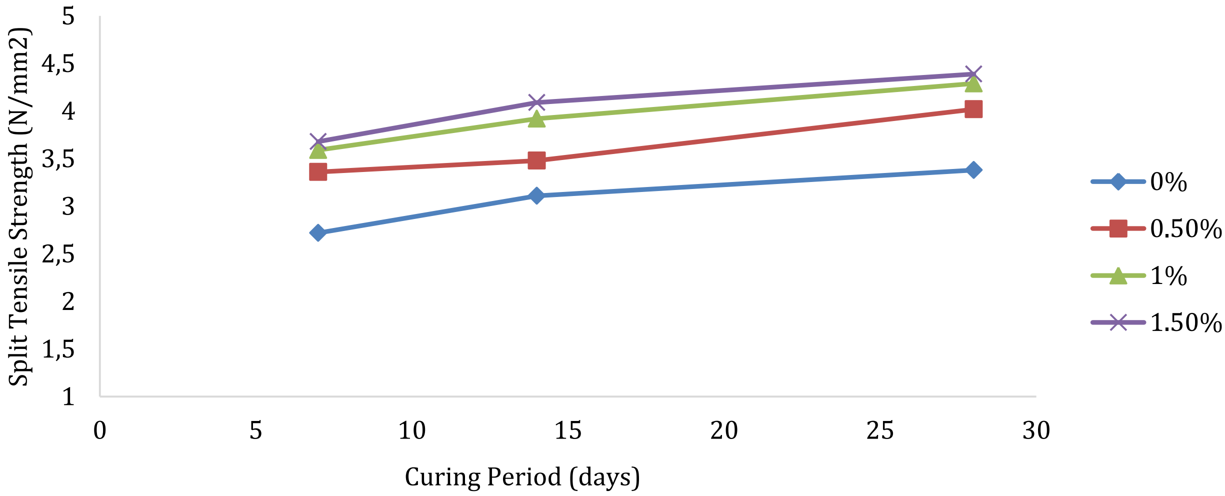

Figure 6 – Split Tensile Strength of Concrete Containing WCWF

Relationship between Flexural and Compressive Strengths. The relationship between flexural strength (F_s) and compressive strength (C_s) is shown in Figure 7.

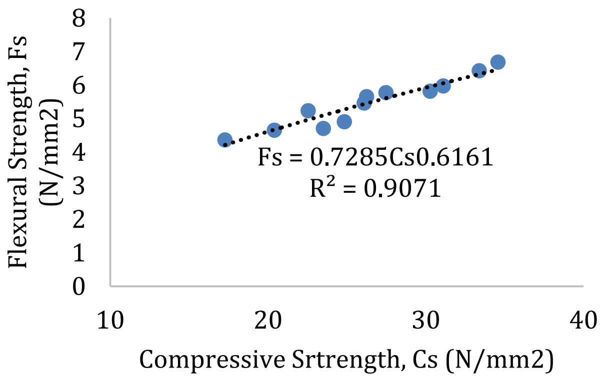

Figure 7 – Relationship between Flexural and Compressive Strength of Concrete Containing WCWF

Equation (4) shows the mathematical expression that relates compressive with flexural strengths.

$$F_s = 0.7285{C_s}^{0.6161} \quad (4)$$

The equation agrees with the general equation, $F_r = b{F_c}^n$ for the relationship between compressive and flexural strength of concrete, where F_r is the flexural strength, F_c is the compressive strength, b is a coefficient (varies from 0.33 to 0.94), and n is power (varies from 1/2 or 2/3). The b and n depend on strength levels, aggregate properties, sample geometry, compaction, curing conditions, admixture type, etc. [30]. The model equation has a coefficient of determination (R^2) of 0.9071 (90.71 %), and the higher the R^2 value, the better the model fits the data. Also, a higher R^2 value indicates that the variation in flexural strength is due to variation in compressive strength.

Relationship between Split Tensile and Compressive Strengths. Figure 8 shows the relationship between split tensile strength (St_s) and compressive strength (C_s).

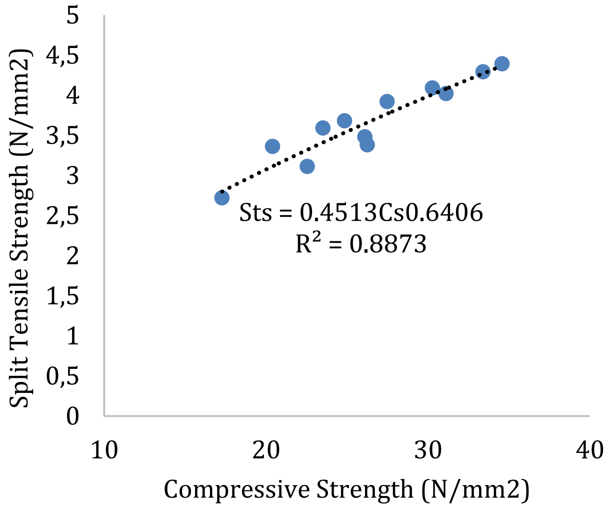

Figure 8 – Relationship between Split Tensile and Compressive Strength of Concrete Containing WCWF

The mathematical expression is presented in equation (5).

$$S_{ts} = 0.4513{C_s}^{0.6406} \quad (5)$$

This model equation also agrees with the general equation $F_r = b{F_c}^n$, presented above. The R^2 for the model is 0.8873 (88.73 %), which indicates a good relationship between the split tensile strength and compressive strength in the model. This relationship agrees with the results obtained from standard concrete without fibres [31].

Relationship between Flexural and Split Tensile Strengths. The relationship between flexural strength and split tensile strength is shown in Figure 9, and equation (6) shows the mathematical expression that relates flexural with split tensile strengths.

$$F_s = 1.2214S_{ts} + 0.985 \quad (6)$$

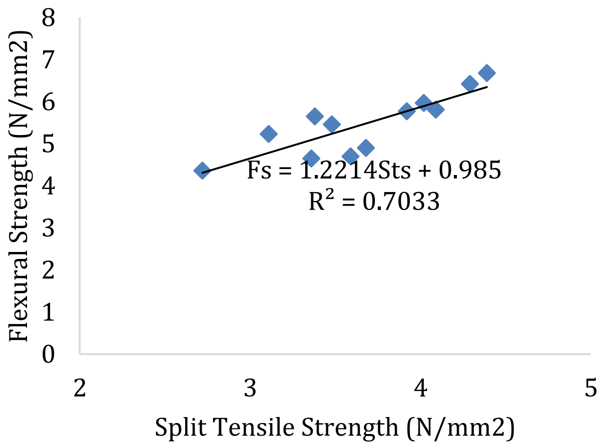

Figure 9 – Relationship between Flexural and Split Tensile Strength of Concrete Containing WCWF

The model equation has R^2 value of 0.7033 (70.33 %), which shows a good relationship between the flexural and compressive strength.

CONCLUSIONS

The relationship between compressive, flexural and split tensile strengths of waste copper wire fibre reinforced concrete was established, and the following conclusions were drawn:

1. There is a general increase in compressive, flexural and split tensile strengths of the concrete with an increase in WCWF and curing period.

2. The following mathematical models were obtained:

2.1. Relationship between flexural and compressive strengths: $F_s = 0.7285{C_s}^{0.6161}$

2.2. Relationship between split tensile and compressive strengths: $S_{ts} = 0.4513{C_s}^{0.6406}$

2.3. Relationship between flexural and split tensile strengths: $F_s = 1.2214S_{ts} + 0.985$

3. The models have R^2 values greater than 70 %, and the higher the value of R^2, the better the model fits the data. This indicates that the model's predictors influenced the variations in the responses.

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