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EFFECT OF VARYING FIBRE LENGTH ON THE PROPERTIES OF RECYCLED TYRE STEEL FIBRE CONCRETE

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ABSTRACT

Purpose: *Tyre waste is a global environmental challenge, with millions of tyres discarded annually. Efforts towards recycling waste tyres involve their breakdown to component materials for use in various aspects of industry. Recycled tyre steel bead wires are one of such components. This study assesses the effect of varying recycled tyre steel fibre (RTSF) lengths on workability, compressive strength and tensile strength of RTSF concrete.*

Design/methodology/approach: *An experimental research design was adopted. RTSF length was the independent variable and the dependent variables comprised workability, measured using the slump test (mm), compressive strength and tensile splitting strength, measured on 50 x 50 mm cube and 150 x 300 mm cylinder specimens on the 28^th^ day. Control variables were concrete mix proportion, a constant fibre diameter (1 mm) and volume fraction (1%), other fibre characteristics, curing conditions and testing procedures.*

Findings: *The findings showed that the inclusion of RTSF reduced concrete slump to 0 mm in mixes with long fibres. Incorporation of RTSF to concrete increased compressive strength by 15% and tensile splitting strength up by 25% for the longest fibres. Concrete with mixed fibre lengths gave strength values comparable to RTSF concrete specimens with fibres of length equal to the average length of the mixed fibre specimens. Crack coalescence contributions of RTSF were also observed.*

Research limitations/Implications*: Findings from the study are limited to the use of steel bead wires from "Mecho 4.00 – 8 58J" tricycle tyres, physically assessed to be in good condition and a fibre volume fraction of 1%. The study showed that, concrete performance can be improved through adequate management of the length of RTSF incorporated into concrete mixes.*

Practical implications: *The study recommended that RTSF length should be considered as an important independent variable in the design of RTSF concrete.*

Originality/value *– The study revealed the impact of RTSF length on workability, compressive and tensile splitting strength of concrete. The findings will provide a basis for optimisation of properties of RTSF concrete.*

Keywords: Compressive strength; Fibre length variation; Recycled tyre steel fibre (RTSF); Tensile splitting strength; Sustainability.

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1.0 INTRODUCTION

The construction industry is undergoing a paradigm shift towards sustainability, which is driven by the need to reduce environmental impact and promote the use of recycled materials. Recycled materials such as waste ceramic tiles, glass and bricks have been applied to production of concrete as pozzolanas, to improve concrete matrix strength and durability characteristics. They have also been adopted as crushed aggregates to replace naturally quarried aggregates, partially or wholly. Other concreting related applications of recycled materials have included their application as workability enhancers, tension reinforcement and fibre reinforcement. In the application of recycled waste materials as fibre reinforcement, the use of waste tyre steel wires has gained significant attention in recent times.

Tyre waste is a global environmental challenge, with millions of tyres discarded annually. These discarded tyres end up in landfills where they pose long term toxic hazards due to their non-biodegradable nature. Economic and environmentally friendly disposal methods have been implemented in several areas of industry. The United States Tire Manufacturers Association, USTMA (2022) noted some of such areas to include tyre derived fuel, ground rubber, civil engineering and reclamation projects. Processes adopted for recovery of waste tyre recycling material include the mechanical processes which involves the shredding of tyres, the thermal degradation processes such as microwave induced pyrolysis and chemical or cryogenic methods (Tlemat, Pilakoutas and Neocleous, 2003). In developing countries, manual extraction of recycle tyre materials is also a common method. The products of waste tyre recycling through the mechanical and manual processes include crumb rubber, tyre chips and steel fibres (Tlemat, Pilakoutas and Neocleous, 2003; Bdour and Al-Khalayleh, 2010). Application of waste tyre steel fibres to concrete has the potentials to enhance its mechanical properties while contributing to environmental sustainability and resource conservation. However, the performance of recycled tyre steel fibre (RTSF) concrete depends on factors such as fibre length, shape, dosage and distribution (Aiello *et al*., 2009; Krolo *et al*., 2012; Michalik *et al*., 2022; Roshan *et al*., 2023).

Performance of concrete is considered both at its fresh and hardened state. Though compressive, tensile and flexural strength properties, at its hardened state are of great importance for design purposes, workability requirements, at its fresh state, ensure ease of handling and placement. Both fresh and harden state properties are influenced by fibre length characteristics. Longer fibres reduce workability, making fresh concrete stiffer and more difficult to handle (Mohammed *et al*., 2021). The ability of hardened concrete to withstand axial loads is defined by its compressive strength. RTSF enhances the compressive strength of concrete by delaying crack initiation, bridging microcracks and preventing their propagation. Fibre reinforced concrete with longer fibres have been proven to exhibit better crack bridging characteristics, leading to higher compressive strength (Yin *et al*., 2019). Tensile strength is a key indicator of concrete's resistance to tensile stresses. Weak resistance of plain concrete to tensile stress makes it imperative to provide tension reinforcement at tensile zones. Discrete fibres randomly orientated in these regions enhance tensile strength, through delayed crack initiation, micro and macro cracking bridging. While longer fibres are key to bridging of macro cracks, shorter fibres are particularly effective at controlling micro cracks (Wang *et al*., 2022), enhancing ductility and energy absorption under tensile load, relative to the plain concrete.

Existing studies have emphasised on steel fibres sourced from waste tyre recycling plants, where mechanical and thermal degradation processes are adopted. These processes provide steel fibres with mechanical properties modified through thermal treatment, significant dimensional variability and presence of rubber fragment impurities. The length and surface roughness of RTSF can vary significantly depending on the source and processing method. This variability poses challenges for standardization and quality control, making it difficult to achieve consistent performance (Groli *et al*., 2019).

Existing studies (Tlemat, Pilakoutas and Neocleous, 2003; Bdour and Al-Khalayleh, 2010; Groli *et al*., 2019) also take little consideration of steel fibres derived from manually extracted waste tyre bead wire which are not limited by influences of length and surface roughness variabilities or presences of impurities. Manual extraction of re-useable waste tyre components is common practice in developing countries, where manual labour is cheap and readily available. Waste tyre components are commonly recycled into rubber ropes, baskets, rubber dampers, steel binding wires amongst others. Manual extraction of re-useable waste tyre components is energy clean and provides steel bead wires with dimensional and mechanical characteristics as provided at the time of manufacture of the tyres.

Benefits and shortcomings of both short and long fibres, in fresh and hardened concrete, pose challenges in selection of optimum fibre length for concrete mixes. Assessments in most studies have focused on the use of either short or long fibres (Tlemat, Pilakoutas and Neocleous, 2003; Bdour and Al-Khalayleh, 2010; Groli *et al*., 2019). Consideration of RTSF concrete mixes with two or more fibre lengths, proportioned to provided designed performance characteristics has found little consideration in literature or general application. It is yet to be established, if fibre length proportioning in RTSF concrete could provide the combined benefits of long, intermediate and short fibres, in a single RTSF concrete.

In this light, the present study assesses the effect of varying RTSF lengths on the workability, compressive and tensile strengths of fresh and hardened RTSF concrete, with a view to improving RTSF concrete performance and optimising the application of RTSF in concrete production and sustainability considerations.

2.0 LITERATURE REVIEW

2.1 Factors affecting properties of recycled tyre steel fibre reinforced concrete (RTSFC)

Factors affecting Workability of RTSFC

Workability reductions upon RTSF addition are among the most consistently reported outcomes in literature. At equal water to binder ratio and paste content, slump generally decreases as fibre volume fraction increases, average fibre length and aspect ratio increases, fibre surface roughness and residual rubber contamination increases and fibre dispersion becomes less uniform (Su *et al.*, 2023; Zia *et al*., 2023; Michalik *et al*., 2022). Mechanically, fibres elevate inter-particle friction and create a mechanical network that resists flow, while their large specific surface raises paste demand for lubrication. Slump reductions of between 10 to 30 percent have been reported at moderate volume fractions (between 0.5 and 1.5 %), with sharper losses at higher dosages (Su *et al.*, 2023; Zia *et al.*, 2023).

Factors Affecting Compressive Strength of RTSFC

The influence of RTSFs on compressive strength is nuanced. Unlike tensile and flexural response, which are directly governed by crack bridging, compressive strength in normal strength concrete is controlled by paste quality, aggregate interlock, and quantity of defects (voids and microcracks). RTSFs can marginally enhance compressive strength at low to moderate dosages by restraining lateral dilation and delaying microcrack coalescence, which is analogous to confinement, yet the empirical signals are small relative to measurement scatter (Aiello *et al*., 2009; Krolo *et al*., 2012; Michalik *et al*., 2022; Roshan *et al*., 2023). Where pronounced decreases in compressive strength are observed, they are commonly traced to results of poor workability such as entrapped air, honeycombing, or fibre balling, rather than an intrinsic weakening effect of fibres (Su *et al.*, 2023; Zia *et al*., 2023). Fibre geometry and cleanliness play secondary roles, influencing compressive strength. Higher aspect ratio may marginally improve post-peak behaviour in compression (energy absorption), but its effect on peak compressive strength is limited. Purified fibres may contribute to a slightly denser interfacial transition zone (ITZ) and improved load transfer, yet the gains are typically overshadowed by variability in fresh-state quality (Senesavath *et al*., 2022).

Factors Affecting Tensile Strength of RTSFC

Tensile properties measured through split cylinder tests, direct tension or flexure, are where RTSFs deliver their most robust benefits. Across studies, increases in split tensile strength of 10 to 70 % relative to plain concrete have been reported within typical dosage ranges, with greater effects on post-cracking behaviour and toughness indices (Abdul Awal *et al*., 2015; Peng, Niu and Long, 2014; Fauzan *et al*., 2017; Peng *et al*., 2016; Cheng, Wang and Yang, 2011; Yang *et al.,* 2015; Liew and Akbar, 2020; Roshan *et al*., 2023; Michalik *et al*., 2022; Gholami *et al*., 2023). Aksoylu *et al*. (2022) noted that additions of recycled steel wire fibres into concrete by 1%, 2% and 3% increased compressive strength by 17.2%, 30.8% and 46.4% respectively; and tensile splitting strength by 14.4%, 25.1% and 36.7%, respectively. The principal mechanisms are crack bridging, pull-out resistance governed by mechanical anchorage, frictional bond enhanced by surface roughness or hooks/crimps, and the activation of a three-dimensional fibre network capable of redistributing stresses. Fibre dispersion quality and orientation statistics strongly modulate the outcome; poor dispersion or preferential alignment can reduce the effective number of fibres intersecting potential crack planes. Fibre cleanliness again matters. Purified fibres after de-rubberization and often with reduced oil/impurity residues, show higher bond strength and pull-out work than non-purified fibres, translating to higher split tensile and flexural strengths (Senesavath *et al*., 2022).

2.2 Effect of varying fibre length on properties of fresh and hardened RT-SFRC

Fibre length typically reported as an absolute length (l) and implicitly through aspect ratio (l/d), has opposing effects on fresh and hardened properties. Longer fibres and higher aspect ratios increase the probability that a fibre will cross a crack plane and remain engaged at larger crack openings, thereby improving tensile capacity, flexural strength, and fracture energy (Wang *et al*., 2024; Gul *et al*., 2021). Yet, the same attributes exacerbate workability losses by enhancing interlock and the likelihood of fibre clustering. Many authors thus report an optimum length (or length distribution) contingent on fibre volume fraction, matrix rheology, and placement method. Wang *et al*. (2024) used recycled tyre cord filaments and showed that increasing length improved tensile and flexural response up to threshold beyond which dispersion degraded. Gul *et al*. (2021) similarly found that lengths in the 7.6 – 10.2 cm range at 1 – 4 % volume significantly altered mechanical response, with optimal combinations depending on the targeted property.

On the fresh -state side, studies consistently document reductions in slump with increasing length, although the magnitude can be non-monotonic when mix design changes are introduced to maintain workable consistencies (Hindu *et al*., 2019). In some mixes, very short RTSFs produce more severe slump losses than longer ones at the same mass dosage because short fibres can pack densely and raise specific surface area; however, this behaviour is matrix-specific and sensitive to grading and high range water reducers level (Hindu *et al*., 2019). From a practical standpoint, controlling the fibre length distribution, by sieving or shredding to target bands can reduce balling and improve consistency while preserving the mechanical benefits of a tail of longer fibres.

Effect of varying fibre length on workability

The most direct and visible consequence of increasing fibre length is a reduction in workability. Longer RTSFs create an interlocked skeleton within the fresh matrix, increasing yield stress and plastic viscosity in rheological terms. When combined with high volume fractions, this interlock can lead to fibre balling, pump blockages, or surface tearing during finishes. Evidence from experimental programs indicates that slump reduction per unit fibre content grows with aspect ratio, but that mix adjustments can partly offset the effect (Su *et al.*, 2023; Zia *et al*., 2023). Hindu *et al*. (2019) reported complex responses at constant dosing, certain longer lengths produced slightly better slump than shorter lengths, likely reflecting differences in specific surface area and packing of the fibre.

Effect of varying fibre length on compressive strength

Peak compressive strength is controlled by matrix quality and defect density, fibre length exerts only an indirect influence through its impact on workability and air content. Comparative studies that normalize slump using admixtures show minimal increases in compressive strength across fibre lengths at the same volume fraction (Su *et al.*, 2023; Roshan *et al*., 2023). Where longer fibres correlate with lower compressive strength, post-hoc examinations often reveal increased voids or segregation associated with inadequate consolidation in stiff mixes. Notably, even when compressive strength does not increase, long fibres can substantially enhance compressive toughness and residual capacity under sustained or cyclic loading, which may be more relevant to structural performance and durability (Zia *et al*., 2023; Chen *et al*., 2023). In Ultra high-performance concrete, the peak compressive strength is dominated by the dense matrix; fibre length primarily modulates strain-hardening and post-peak dissipation rather than the strength maximum (Alsaif *et al*., 2024; Yu *et al*., 2025).

Effect of Varying Fibre Length on Tensile Strength of RTSFC

Tensile and flexural properties exhibit the clearest positive sensitivity to fibre length and aspect ratio. With adequate embedment and anchorage, longer fibres increase the maximum bridging stress and widen the crack-opening range over which fibres remain engaged. Studies report significant increases in split tensile strength and flexural residual strengths as fibre length increases, provided dispersion is maintained (Wang *et al*., 2024; Gul *et al*., 2021; Michalik *et al*., 2022). In rubberized matrices, longer fibres offset reductions in tensile capacity from rubber aggregates, though workability trade-offs necessitate admixture optimization (Flores-Medina *et al*., 2023). Ultimately, an application-specific optimum fibre length exists, balancing pull-out energy against dispersion-limited fibre effectiveness. Processing route also matters. RTSFs derived as tyre cords filaments (with relatively uniform diameters) exhibit different bond and length -effect trends than heterogeneous bead/belt-derived fibres. Studies on recycled tyre cord filaments show pronounced gains with increasing length in the 30 – 60 mm range (Wang *et al*., 2024), whereas heterogeneous RTSFs sometimes require modestly higher dosages than ISFs to reach comparable tensile performance (Hameeda *et al*., 2025).

End-of-life tyres constitute a persistent waste stream with significant environmental implications. Through pyrolysis or mechanical shredding and separation, steel wires fraction, referred to as recycled tyre steel fibres (RTSF), whose high tensile strength and rough/irregular morphology make them suitable as discontinuous reinforcement in cementitious matrices, are obtained. The processes of pyrolysis and mechanical shredding are designed to breakdown waste tyres to manageable materials and sizes. This is without concern for the physical or chemical effects of the processes on the embedded steel. Compared with industrial steel fibres (ISFs), RTSFs obtained mechanically are inherently heterogeneous: lengths vary from a few millimetres to several centimetres, diameters are non-uniform, and the shredded product can contain kinks, crimps, hooks, and residual rubber (Bdour and Al-Khalayleh, 2010; Groli *et al*., 2019). RTSF extracted through pyrolysis and mechanical shredding form the bulk RTSF assessed in the studies reviewed. However, RTSFs obtained manually, is extracted with the sole objective of obtaining steel wires, through controlled processes. Manual extraction provides fibres with less dimensional and morphological inconsistencies. With adequate sorting and cleaning, presence of rubber impurities would be reduced.

Studies in literature showing the influence of fibre length on workability and strength properties of RSTF concrete are sparse. Those available adopt the aspect ratio (*l/d*), which is not specific to fibre length. Comparisons across studies adopting different fibre lengths often yield inconclusive or non-standardised insights into the isolated effect of fibre length.. The effect of well-proportioned fibres with varying lengths on RTSFC properties is also not clearly established in the literature. The present study fills these gaps so as to provide performance consistencies and promote novel applications of recycled tyre steel fibres in concrete production.

3.0 MATERIALS AND METHODS

3.1 Research design

This study adopted an experimental research design to evaluate the effect of varying RTSF lengths on selected properties of fresh and hardened concrete. RTSF length was the independent variable and the dependent variables comprised: workability (assessed using the slump test, and measured in mm), compressive strength (measured in MPa) and the tensile splitting strength (measured in MPa). Control variables were maintained constant to allow observation and measurement of changes solely due to the independent variable. Control variables included concrete mix proportions, a constant fibre volume fraction (1%), and other fibre characteristics, curing conditions and testing procedures.

Concrete specimens were prepared into five groups; CL-0 with no fibres, CL-30 with 30 mm straight fibres, CL-40 with 40 mm straight fibres, CL-50 with 50 mm straight fibres and CL-M with equal volume fractions of 30 mm, 40 mm and 50 mm straight fibres (0.333% volume fraction each). The

CL-M group was developed to assess the effect of using equal proportions of fibres with different lengths on concrete properties.

Recycled tyre steel fibre preparation

RTSF used were steel bead wires, 1 mm diameter, 2140 MPa tensile strength (measured from a randomly selected batch, representing 20% of total mass used), and extracted manually from waste Mecho 4.00 – 8 58J tricycle tyres. Waste tyres were sourced from tyre repair shops in Uyo, Akwa Ibom State, Nigeria. The bead areas were cut out of the tyre and stripped of the steel bead wires. Bead wires were unbundled, strands tied, desired lengths measured using a tape, cutting points were marked and cut using a grinding machine as shown in Figure 1 and Figure 2. A tolerance of ± 3 mm was achieved in fibre length. Residual pieces of rubber in the recycled tyre steel fibres were carefully sorted and disposed of.

Figure 1. Cutting of fibres to desired lengths using a grinder.

Figure 2. Typical recycled tyre steel fibres.

Concrete preparation

Cement used for the work was Dangote Portland limestone cement, with compressive strength of 42.5 MPa, produced in conformity with the Nigeria Industrial standard, NIS, 444-1 (2010). Fine aggregate was river sand with particle sizes not exceeding 4.75 mm. Sieve analysis was carried out on fine aggregates in accordance with ASTM C136 / AASHTO T27 (ASTM, 2019) standard procedures, using a mechanical sieve shaker. Coarse aggregate was granite with particle sizes ranging between 4.75 mm and 19 mm. Specific gravity of aggregates were carried out in accordance with ASTM D854 (ASTM D854, 2014) while that of steel fibres were carried out to ASTM B 311 (ASTM B 311, 2022). Bulk density of aggregates was carried out in accordance with BS EN 11272 (BS EN ISO 11272, 2017). Portable water from the laboratory water supply mains was used for both preparation and curing of specimens.

Trial mixes were prepared and tested, aimed at providing a plain concrete mix with minimum compressive strength of 20 MPa and adequate consistency. The plain concrete mix proportioned as shown in table 1, gave a mean compressive strength of 22.1 MPa, and was adopted as the control concrete mix for the study.

Table 1: Concrete mix proportion used in specimen preparation in the study

Materials	Cement	Fine aggregate	Coarse aggregate	Water	RTSF
Mass (kg per m^3 of concrete)	0.143	0.286	0.572	0.0715	0

Mixing of specimens was carried out with the aid of a mechanical mixer. Concrete test specimens were prepared, using steel moulds, compacted by means of rodding, demoulded and cured following the guidelines of BS EN 12390-2 (BSI, 2019). Concrete specimens comprised 50 x 50 x 50 mm cubes for compressive strength tests and 150 mm x 300 mm (diameter x length) cylinders for tensile splitting strength tests. Concrete specimens were demoulded after 24 hours and cured in a curing tank until they were ready for testing. Two cube and two cylinder specimens were prepared per concrete mix.

Testing of concrete specimens

Compressive strength tests were carried out to BSEN 12390-3 (2019), while tensile splitting strength tests were carried out to BSEN 12390-6 (2009) requirements. All tests were carried out on the 28th day. A digital compression testing machine was used for both compressive and tensile strength tests. Compressive forces were applied to specimens at a constant loading rate of 5 kN/s in compressive strength test, until failure or no further increase in load was observed. A constant loading rate of 3.5 kN/s was adopted in the tensile strength test. Tensile splitting strength was calculated using the formula:

$$f_{ct} = \frac{2\,F}{\pi\,L\,d} \qquad \ldots Equation\ 1$$

Where;

f_{ct} is the tensile splitting strength, in megapascals (MPa) or in Newtons per square millimetre (N/mm^2);

F is the maximum load, in Newtons (N);

L is the length of the line of contact of the specimen, in millimetres (mm);

d is the designated cross-sectional dimension, in millimetres (mm).

4.0 PRESENTATION AND DISCUSSION OF RESULTS

4.1 Sieve analysis for Fine Aggregates

Result of sieve analysis carried out on fine aggregate used in the study is as presented in Table 1. From values presented in table 1, a particle size distribution curve was plotted, as shown in Figure 3.

Table 1. Sieve analysis result carried out on Fine Aggregate.

Sieve Size (mm)	Mass Retained (g)	Cumulative mass Retained (g)	% Retained (%)	Cumulative % Retained (%)	% Passing (%)
4.75	5	5	1.0	1.0	99.0
2.36	30	35	6.0	7.0	93.0
1.18	60	95	12.0	19.0	81.0

0.600	120	215	24.0	43.0	57.0
0.300	135	350	27.0	70.0	30.0
0.150	100	450	20.0	90.0	10.0
0.075	30	480	6.0	96.0	4.0
Pan	50	500	10.0	100.0	0.0

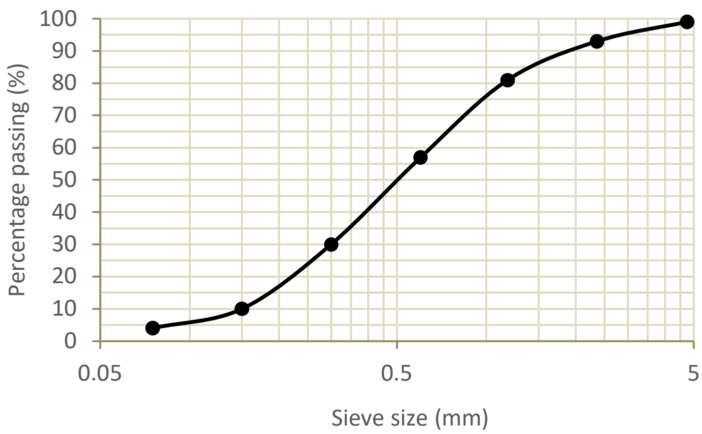

Figure 3. Particle size distribution curve for fine aggregate

From Table 1 and Figure 3, the Finess modulus, Coefficient of uniformity (C_u) and Coefficient of curvature (C_c) were calculated. The Finess modulus (FM) given by the relationship;

$$Finess\ modulus\ (FM) = \frac{(Cummulative\ percentage\ retained\ on\ standard\ sieve)}{100} \quad \ldots Equation\ 1,$$

gave a value of 2.30. This value falls within the acceptable range of 2.3 to 3.1 as specified by ASTM C33/C 33M (ASTM, 2008). The Coefficient of uniformity (C_u) given by the relationship;

$$\text{Coefficient of uniformity (Cu)} = \frac{D60}{D10} \quad \ldots\ Equation\ 2,$$

gave a value of 4.35, while the Coefficient of curvature (Cc) defined by;

$$\text{Coefficient of curvature (Cc)} = \frac{(D30)^2}{D60 \times D10} \quad \ldots\ Equation\ 3,$$

gave a value of 0.92. The C_u value of 4.35 and a Cc value of 0.92 (though slightly lower than 1) implied that fine aggregate used had a wide range of particle sizes, with a relative abundance of intermediate particles, and is generally well graded. Therefore, fine aggregate was ideal for production of concrete of adequate consistency.

Specific gravity and bulk density

The values recorded for specific gravity and bulk density of fine aggregate 2.68 and 1589 kg/m^3 respectively. RTSF had specific gravity of 7.81. This would make concrete containing RTSF denser than that of plain concrete.

Slump test

Slump test results showed decreases in slump heights, measured with increases in the length of fibres incorporated to the concrete mix, despite a constant fibre volume fraction maintained across the RTSF concrete samples. Concrete specimen CL-0 with no fibre incorporated, gave the highest slump value (46 mm), concrete specimens CL-50 showed no slump and CL-M with equal volume fractions of fibres with varying length had a slump height of 9 mm. Results of slump test are as summarised in Figure 4.

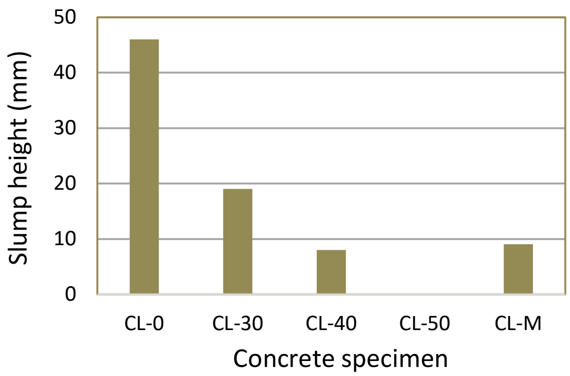

Figure 4. Slump height measurements of concrete specimens

Decreases in slump suggested that the presence of RTSF fibres, particularly longer length fibres, interfered with the mobility and compatibility of fresh concrete mixes. Generally, it has been reported that slump generally decreases as fibre volume fraction, average fibre length and aspect ratio increases (Su *et al.*, 2023; Zia *et al*., 2023; Michalik *et al*., 2022). At equal volume fractions, longer fibres influence a broader region in fresh concrete, increasing inter-particle friction through a mechanical network that resisted flow. Though workability of concrete improved with the use of equal proportions of varying fibre lengths, measured average workability for these specimens of RTSF concrete was 80% lower than that of plain concrete. This highlights the additional need for mix adjustments and possible use of lubricating admixtures in RTSF concrete.

Compressive strength of concrete

Plain concrete samples (CL-0) had an average compressive strength of 22.30 MPa. When 30 mm fibres were introduced to give specimens CL-30, the average compressive strength increased to 23.30 MPa. Further increases in fibre lengths to 40 mm and 50 mm in CL-40 and CL-50, led to greater increases in average compressive strength to 24.31 MPa and 25.56 MPa, respectively. Therefore, the concrete specimens CL-50, with the longest fibres provided the highest compressive strength. The CL-M specimen had an average compressive strength of 24.67 MPa, which was higher than those of CL-0, CL-30 and CL-40 but less than that of CL-50, as shown in Figure 5.

Recycled tyre steel fibre concrete specimens showed reduced crack number and length at failure, relative to plain concrete specimens. Figure 6 shows crack distribution over the surface of the CL-40 specimen. Crack number, crack lengths and concrete spalling were observed to decrease with increases in length of RTSF used. The CL-M RTSF concrete specimens displayed crack control properties better than those of the CL-30 specimens but poorer than the CL-50 RTSF concrete specimens.

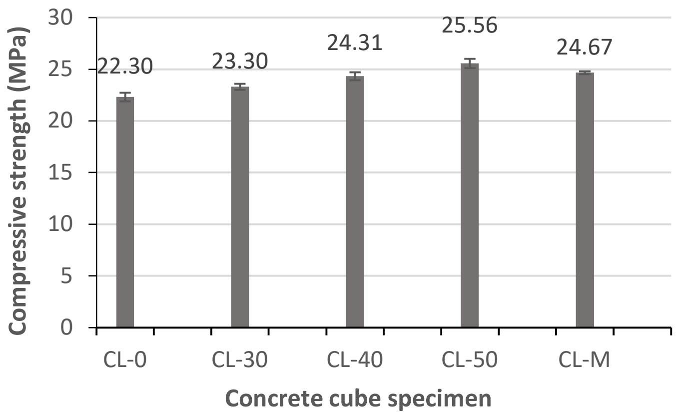

Figure 5. Compressive strength of RTSF concrete specimens

Figure 6. Crack patten at compressive failure of Specimen CL-40

Figure 5 shows that the compressive strength of concrete cubes reinforced with RTSF is clearly influenced by fibre length. Compared to plain concrete, all fibre-reinforced samples demonstrated increased compressive strength. A 14.6% increase in average compressive strength was observed between plain concrete specimens and RTSF concrete with 50 mm long fibres. This confirms the reinforcing effect of RTSF. Findings were in agreement with Aiello *et al*. (2009), Krolo *et al*. (2012), Michalik *et al*. (2022) and Roshan *et al*. (2023); where they explained that RTSFs marginally enhances compressive strength at low to moderate dosages by restraining lateral dilation and delaying microcrack coalescence. Manual extraction, careful cleaning and cutting of steel fibres to specific lengths for use in the preparation of RTSF concrete is believed to have contributed immensely to the increases in strength and small scatters observed in the data obtained. This is unlike a number of observations in few studies where reductions in strength and large standard deviations were observed.

Tensile splitting strength of concrete

Plain concrete samples (CL-0) had an average tensile splitting strength of 2.12 MPa. When 30 mm fibres were introduced to give specimens CL-30, the average tensile splitting strength increased to 2.27 MPa. Further increases in fibre lengths to 40 mm and 50 mm, in CL-40 and CL-50, led to greater increases in average tensile splitting strength, to 2.43 MPa and 2.65 MPa, respectively. Therefore, the concrete specimens CL-50, with the longest fibres, provided the highest tensile splitting strength. The CL-M specimen had an average tensile splitting strength of 2.45 MPa, which was higher than those of CL-0, CL-30 and CL-40 but less than that of CL-50, as shown in Figure 7.

All tensile splitting test specimens failed with the test cylinders developing failure crack along the centre axes of the cylinders. For the CL-0 plain concrete specimens, this crack was continuous and the cylinder split in two. However, for the RTSF concrete specimens, the failure cracks were discontinuous and the cylinder held together by the interlocking fibres at failure.

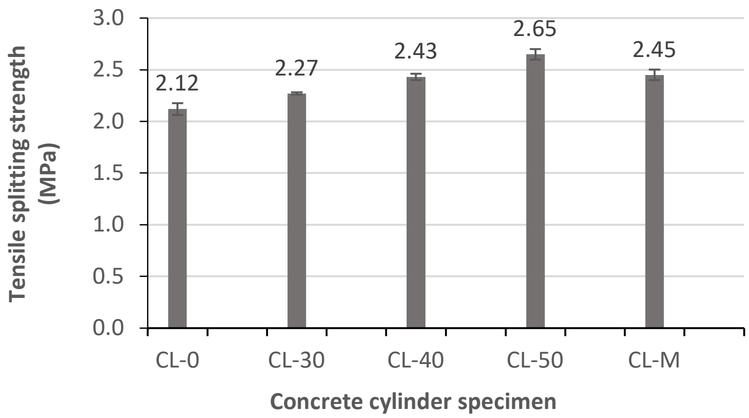

Figure 7. Tensile splitting strength of RTSF concrete specimens

The tensile splitting strength values increased with the inclusion and lengthening of RTSF. The 50 mm straight fibre group recorded a 25% increase in tensile strength due to fibre reinforcement, compared to the plain concrete specimens. These observed improvements align with those of Sukontasukkul *et al.* (2018), Huang *et al.* (2020), Zhang *et al.* (2021) and Gao *et al.* (2021), who found that longer RTSF significantly improved tensile splitting strength due to effective crack bridging and stress transfer, creation of stronger internal networks within the concrete, improving post-crack tensile behaviour, and better pull-out resistance.

Influence of use of varying fibre length

Use of equal volume fractions of fibres with varying lengths gave average responses for slump, compressive and tensile splitting strength. Mixed fibre lengths provided the combined advantages of both long and short fibres, which are better anchorage and higher fibre dispersion, respectively. However, results did not show any significant effect of these on the behaviour of RTSF concrete in slump, compression and tensile splitting strength tests. It was observed that the measured properties of RTSF concrete specimens with mixed fibres of varying lengths were similar to those of RTSF concrete specimens with fibres of length equal to the average length of the mixed fibre specimens. Benefit derived from the use of mixed length fibres therefore lies solely on the slight increases in slump of fresh concrete mixes.

5.0 CONCLUSION AND RECOMMENDATIONS

This study investigated the influence of varying lengths and combinations of Recycled Tyre Steel Fibres (RTSF) on the workability, compressive strength, and tensile splitting strength of concrete. Four RTSF configurations were explored; 30 mm, 40 mm, 50 mm, and mixed lengths (30 mm, 40 mm, 50 mm), alongside a control sample without fibres. For the RTSF concrete samples, a constant fibre volume fraction of 1% was maintained.

Findings showed that the inclusion of RTSF reduced concrete slump to 0 mm in mixes with long fibres. Incorporation of RTSF to concrete increased compressive strength by 15% and tensile splitting strength by 25%. Concrete with mixed fibre lengths behaved similarly to RTSF concrete specimens with fibres of length equal to the average length of the mixed fibre specimens, but with slight increases in slump. These effect were observed in addition to the crack-bridging and crack coalescence resistance provided by RTSF. This study also confirmed that these responses were achievable with little variations, when clean fibres were used and variations in fibre lengths were well controlled. The study therefore concludes that, concrete performance can be improved through adequate management of the length of RTSF incorporated into concrete mixes.

It is therefore recommended that physical dimensional characterisation of recycled tyre steel fibres should be considered beyond the aspect ratio (length to cross sectional area). Fibre length should be taken as an independent variable, with which RTSF concrete behaviour could be influenced, in the design of RTSF concrete.

6.0 LIMITATIONS OF THE STUDY

Findings from the study are limited to the use of steel bead wires from “Mecho 4.00 – 8 58J” tricycle tyres, physically assessed to be in good condition. The study is also limited to the use of a fibre volume fraction of 1%.

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