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# SYNTHESIS AND CHARACTERIZATION OF PYROLISED RECYCLED STEEL FIBERS FOR USE IN REINFORCED CONCRETE

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## ABSTRACT

The increasing amount of waste tires worldwide has had egregious environmental implications. Such implications are magnified in a developing country like Ethiopia, where an environmentally sound waste removal/recycling platform is still in its rudimental stage. Innovative approaches for reuse of tire products are paramount to claim the enormous potential that lies in tire-recycle and reuse. One area for exploitation in this regard is the use of scrap tires for developing steel fiber reinforced concrete. Results of this study indicate that steel fibers extracted from used tires can improve the concrete flexural and compressive strength. The main contributions of this paper are: a) development and characterization of steel fibers from scrap tires, for use in concrete as Recycled Steel Fiber Reinforced Concrete (RSFRC), b) study of RSFRC's mechanical properties in fresh and hardened state, and c) quantification of the benefits obtained by the concept of RSFRC over conventional concrete. This is done through the appropriate measurement and comparative analysis of slump values, compressive strength, and flexural tensile strength; among other mechanical properties.

## INTRODUCTION

Concrete is one of the most common building materials on earth. Its use in virtually all construction sites has made it a loyal companion for mankind. It is suitable for innovative architectural designs as it can be cast into any desired shape. It also possesses many desirable properties like high compressive strength, stiffness and low thermal and electrical conductivity [1]. The use of this material however, is not without its own predicaments as concrete portrays a significant weakness in tension. Internal micro cracks are inherently present in the concrete and the propagation of such micro cracks contributes to the weak tensile strength, eventually leading to brittle fracture of the concrete [2], [3]. Hence, attempts have been made to impart improvements in the tensile property of concrete by way of using conventional reinforced steel bars and/or by applying restraining techniques. These methods, however, do not improve the inherent tensile strength of the concrete. Furthermore, other desirable properties like toughness, ductility, control of cracking and energy absorption are not ensured as the reinforcement component is only present in certain pockets of the structural member.

In order to achieve all the above mentioned properties, it is essential to distribute the reinforcement uniformly throughout the cross-section. Such a way of reinforcing the brittle matrix is possible by adding to the constituents of the concrete mix, short fibers of small diameter that are either metallic or nonmetallic. This new material with improved mechanical properties is called "fiber reinforced concrete" [2], [3]. The American Concrete Institute (ACI) also defines this material as a concrete made of hydraulic cements containing fine and/or coarse aggregates and discontinuous discrete fibers [4]. The use of fibers in building materials to improve their behavior is an old and intuitive concept. The practice of adding straw fibers to a mud in wall construction to create a composite with a better performance dates back to primitive times. In modern times, a wide range of engineering materials (including ceramics, plastics, cement, and gypsum products) incorporate fibers to enhance composite properties. There are numerous fiber types available for commercial and experimental use. It is possible to make several classifications among fiber types. Fibers can be divided into two groups: those with elastic moduli lower than the cement matrix; such as cellulose, nylon, and polypropylene and those with higher elastic moduli such as asbestos, glass, steel, and carbon [5]. Regarding fibers' usage in concrete, one may have Steel Fiber Reinforced Concrete (SFRC), Glass Fiber Reinforced Concrete (GFRC), Synthetic Fiber Reinforced Concrete (SNFRC) or Natural Fiber Reinforced Concrete (NFRC) [6].

Steel fibers extracted from used tires (RSFRC) is seen as a potential contestant for steel fiber reinforced concrete (SFRC). Such endeavor stems from the need to efficiently recycle scrap tires. This global challenge has even greater ramifications for a developing country like Ethiopia; where the environmental risks and the economic opportunities to a proper disposal of such waste are overlooked. Even though tire recycling is very much undermined in Ethiopian case, used tire is a very re-usable material. There are many applications for the re-use, recycling and recovery of used tires: from repair by retreading and re-grooving to creating recycled rubber sports, garbage containers and playground surfaces, to engineering uses such as fiber reinforced concrete production and landfill engineering. Many researches have been devoted to the use of steel fibers recovered from waste tires in concrete [7], [8], [9], [10], [11]. The concrete obtained by adding steel fibers has shown a satisfactory improvement of the fragile matrix, mostly in terms of post cracking behavior. In addition, it was indicated that the mechanical behavior of concrete reinforced with fibers extracted from used tires is comparable to that of conventional steel fiber reinforced concrete. As a consequence, recycled steel fiber reinforced concrete (RSFRC) appears to be a promising candidate for both structural and non-structural applications [10].

Section II of this paper gives an overview of tires and the recycling process. Section III discusses the experimental program in-depth, which includes the materials used, specimen preparation, and the testing procedure. Results and discussions are carried out in section IV; while the conclusions and suggestions for future study are forwarded in Section V.

## TIRES AND THE RECYCLING PROCESS

Tire is a thermoset material that contains cross linked molecules of Sulphur and other chemicals [13]. The general materials of construction of motor vehicle tires include natural rubber, synthetic rubber compounds, steel, polymeric fiber, fabric, and textiles; and fillers [14]. The materials and percentages used in tires are primarily a function of the type of vehicle and use, and the design preferences and proprietary formulas of the tire manufacturers. The construction of tires is relevant to the recycling of tire-derived materials, because a tire is an integrated mixture of materials that are a byproduct of rigorous thermal and adhesive processes. Recovery of marketable materials from tires therefore requires overcoming all of the aspects of integration that make tire a premium consumer product. Hence, tires can undergo several processes so that usable materials can be recycled. These processes may involve crumbling (reducing rubber compounds to a fine granular or powdered form), Cryogenic fragmentation (method of crumbing in which tires are shredded and cooled to below minus 80 degrees Celsius), Gasification (the process of converting a carbon containing material into a gas which can be used as fuel), Pyrolysis (an alternative to incineration of tires, which minimizes atmospheric emissions) or De-vulcanization (the process of breaking down the Sulphur cross-links in used tire rubber and leaving the original polymer chains unbroken so that the resultant de-vulcanized recyclate rubber can be used to produce high quality new rubber products) [12]. The method of pyrolysis has been adopted in this research.

Steel fibers recovered by the method of pyrolysis are known as Pyrolysed Recycled Steel Fiber (PRSF) and they are usually clean from rubber and contain carbon black on the surface. The tensile property is not affected in most cases and also they are not as such easy to cut. The steel component separated from rubber can be used as fibers in concrete. Researches, such as the one carried out at the University of Sheffield [15], demonstrated that steel fibers recovered from waste tires (RSF) can be successfully used to prepare FRC. In addition, it was indicated that the mechanical behavior of RSFRC is comparable to that of SFRC. Therefore, it can be presumed that the design models developed to evaluate the flexural resistance of conventional SFRC are also applicable for RSFRC [16].

## EXPERIMENTAL PROGRAM

A bead wire is retrieved from used tires using pyrolysis process. Three grades of RSFRC: C-25, C-40 and C-60 (cubic compressive strength of 25, 40, and 60 MPa, respectively) were produced to represent grades of Normal Strength, Intermediate Strength, and High Strength concrete, respectively. Comparison with plain concrete (the control mix) was made to capture the extent of improvements offered by the fiber reinforcing material. Investigation of the properties of the constituent material and preliminary characterization of the recovered steel fibers was made. Thereafter, the slump test and fresh density, as well as compressive strength and flexural tensile strength were evaluated for each mix.

## MATERIALS

### *A. CEMENT*

The cement used in all mixes was the locally manufactured Portland Pozzolana Cement (PPC) which was produced in accordance with EN 196 and BS 1370. Chemical composition, physical, mechanical and other characteristic of the cement, are presented in Table I

### B. AGGREGATES

The aggregates used were prepared to meet the gradation requirements of the Ethiopian Standard [17]. The coarse aggregate used for the preparation of the specimens was a crushed basaltic stone with maximum size of 19mm. Sieve analysis results and other characteristics of the aggregates are presented in Table II.

### C. WATER

Potable (tap) water supplied by the municipality was used for all concrete mixes.

### D. CHEMICAL ADMIXTURES

To obtain sufficient consistency in the RSFRC mixes; high performance, superplasticizing admixture with the commercial name Conplast SP 430 was used in all mixes. Conplast SP430 conforms with BSEN 934-2, BS 5075 Part 3 and with ASTM C494 as Type A and Type F, depending on dosage used. This superplasticizer has a specific gravity of 1.18, with an alkali content (Sulphonated naphthalene) of 55g. In this research work, 1% of admixture per cementitious material (i.e. 1.0 liter/100 kg) was used in all mixes.

*Table I. Chemical, Physical, and Mechanical Properties of Cement Used*

| No. | Chemical Properties | | No. | Physical and Mechanical Properties | |
|---|---|---|---|---|---|
| 1. | Material | Percentage (%) | 1. | Specific gravity (g/cm$^3$) | - |
| 1.1 | $SiO_2$ | 29.14 | 2. | Specific Surface Area (cm$^2$/g) | 2970 |
| 1.2 | $Al_2O_3$ | 5.91 | 3. | Initial Setting time (min) | 155 |
| 1.3 | CaO | 6.76 | 4. | Final Setting time (min) | 195 |
| 1.4 | MgO | 55.86 | 5. | Soundness (mm) | 1.25 |
| 1.5 | $SO_3$ | 1.52 | 6. | Compressive strength (N/mm$^2$) | |
| 1.6 | Sulfur content | 2.46 | 6.1 | 2nd day | 13.8 |
| 1.7 | Chloride content | 0.01 | 6.2 | 28th day | 36.6 |
| 2. | Loss on Ignition (LOI) | 2.31 | 7. | Heat of Hydration (kJ/kg) | |
| 3. | Pozzolana | 25.00 | 7.1 | 3rd day | 153 |
| | | | 7.2 | 28th day | 258 |

*Table II. Sieve analysis and physical characteristics of the aggregates*

| I. Sieve Analysis | | |
|---|---|---|
| Sieve Size | % Passing | |
| | Coarse Aggregate | Fine Aggregate |
| 19mm | 100.00 | |
| 12.5mm | 51.47 | |
| 9.5mm | 21.89 | |
| 4.75mm | 1.76 | 98.20 |
| 2.36mm | | 95.40 |
| 1.18mm | | 84.40 |
| 600µm | | 41.80 |
| 300µm | | 12.00 |
| 150µm | | 2.00 |
| Fineness Modulus | 2.25 | 2.66 |
| II. Physical Properties | | |
| Silt Content (%) | - | 1.20 |
| Moisture Content (%) | 1.37 | 2.04 |
| Absorption Capacity (%) | 4.38 | 1.72 |
| Bulk Specific Gravity | 2.79 | 2.41 |
| Bulk Specific Gravity (SSD Condition) | 2.84 | 2.51 |
| Apparent Specific Gravity | 2.93 | 2.69 |
| Crushing Value (%) | 17.83 | - |
| Los Angeles Abrasion (%) | 14.90 | - |

## RECYCLED STEEL FIBER

Since the diameter and tensile strength of steel fibers in a tire vary from one factory product to another, the tires used for the extraction of the steel fibers are all from the same source. The steel fibers were purchased from suppliers who primarily used the tires for heating sheet metals to produce different household utensils (Figure 1). The steel fiber used in this research was obtained by burning of waste tires (pyrolysis process). The steel fibers were undamaged as the tires were burnt at a relatively low temperature. They are clean from rubber and contain carbon black on the surface as shown in Figure 2.

Three types of steel fiber diameters are recovered depending on the type of cord used in the tires. These are steel cords twisted together into a core strand of 0.72 and0.77 mm as well as a bead wire with a diameter of 0.89 mm. Among these, only the later was used in this research in order to have a consistent diameter. This 0.89 mm diameter-bead wire was also cut at a length of 20mm, 40 mm, and 60mm (Figure 3 and 4) and was readied for mixing.

*Figure 1. Defective bead wires readied for the pyrolysis process*

*Figure 2. Steel fibers (bead wire) extracted from burnt tires*

*Figure 3. Cutting the steel fibers into the desired length*

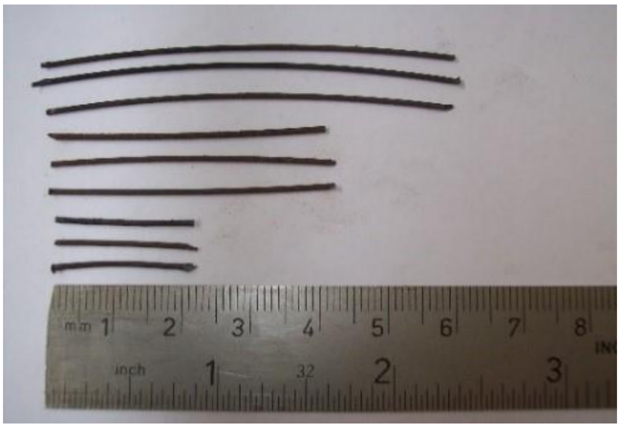


*Figure 4. The three lengths of steel fibers used in the mix*

Mechanical properties of steel fibers were evaluated by tensile tests on 10 randomly chosen samples. The test was performed both on the recovered and the virgin steel fiber for comparison purposes, and also in order to examine the effect of burning on the tensile strength. The tensile test was carried out by Testometric machine (M350-5kN) shown in Figure 5. Table III reports the values of breaking load, tensile strength, and elongation at break for both recovered steel fiber (RSF) and virgin steel fiber (VSF).

An average tensile strength of 970.2 MPa and 1892.6 MPa were found for the RSF and VSF, respectively. The tensile strength of the RSF has decreased nearly by half (48.7 %) from that of the VSF. The lower value is mainly due to the burning process. The test results obtained for the RSF is highly variable compared to the VSF, as the tires were burnt under uncontrolled temperature. However, the obtained results are in good agreement with experimental results reported in [16], where an average value of 1250 MPa was found for the RSF used. The results also satisfy ASTM A820 requirements [18], which set the minimum average tensile strength and the minimum tensile strength of the specimen to be 345 MPa and 310 MPa, respectively. Moreover, from the results reported in Table III, it is possible to deduce that, as far as tensile strength concerned, RSF are comparable to industrial steel fibers (ISF). Depending on the type of steel, production processes and shape, ISF may present tensile strength in the range of 300-2000 MPa [16].

*Figure 5. Testometric Machine for tensile strength of steel fiber*

*Table III. Tensile strength, breaking load, and elongation at break for RSF and VSF*

| Sample No. | Breaking Load (N) | | Tensile Strength (MPa) | | Elongation at Break (%) | |
|---|---|---|---|---|---|---|
| | RSF | VSF | RSF | VSF | RSF | VSF |
| 1 | 424.6 | 1156.1 | 682.5 | 1858.3 | 5.4 | 12.2 |
| 2 | 574.9 | 1148.5 | 924.1 | 1846.1 | 6.8 | 13 |
| 3 | 476.1 | 1146.9 | 765.2 | 1843.6 | 4.4 | 9.9 |
| 4 | 571.9 | 1146.9 | 919.3 | 1842.3 | 4.9 | 9.7 |
| 5 | 432 | 1154.5 | 694.5 | 1855.8 | 7.2 | 10.9 |
| 6 | 443.4 | 1134.2 | 712.8 | 1823.1 | 3.8 | 8.9 |
| 7 | 642.8 | 1261.6 | 1033.3 | 2027.9 | 4.6 | 9.4 |
| 8 | 1021.1 | 1252.9 | 1641.3 | 2013.9 | 6.3 | 12.2 |
| 9 | 862.7 | 1241.8 | 1386.7 | 1996.1 | 6.5 | 10.5 |
| 10 | 585.9 | 1131.6 | 941.8 | 1819 | 11.4 | 10.9 |
| Min. | 424.6 | 1131.6 | 682.5 | 1819 | 3.8 | 8.9 |
| Mean | 603.5 | 1177.4 | 970.2 | 1892.6 | 6.1 | 10.8 |
| Max | 1021.1 | 1261.6 | 1641.3 | 2027.9 | 11.4 | 13 |
| S.D. | 196.79 | 52.25 | 316.3 | 84.07 | 2.17 | 1.35 |

## MIX PROPORTIONS

The Department of Environment (DOE) mix design method was adopted to proportion the mixes. Three different grades of concrete were designed to give a slump value of 10-30 mm and a 28-day compressive strength of 25 MPa ("Mix Series I"), 40 MPa ("Mix Series II") and 60 MPa ("Mix Series III); with a water to cement ratio of 0.53, 0.42, and 0.33, respectively (Table IV). Plain concrete mixes were designated as "Control" mix in each series. For those mixes with fiber present, a volume fraction of 0.5%, 1.0%, and 1.5% of fibers, and a fiber length of 20mm, 40mm, and 60mm were used. Each of these mixes was designated to refer to the mix series, volume fraction, and fiber length respectively. For example; a concrete mix designated as $M_1V_{0.5}L_2$ shall be read as a sample obtained from Mix 1; with a fiber of volume-fraction 0.5%, and length 2cm.

## SPECIMEN PREPARATION

Initially, a certain amount of water for adjustment obtained from the mix design was added to the measured aggregates and left for a short while to bring the aggregates to the Saturated Surface Dry condition (SSD). The fine aggregate, coarse aggregate, and cement were dry mixed for about a minute. The fibers were added during the dry mix as a rainfall, very carefully in order to avoid balling effect. This was then followed by the addition of two third of the total mixing water. After two minutes of mixing, remaining mixing water together with superplasticizer was added. Mixing was ceased after four minutes for all mixes.

The specimens for the testing of mechanical properties in the hardened state were casted in two layers using appropriate molds, wet inside with a release agent and thereafter, placed on a vibration table. The vibrating procedure was executed in order to obtain a more homogeneous distribution of fibers. For each mix series, nine 150 mm cubes were casted. The molds were left to cure for 24 hours. Once hardened, the specimens were carefully demolded and placed in a curing room for 7, 28, and, 56 days for compressive strength tests, and 28 days for flexure tests at approximately 95±5% RH (Relative Humidity) and 22±2°C temperature.

*Table IV. Mix proportions for the three mix series*

| Mix Designation | Cement Quantity (kg/m$^3$) | W/C Ratio | Water (liter) | Fine Agg. (kg/m$^3$) | Coarse Agg. (kg/m$^3$) | Steel fiber (kg/m$^3$) | Admixture (l/m$^3$) |
|---|---|---|---|---|---|---|---|
| Mix Series I (C-25) | | | | | | | |
| Control-1 | 340 | 0.53 | 180 | 670 | 1270 | 0 | 3.4 |
| $M_1V_{0.5}L_2$ | 340 | 0.53 | 180 | 670 | 1270 | 39.3 | 3.4 |
| $M_1V_{0.5}L_4$ | | | | | | | |
| $M_1V_{0.5}L_6$ | | | | | | | |
| $M_1V_{1.0}L_2$ | 340 | 0.53 | 180 | 670 | 1270 | 78.6 | 3.4 |
| $M_1V_{1.0}L_4$ | | | | | | | |
| $M_1V_{1.0}L_6$ | | | | | | | |
| $M_1V_{1.5}L_2$ | 340 | 0.53 | 180 | 670 | 1270 | 117.9 | 3.4 |
| $M_1V_{1.5}L_4$ | | | | | | | |
| $M_1V_{1.5}L_6$ | | | | | | | |
| Mix Series II (C-40) | | | | | | | |
| Control-2 | 430 | 0.42 | 180 | 575 | 1250 | 0 | 4.3 |
| $M_2V_{0.5}L_2$ | 430 | 0.42 | 180 | 575 | 1250 | 39.3 | 4.3 |
| $M_2V_{0.5}L_4$ | | | | | | | |
| $M_2V_{0.5}L_6$ | | | | | | | |
| $M_2V_{1.0}L_2$ | 430 | 0.42 | 180 | 575 | 1250 | 78.6 | 4.3 |
| $M_2V_{1.0}L_4$ | | | | | | | |
| $M_2V_{1.0}L_6$ | | | | | | | |
| $M_2V_{1.5}L_2$ | 430 | 0.42 | 180 | 575 | 1250 | 117.9 | 4.3 |
| $M_2V_{1.5}L_4$ | | | | | | | |
| $M_2V_{1.5}L_6$ | | | | | | | |
| Mix Series III (C-60) | | | | | | | |
| Control-3 | 550 | 0.33 | 180 | 500 | 1193 | 0 | 5.5 |
| $M_3V_{0.5}L_2$ | 550 | 0.33 | 180 | 500 | 1193 | 39.3 | 5.5 |
| $M_3V_{0.5}L_4$ | | | | | | | |
| $M_3V_{0.5}L_6$ | | | | | | | |
| $M_3V_{1.0}L_2$ | 550 | 0.33 | 180 | 500 | 1193 | 78.6 | 5.5 |
| $M_3V_{1.0}L_4$ | | | | | | | |
| $M_3V_{1.0}L_6$ | | | | | | | |
| $M_3V_{1.5}L_2$ | 550 | 0.33 | 180 | 500 | 1193 | 117.9 | 5.5 |
| $M_3V_{1.5}L_4$ | | | | | | | |
| $M_3V_{1.5}L_6$ | | | | | | | |

## TESTING PROCEDURE

### TESTING OF FRESH CONCRETE

The workability of freshly mixed concrete is a measure of its ability to be mixed, handled, transported; and, most importantly, placed and consolidated with a minimal loss of homogeneity and minimal entrapped air [4]. In this regard, slump test, in accordance with the Ethiopian Standard [17] was performed for each mix in the fresh state to investigate workability.

## TESTING OF HARDENED CONCRETE

Compressive strength tests were carried out by an oil-pressure machine with a nominal capacity of 3000 kN. Dimension and weight of each specimen were accurately measured before testing. The 7, 28, and 56-days compressive strength of each mix were determined in accordance with the Ethiopian standard [17]. The load was applied at a constant rate of 0.442 MPa/s and the compressive strength was measured to the nearest two digits after a decimal. Average of the test results of three specimens belonging to a mix was accepted as a compressive strength of that mix for the testing day. Specimens were tested so that the direction of loading was orthogonal with the direction of casting.

Two-point loading was used to determine the flexural tensile strength. Average of the test results of two beam specimens belonging to a mix were accepted as the flexural tensile strength of that mix. Similar to the compressive strength test, the direction of loading was also orthogonal with the direction of casting.

## RESULTS AND DISCUSSION

### TEST RESULTS OF FRESH CONCRETE

### *SLUMP TEST*

The characteristics of RSFRC in its fresh state are influenced significantly by the aggregate content, fiber geometry and volume fraction. This was seen in the study as well. The slump values varied between 0-91mm. Further results, including the effect of volume-fraction of steel fiber reinforcement on the workability of concrete can be seen in Figure 6. Despite lowest slump value obtained, almost all mixes were workable, had even distribution of fibers without balling effect and responded well to mechanical vibration and could be placed and compacted without much effort. As a result of this it can be concluded that slump test provides little indication of either the workability or the ease with which RSFRC can be compacted. Since this test is inadequate and cannot distinguish the effects of fiber inclusion on the consistency of SFRC, as suggested by ACI code to obtain a more reliable measures of workability inverted slump cone test or Vebe test should be used.

### TEST RESULTS OF HARNDENED CONCRETE

### *COMPRESSIVE STRENGTH*

The mean 28-day compressive strength ($f_{comp,28}$) test results are shown in Table 5 and Figure 7. These results are accompanied by the standard deviation (SD) and the relative strength gain in percent (RSG-%) or loss as a mean of three tested samples, to that of the control mix.

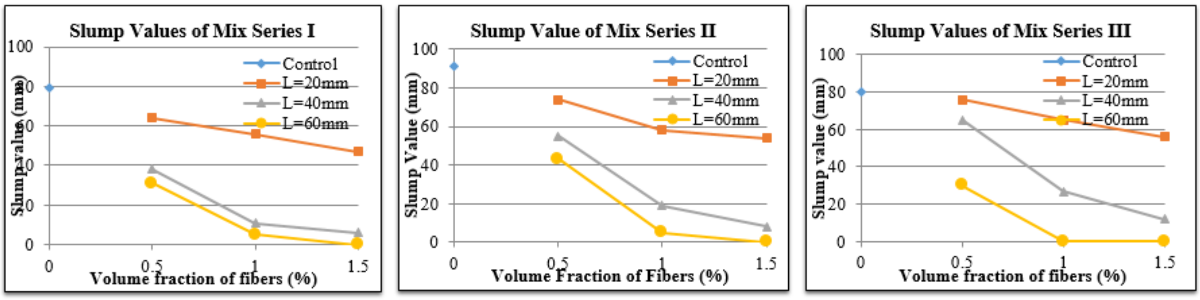


*Figure 6 Slump values for (a) Mix Series I, (b) Mix series II, and (c) Mix Series III*

As reported in Table V, the 28th day mean compressive strength for the plain control mix in Mix Series I was found to be 28.05 MPa. In this mix series, addition of steel fibers of different length and volume ranging from 0.5% to 1.5% has resulted varying results; ranging from 27.72 MPa to 31.37 MPa, with a maximum relative strength loss and gain of 1.17% and 11.77%, respectively. For this mix of concrete with a normal strength, fiber length of 4cm was seen to be the optimum for a superior relative strength gain (11.77%). Such a scenario can also be inferred if one aims to keep the volume-percentage of fibers constant. Albeit contending results in ($M_1V_{0.5}L_6$), a fiber length of 4cm can produce a better mix regarding compressive strength.

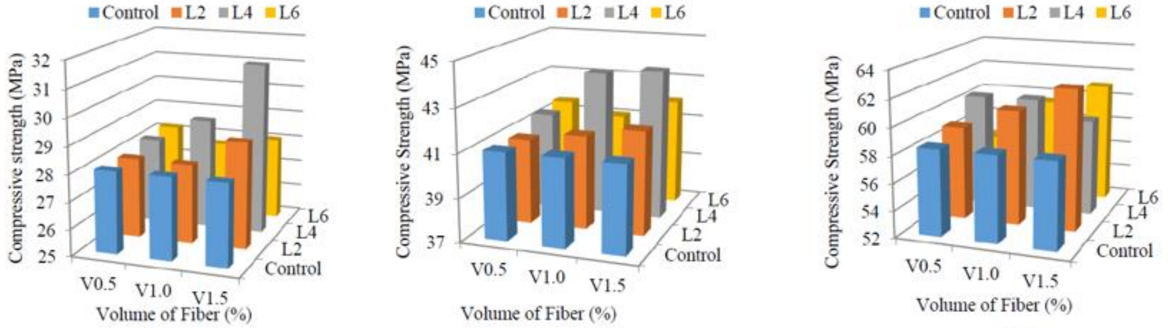
This is also true in “Mix-Series 2”; where the optimum amount of fiber length was found to be 4cm. Compressive strength values ranging from 40.92 to 43.94 MPa with a maximum relative strength loss and gain of 0.29% and 7.07% respectively, were obtained by inclusion of fibers of different length and volume. These values were obtained through comparison with mean compressive strength of the control plain mix; which was found to be 41.03 MPa.

*Table V 28-day mean compressive strength tests for the different mix series*

| Mix Series I | | | | Mix Series II | | | | Mix Series III | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Mix Designation | $f_{comp,28}$ (MPa) | SD | RSG (%) | Mix Designation | $f_{comp,28}$ (MPa) | SD | RSG (%) | Mix Designation | $f_{comp,28}$ (MPa) | SD | RSG (%) |
| Control-1 | 28.05 | 0.65 | | Control-2 | 41.03 | 0.67 | | Control-3 | 58.4 | 1.39 | |
| $M_1V_{0.5}L_2$ | 27.97 | 0.33 | -0.28 | $M_2V_{0.5}L_2$ | 40.92 | 0.12 | -0.29 | $M_3V_{0.5}L_2$ | 58.98 | 1.21 | 1 |
| $M_1V_{0.5}L_4$ | 28.2 | 0.58 | 0.54 | $M_2V_{0.5}L_4$ | 41.51 | 0.99 | 1.17 | $M_3V_{0.5}L_4$ | 60.45 | 0.77 | 3.51 |
| $M_1V_{0.5}L_6$ | 28.23 | 0.61 | 0.66 | $M_2V_{0.5}L_6$ | 41.58 | 0.59 | 1.33 | $M_3V_{0.5}L_6$ | 56.25 | 0.51 | -3.68 |
| $M_1V_{1.0}L_2$ | 27.94 | 0.79 | -0.4 | $M_2V_{1.0}L_2$ | 41.32 | 0.84 | 0.69 | $M_3V_{1.0}L_2$ | 60.56 | 2.2 | 3.7 |
| $M_1V_{1.0}L_4$ | 29.09 | 1.38 | 3.71 | $M_2V_{1.0}L_4$ | 43.66 | 0.86 | 6.39 | $M_3V_{1.0}L_4$ | 60.52 | 1.45 | 3.63 |
| $M_1V_{1.0}L_6$ | 27.72 | 0.42 | -1.17 | $M_2V_{1.0}L_6$ | 41.06 | 0.46 | 0.06 | $M_3V_{1.0}L_6$ | 59.5 | 0.61 | 1.88 |
| $M_1V_{1.5}L_2$ | 28.95 | 0.49 | 3.2 | $M_2V_{1.5}L_2$ | 41.78 | 0.5 | 1.82 | $M_3V_{1.5}L_2$ | 62.41 | 0.73 | 6.87 |
| $M_1V_{1.5}L_4$ | 31.35 | 0.32 | 11.77 | $M_2V_{1.5}L_4$ | 43.94 | 1.38 | 7.07 | $M_3V_{1.5}L_4$ | 59.17 | 0.45 | 1.31 |
| $M_1V_{1.5}L_6$ | 28.07 | 1.25 | 0.08 | $M_2V_{1.5}L_6$ | 41.97 | 0.48 | 2.27 | $M_3V_{1.5}L_6$ | 61.02 | 0.6 | 4.48 |

Hence, even though a direct relationship between aspect ratio, volume percentage of fibers, and compressive strength gain could not be mapped; it was evident that concrete mixes with the aspect ratio of 45 showed consistent strength improvements with the increase in fiber volume for normal and intermediate concrete mixes (Mix Series I and II).

The mean compressive strength of the plain control mix in mix series III; which was primarily designed for characteristic strength of 60 MPa at 28th day was found to be 58.40 MPa (2.7% lower than the characteristic strength). This was mainly due to the slower rate of early strength development of the type of cement used. However, the 56th day mean compressive strength value was 66.47 MPa with a relative strength gain of 10.78% to that of the characteristic strength. In this high-strength concrete mix series, aspect ratio of 22.47 produced a relative strength increment with increase in volume percentage. The highest relative-strength-gain (6.87%) was obtained by using a fiber length of 2cm and a volume of 1.5%. Several combinations of aspect ratios and volume percentages of fiber produced different results according to each mix series. Because the maximum observed strength gain did not exceed 4MPa (in Mix Series III); it is not advisable to target considerable improvements in compressive strength by steel fiber inclusion. If what is desired is a strength increase, it can be achieved through much easier and cheaper methods (e.g. lowering the w/c ratio, changing the cement type etc.).



(a) (b) (c)

*Figure 7 Compressive strength test results of (a) Mix Series I, (B) Mix Series II, and (c) Mix Series III.*

### *FLEXURAL STRENGTH*

Results for the mean 28-day flexural tensile strength (fflex,28), are shown in Figure 8. These results are further elaborated in Table VI, where the standard deviation (SD) of the specimens and the relative flexural strength gain in percent (RFSG-%) or loss to that of the control mix are shown.

The flexural tensile strength of the control plain mix in Mix Series I was found to be 6.18 MPa. Flexural tensile strength values ranging from 6.84 MPa to 13.71 MPa with a relative flexural tensile strength gain of 10.68 % to 121.84% were obtained by inclusion of fibers of different length and volume. Unlike the compressive strength, fiber inclusion did not reduce the flexural strength values. In this mix series; the highest flexural tensile strength was observed in those specimens having the lowest aspect ratio irrespective of fiber volume percentage. Such values were recorded at mixes $M_1V_{0.5}L_6$, $M_1V_{1.0}L_6$ and $M_1V_{1.5}L_6$; with a relative flexural tensile strength gains of 32.52%, 63.11%, and 121.84%, respectively.

In Mix Series II, the flexural tensile strength of the control mix is 8.34 MPa and where fiber is present; the tensile strength values ranged from 8.64 to 14.79 MPa. A relative flexural tensile strength-gain of 9.09% to 86.79% was registered by adding fibers of different volume and length to the concrete. Similar to that of the first mix series, an increase in length and volume of fibers has increased the flexural tensile strength.

The flexural tensile strength of the control mix in Mix Series III was 8.73 MPa. The minimum and maximum flexural tensile strength values were registered in $M_3V_{0.5}L_2$ and $M_3V_{1.5}L_6$, with values of 8.85 and 16.14 MPa and a relative flexural tensile strength-gain of 1.37% and 84.88%, respectively.

***Table VI 28-day mean flexural tensile strength tests for the different mix series***

| Mix Series I | | | | Mix Series II | | | | Mix Series III | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Mix Designation | $f_{flex,28}$ (MPa) | SD | RFSG % | Mix Designation | $f_{flex,28}$ (MPa) | SD | RFSG % | Mix Designation | $f_{flex,28}$ (MPa) | SD | RFSG % |
| Control-1 | 6.18 | 0.42 | | Control-2 | 7.72 | 0.25 | | Control-3 | 8.73 | 0.13 | |
| $M_1V_{0.5}L_2$ | 6.84 | 0.42 | 10.68 | $M_2V_{0.5}L_2$ | 8.34 | 0.42 | 5.30 | $M_3V_{0.5}L_2$ | 8.85 | 0.13 | 1.37 |
| $M_1V_{0.5}L_4$ | 6.96 | 0.25 | 12.62 | $M_2V_{0.5}L_4$ | 8.64 | 0.59 | 9.09 | $M_3V_{0.5}L_4$ | 9.09 | 0.21 | 4.12 |
| $M_1V_{0.5}L_6$ | 8.19 | 1.57 | 32.52 | $M_2V_{0.5}L_6$ | 9.24 | 0.76 | 16.67 | $M_3V_{0.5}L_6$ | 9.21 | 0.81 | 5.50 |
| $M_1V_{1.0}L_2$ | 7.17 | 0.13 | 16.02 | $M_2V_{1.0}L_2$ | 8.46 | 0.17 | 6.82 | $M_3V_{1.0}L_2$ | 9.30 | 0.17 | 6.53 |
| $M_1V_{1.0}L_4$ | 7.89 | 0.38 | 27.67 | $M_2V_{1.0}L_4$ | 9.6 | 0.76 | 21.21 | $M_3V_{1.0}L_4$ | 12.0 | 1.01 | 37.46 |
| $M_1V_{1.0}L_6$ | 10.08 | 1.61 | 63.11 | $M_2V_{1.0}L_6$ | 12.57 | 1.99 | 58.71 | $M_3V_{1.0}L_6$ | 12.84 | 0.34 | 47.08 |
| $M_1V_{1.5}L_2$ | 8.07 | 0.72 | 30.58 | $M_2V_{1.5}L_2$ | 8.7 | 0.17 | 9.85 | $M_3V_{1.5}L_2$ | 11.37 | 0.21 | 30.24 |
| $M_1V_{1.5}L_4$ | 8.64 | 0.42 | 39.81 | $M_2V_{1.5}L_4$ | 9.6 | 0.76 | 21.21 | $M_3V_{1.5}L_4$ | 13.53 | 3.18 | 54.98 |
| $M_1V_{1.5}L_6$ | 13.71 | 0.72 | 121.84 | $M_2V_{1.5}L_6$ | 14.79 | 0.04 | 86.79 | $M_3V_{1.5}L_6$ | 16.14 | 2.63 | 84.88 |

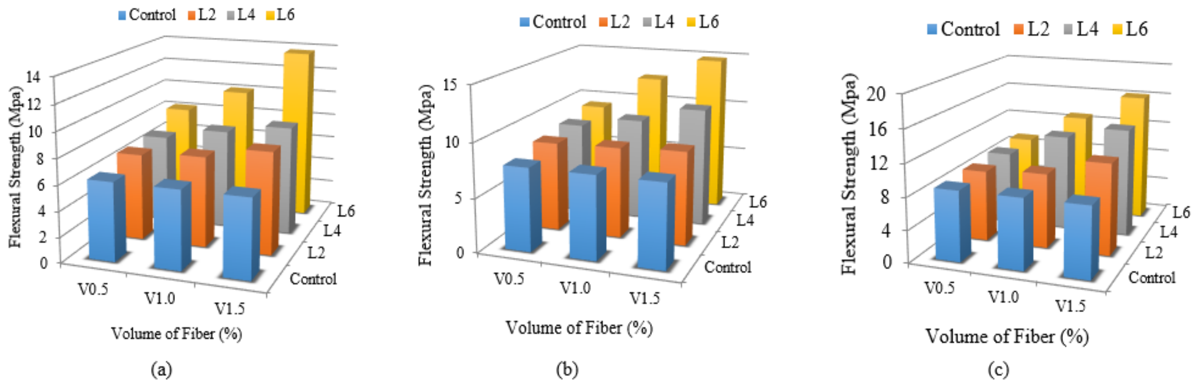


***Figure 8 Flexural tensile strength tests of (a) Mix Series I, (B) Mix Series II, and (c) Mix Series III***

From the test results it can be noted that lowest values of tensile strength were obtained in those mixes incorporating smaller length and volume of fibers, whereas, highest values were recorded for those mixes with higher aspect ratio and volume of fibers. This can be explained by the fact that failure in flexure for steel fiber reinforced concrete is mainly due to fiber pull out. As a result, when the fiber length and volume increases the peak flexural strength required to bring the samples to failure will definitely increase resulting higher flexural tensile strength. This increase in flexural tensile strength is prominent in normal strength concrete mixes (Mix Series I), where a relative increase of up to 121% was observed. Compared to the other fiber lengths, the relative flexural strength gain by 20mm fiber length is not as such appreciable. This is because of the fiber's lower length: the strength required to pull out the fiber from the concrete matrix will certainly be lower than the other fiber lengths.

## CONCLUSION AND FUTURE WORK

In this research, the experimental work carried out to evaluate the fresh and hardened properties of SFRC made with fibers extracted from used tires is studied. The conclusions drawn are on the basis of results obtained by slump, compression, and flexural tensile strength tests.

The mean tensile strength of the steel fibers recovered from used tire is lower than the virgin steel fiber (VSF) nearly by half (48.7%) and the test results recorded for the individual samples are highly variable due to the uncontrolled burning temperature used to recover them. However, the obtained results are in good conformity with the experimental results reported by other researchers and meet the requirements specified by ASTM 820. From the test results obtained it is also possible to deduce that, as far as tensile strength is concerned, the steel fibers recovered from used tires are comparable to industrial steel fibers (ISF).

Regarding the concrete mix, the RSFRC appeared to be relatively stiff and unworkable without the presence of the superplasticizer. The materials tend to "hang together" and resist movement compared to the control mixes. The incorporation of steel fibers strongly affected the workability of the fresh concrete. The test results indicated that as the volume of fraction increases the workability tends to decrease significantly.

A relative compressive strength loss and gain ranging from 0.28-3.68% and 0.08-11.77%, respectively, was obtained by introducing fibers of different length and volume to the concrete. From the results acquired it is possible to deduce that it is unlikely to achieve considerable improvements in compressive strength by steel fiber inclusion and the ultimate strength is only slightly affected by the presence of steel fibers. If what is desired is a strength increase, it is clearly much easier (and much cheaper) simply to redesign the plain concrete mix, primarily by reducing the w/c ratio and by changing the cement type.

Fiber inclusion of all lengths and volume fractions resulted in substantial increase in flexural tensile strength values. A similar pattern was exhibited in all mix series with regard to increment in flexural tensile strength when both the fiber length and volume of fibers increased. Compared to the other fiber lengths the relative flexural tensile strength gain by 20mm fiber length is not as such appreciable due to its lower aspect ratio. Utilization of 1.5% fiber volume and 60mm fiber length is found to be more efficient on flexural tensile strength of all mix series.

Further research shall consist in-depth characterization of the mechanical properties (such as flexural toughness and impact resistance) of hardened fiber reinforced concrete. Evaluation of the performance of specimens reinforced with the conventional industrial steel fibers and virgin steel fibers recovered from used tires is another possible continuation of this study. The use of SFRC to replace the minimum reinforcement recommended on ground slab for shrinkage and temperature, as well as development of rational design procedures to incorporate the properties of SFRC to replace stirrups provided for shear in load carrying beams are also some of the few promising prospects for extending this research.

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