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Tire Waste Steel Fiber in Reinforced Self-Compacting Concrete

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The accumulation of waste tires leads to environmental degradation caused by uncontrolled dumping in landfills, which are prone to fire and emit harmful gases like carcinogens. Reusing this as reinforcement to self-compacting concrete (SCC) is an alternative way to address the issue. For over a decade, SCC emerged in the construction industry due to its enhanced mechanical properties and capacity to self-consolidate on its own. However, there is still limited literature describing the behavior of SCC with tire waste steel fiber (TWSF). This study provides an overview of the extraction, quantification, geometric characterization, surface characterization, and application of TWSF to self-compacting concrete to determine workability and the compressive strength of SCC with TWSF. A total of five mixes were prepared, including the control noted as SCC without fiber and SCC with TWSF, with fiber content ranging from 0.7 %, 1 %, 2 %, and 3 %. The fresh properties were evaluated using the European Federation for Specialist Construction Chemicals and Concrete (EFNARC) standards such as slump flow test, T500, L-Box, and wet sieving or GTM Screen Stability Test. In addition, the compressive strength was determined after 28 days. The investigation reveals that these fibers can be retrieved in three ways: manually cutting the tire's edge, using a specialized machine to pluck the fibers, or incinerating them. It was projected that 4.85 - 7.16 x 10^5 t of TWSF might be generated annually. The result of the inclusion of TWSF in SCC does not significantly affect the workability. However, there is a reduction in the passing ability of about 11.713 % and 186.75 % for GTM screen stability, but all mixes are still within the acceptable ranges specified on the EFNARC standard. In contrast, the results reveal that adding 3 % TWSF to SCC enhances compressive by 31 %, which might be due to the fiber's uneven surface, increasing the bond between the fiber and concrete. As a result, the TWSF can be utilized to strengthen the SCC and fully applied in the construction industry. Additionally, it is advantageous to combine TWSF with SCC to extend its life resulting in lower carbon emissions produced during the production processes.

1. Introduction

The global tire recycling sector accounts for over 1.6 - 1.7 x 10^9 new tires each year, whereas around 1 x 10^9 are generated as a waste, and 1 x 10^8 only go to the recycling industry (Goldstein Market Intelligence, 2020). The tires are designed and made extensively with numerous complex procedures, rendering them indestructible and making recycling very difficult. It was typically composed of 26 % fillers, 14 % antioxidants, antiozonants, and curing systems, 19 % are natural rubber, 24 % synthetic polymers, 12 % steel beads, and 4 % are textile (U.S. Tire Manufacturers Association, 2021). The accumulation of waste tires has become the world's growing problem because uncontrolled dumping into landfills and junkyards degrades the environment by releasing chemicals into the air, ground, and water. Tires are highly flammable materials and can release harmful gases such as carcinogens, zinc oxide, dioxins, sulfur dioxide, fine particulate matter (PM2.5), and polynuclear aromatic hydrocarbons (Downard et al., 2015). Furthermore, diseases including encephalitis and dengue fever have been documented in the vicinity of pile waste tires, which act as mosquito breeding grounds (Reschner, 2003). This issue attracts the attention of numerous researchers, industries, and professionals to control the growing dilemma on waste management and protest nature and people. Researchers later found that tire

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rubbers can be used to replace aggregates in concrete, and TWSF can be used as an additive or reinforcement to concrete in replacement to manufactured steel fiber (MSF). Steel fiber is considered to have the most significant favorable impact on concrete. Based on the study by Zhang et al. (2020), when the MSF content increases from 0.5 % to 2.0 % by volume, the compressive strengths increase about 4 - 24 %. The inclusion of fiber in concrete prolongs its serviceability, reducing the carbon emission brought by the continuous production of cement and the transportation of constituent materials (Adesina, 2020).

However, according to Siraj (2009), using 1 % MSF automatically doubles the material cost of the concrete. Furthermore, steel fiber manufacturing contributes a more significant carbon emission that harms the environment. On the other hand, steel fiber derived from waste tires is a better substitute because it is more sustainable and fosters a circular economy. This fiber in concrete is a more economically viable solution to manage the waste tires and another method to extend the lifespan of the concrete. There are various studies carried out to investigate the effect of TWSF to concrete. The result exhibits that TWSF can be used as an alternative material to MSF. Based on Awolusi et al. (2020), this fiber increases the compressive and flexural strength by more than 10 % and 50 %. However, it can also increase the slump flow by more than 80 %, which can be controlled or avoided through careful mixing proportioning of aggregates, fibers, and other constituent materials. In order to address this issue, various researchers explored the combination of SCC and steel fiber to determine the effect of TWSF on SCC's workability and mechanical properties. SCC is popularly known for its flowability and self-consolidating capability without internal and external vibration. This type of concrete has a high fluidity allowing it to self-level, penetrate into complicated areas, and formworks and rebar orientations. Though it is more viscous, it has more strength and is more flexible than normal concrete, which is more demanded by today's building industry. This type of concrete has been used for decades and has become more efficient for structures with complicated shapes and rebar orientation. It was first developed by Professor Hajime Okamura, a Japanese professor, in 1988 (Okamura and Ouchi, 2003) and flourished in the European country in the succeeding years where the EFNARC representing concrete guidelines were produced (EFNARC 2005). Currently, few studies are carried out to study the performance of SCC with TWSF. On the other hand, some of it discovered improved mechanical characteristics. Based on the study by Simalti and Singh (2021), the maximum gain in compressive strength in Recycled Steel Fiber (RSF) with a 1.5 % volume fraction is 26.22 % at 90 days compared to the control mix, while for flexural and split tensile strength is 5.79 % and 28 %. Alternatively, Younis et al. (2019) discovered that the maximum amount of RSF 60 kg/m^3 in SCC increased compressive and flexural strength by 7.9 % and 60 %.

This study provides an overview of the extraction, quantification, geometric characterization, surface characterization, and application of TWSF to self-compacting concrete to determine workability and the compressive strength of SCC with TWSF. Additionally, this study roughly estimates the amount of carbon emission of the concrete. The fresh properties were evaluated using slump-flow, T500, L-box, and GTM screen stability. Meanwhile, a Universal Testing Machine (UTM) determined the compressive. Although the addition of TWSF to SCC is not new, relatively little research has been done to understand how SCC behaved when this fiber was included. The utilization of this fiber in SCC will aid in the reduction of environmental issues and harmful gas emissions linked with the manufacturing of steel fiber and Portland cement.

2. Materials and methods

The cementitious materials used to produce self-compacting concrete were Portland cement type 1. The binder used had a carbon footprint of approximately 30 % and had a very low shrinkage rate. The coarse crushed aggregates up to 3/8 inches (9.525 mm) in size were used in the study. Meanwhile, the maximum size of the fine aggregates employed is 4.74 mm. The sizing of the aggregates was based on EFNARC 2005 Guidelines. The study utilized a polycarboxylate ether-based superplasticizer (SP), Sika Viscocrete 4100, to increase the self-consolidating properties. This SP is a high-range water reducer and improved fresh concrete characteristics with a specific gravity of 1.05 ± 0.03 kg/L. The tire waste used in this research was collected from the local maker of pottery made from used tires originally acquired from junk and vulcanizing shops. The inner portion of the tire, considered a waste in the pottery maker, is sliced by a knife to exclude it from the entire used tire. In order to extract the tire steel beads, various methods may be employed to finally retrieve the steel beads from the tire rubber, including manual slicing, pulling by specialized equipment with a hook, and incineration. When considering the preservation of the mechanical and chemical properties of the steel fiber, it is suggested to use manual cutting of the edge of the tires to retrieve the tire beads to prevent any damage to the steel fiber.

In this study, the tire beads were retrieved manually by cutting the edge of the tires using a knife, gradually pulling the tire beads to reduce any alteration in the fiber properties, and selected the best steel beads. Following the extraction of the beads, particulate materials such as excess rubber and rust were removed using a steel brass and knife. Finally, the wires were cut using a cut-off machine to produce a TWSF. Presented in Figure 1a is the systematic extraction of TWSF. The tire beads were cut using a cutting disk. The extracted TWSF varies in length and diameter (0.9 mm or 1.2 mm) due to the type of waste tires and cutting process. That is why a total of 160 fibers were randomly picked to identify the distribution of fibers length. Figure 1b indicates the frequency distribution of fiber's where the length of 28.9-31.6 mm has the highest number. The TWSF density was 13,237.06 kg/m^3, as determined by the volume displacement method.

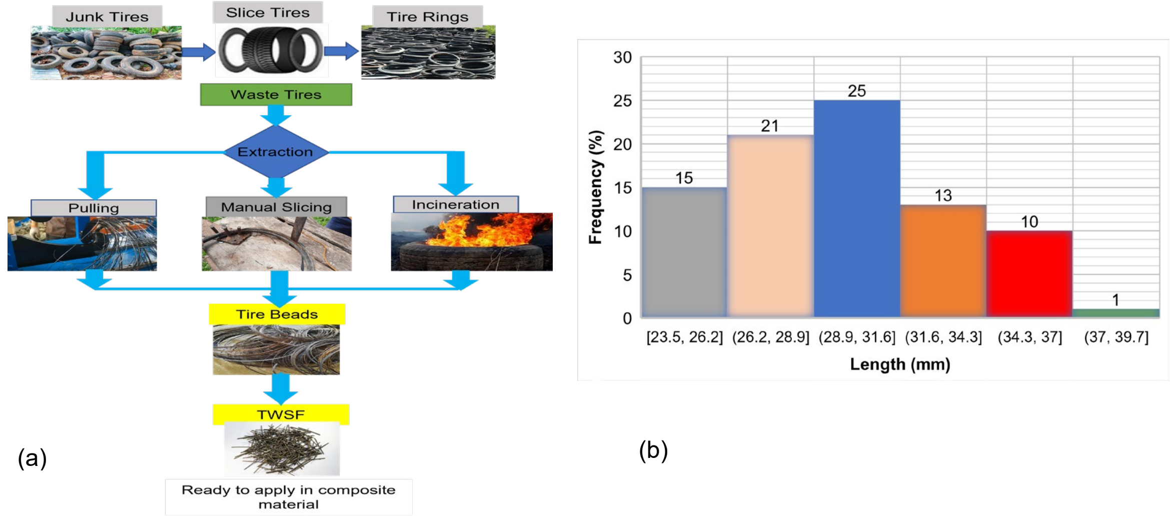

Figure 1: (a) Extraction Process of TWSF (b) TWSF Length Frequency Distribution

The quantity and diameter of TWSF differ in every type of vehicle. Presented in Table 1 is the amount of tire beads that can be collected per tire size ranging from 15 to 17 inches in diameter, which ranges from 0.310 to 0.960 kg. The tire bead diameter is also different for every type of tire, from 0.90 to 1.2 mm measured using digital vernier caliper. As depicted in Figure 2, the geometric and surface characterization was performed using an optical microscope. The end-to-end lengths of fibers were measured using a digital vernier caliper, and photos were analyzed using the free Image J program to quantify the fiber's diameter along its length. It was noticed that the selected sample varies in diameter, length, and surface due to the presence of unremoved rubbers, cutting procedures, and local corrosion. Based on the analysis, the average diameter of the selected TWSF is 1.11 mm and varies along the given length. This non-uniform surface is a suitable fiber property since this increases the bond when included in a composite material.

Table 1: Quantity of fibers per diameter of tires

Tire Diameter (in)	Quantity (kg)	TWSF diameter (mm)
15	0.31-0.34	0.90-1.2
17	0.57-0.96	1.2

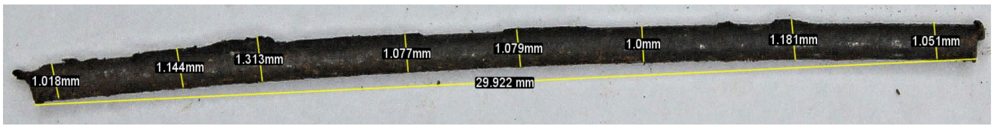

Figure 2: Surface texture, length, and diameter of TWSF

To determine the effect of a low dosage of TWSF on SCC, three distinct small fiber content percentages based on the weight of the binder: 0 %, 0.7 %, 1 %, 2 %, and 3 %, were included in the mixture. The percent fiber less than 1 % represents another data point to describe the effect and confirm if a very small amount of TWSF impacts the SCC's fresh and mechanical properties.

2.1 Concrete mixture proportioning

The concrete process commenced by mixing the sand, gravel, and cement within 2-3 minutes in a tilted position of about 30 degrees. The addition of 80 % of the water comes next, alongside with superplasticizer (Sika Viscocrete 4100). It was then mixed for 2-3 minutes before adding the fiber. Finally, the remaining water should be added and mixed for 5 minutes when the balling effect occurs. The total mixing time should be 15 minutes after the water is added. Additionally, the mix proportions used in the study are tabulated in Table 2, where SCC denotes for control mix, and TWSF-0.7, TWSF-1, TWSF-2, and TWSF-3 stand for mixtures with a varying fraction of tire waste steel fiber. There are three replicates for each specimen.

Table 2: Mixture Proportion of SCC + TWSF

Mix Id	Cement (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregates (kg/m^3)	Superplasticizer (%)	Water (L/m^3)	Fiber (%)
SCC	465	780	680	1.2	209.5	0
TWSF- 0.7	465	780	680	1.2	209.5	0.7
TWSF-1	465	780	680	1.2	209.5	1
TWSF-2	465	780	680	1.2	209.5	2
TWSF-3	465	780	680	1.2	209.5	3

2.2 Testing method

2.2.1 Fresh properties

The fresh properties, also known as rheological properties, were assessed using EFNARC 2005 criteria. Various properties were used to evaluate the fresh characteristics, including slump-flow using Abrams cone and T500 for filing ability, L-box for passing ability, and GTM screen stability for segregation resistance.

2.2.2 Compressive strength

The compressive strength test is carried out in a specimen that measures 200 mm in length and 100 mm in diameter after 28 days. The test was carried out according to ASTM C39 (2014) guidelines. The samples were tested on Shimadzu universal testing machine with a loading capacity of 2000 kN and a loading rate of 2.5 kN/s.

2.2.3 Carbon footprint

Indications in the literature link the carbon footprint of concrete to the unit volume of cement used and the compressive strength. Habert and Roussel (2009) developed an empirical relationship that estimates unit CO_2 emissions as a function of cylinder compressive strength, as shown in Eq(1).

$$kg\ of\ CO_2/\ m^3\ of\ concrete = \rho\sqrt{Class\ of\ concrete} \tag{1}$$

Where *p* denotes a constant of 46.5 $kgCO_2$, this equation is quite effective in estimating carbon emission, according to (Fantilli et al., 2019).

3. Results and discussion

3.1 Fresh concrete properties

The fresh properties test conducted on all mixes reveals that TWSF does not significantly affect the mixed workability when introduced to SCC. The slump flow spread for the five mixes shows no trend. The spread is observed to be within 700 mm to 775 mm, falling into the Slump flow 3 (SF3) category, which can be used for vertical construction with very congested reinforcement and irregular formworks. For the L-Box, the test shows a linear reduction in the passing ability of about 11.71 % when fiber content increased to 3 %. The ratio for SCC is recorded to be within 0.92 to 0.82. This ratio passed on the guidelines set in EFNARC 2005, where the suggested ratio should be equal to or greater than 0.80 demonstrating the concrete's capacity to flow freely even in the presence of intricate reinforcement without being clogged. Similarly, the GTM segregation test exhibits a decrease of 186.75 %, which means that the inclusion of fiber affects the segregation resistance of the fresh concrete. SCC had a value of 8 %, whereas TWSF- 0.7, TWSF-1, TWSF-2, and TWSF-3 had values of 7.8 %, 7.93 %, 4.40 %, and 2.79 %, respectively, indicating a linear reduction. These values fall on class SR2 (<15 % segregation resistance), which can be applied on vertical structures with >80 mm reinforcement gaps. When it comes to the time the mixture spreads or also known as T500, all mixes reach the 500 mm mark of the slump test plate without any segregation and bleeding. The viscosity of all mixes falls into the VS1/VF1 classification, which has been defined as having good filling ability even in tight reinforcement. The good effect of TWSF on SCC workability may be due to the small amount of fiber. Another reason might be the TWSF's stiffness which appears to be the reason for the maintained slump spread even after the fiber is added to the SCC. However, since the quantity of fiber is very low, further investigations are needed to confirm if the stiffness is the main reason for the excellent workability. Presented in Figure 3 are the fresh properties result.

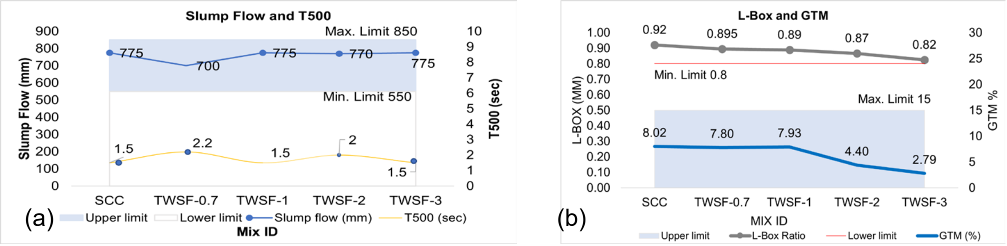

Figure 3: Fresh properties test result of SCC and TWSF mixes (a) Slump Flow and T500 (b) L-Box and GTM

3.2 Compressive strength

Generally, all mixtures obtain a significant increase in compressive strength after 28 days. Presented in Figure 4a is a box plot representation of the result of the compression strength test. The maximum compressive strength was observed for SCC with 3 % TWSF equaled 47.35 MPa. There is a linear increase with a maximum gain of 31 %. These emphasize the effectivity of fiber in increasing the strength as the fiber content increases even if the fiber dosage is lower than 15 % by weight of cement (0.5 % by volume of concrete), minimum amount of fiber in various studies. However, the box plot shows that the range of values for TWSF-0.7 and TWSF-2 experienced a wider spread among other mixes providing unstable values, implying that more specimens are needed to improve statistical results. Furthermore, aside from the increase in compressive strength of concrete due to the presence of fiber, the effect of fiber inclusion was clearly observed after the compression testing, as shown in Figures 4b and c. The control specimen breaks continuously as it reaches its maximum compressive strength. Contrary, the specimen with TWSF also breaks but is still connected and intact, proving the fiber's stitching ability. The increase of fiber content decreases the fracture pattern on the concrete. The variation in the fiber's length affects the fiber's crack-arresting behavior; the longer the fiber, the larger cracks can be stitched, while the shorter the fiber can arrest small cracks. Furthermore, the variation in diameter and surface due to the presence of unremoved rubber, cutting procedures, and local corrosion provides a stronger bond between the concrete and the fibers. Those properties might be the main reason for the enhancement in compressive strength.

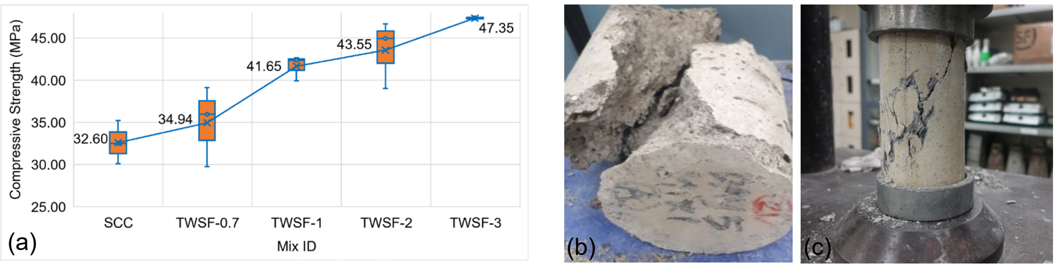

Figure 4: (a) Compressive strength at 28 days, Specimen after compression test (b) SCC (c) SCC + TWSF

3.3 Carbon footprint

Based on the rough estimate shown in Figure 5, the emission of the SCC with 32 MPa is equal to 265.50 $kgCO_2/m^{3,}$ while for concrete with 47 MPa, the emission increased up to 319.97 $kgCO_2/m^3$. However, it is noted that all constituents' materials except the fiber are constant, which depicts that all concrete samples have almost the same emission as the SCC. Hence, to increase the strength of the SCC alone equal to SCC with 3 %, TWSF means having the additional amount of binder, which might generate up to 319.97 $kgCO_2/m^3$. From this data, it can be estimated that having fiber on SCC can reduce emissions by 17 % while attaining higher compressive strength. This supplements the efficiency of adding fiber in reducing carbon emissions.

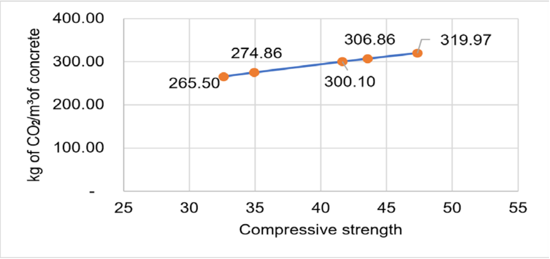

Figure 5: Carbon footprint Estimation based on compressive strength

4. Conclusions

The extraction of TWSF involves various procedures, the most efficient of which are manual cutting of edge, as opposed to the carbon-emitting incineration process. In addition, this procedure can preserve the fiber's stiffness, offering excellent strength to any composite in which it is incorporated. Globally, around 1 x 10^9 waste tires are produced annually, which may yield 4.85 - 7.16 x 10^5 t of TWSF, which is already sustainable to replace MSF. The variation in fiber surface due to unremoved rubber, extraction procedures, and local corrosion is favorable to increase the bond between the fiber and other composite material. Furthermore, the five concrete mixes meet the standard prescribed in EFNARC guidelines and are considered SCC. The inclusion of tire waste steel fiber in the self-compacting concrete has a favorable effect on the fresh and hardened properties. The fresh properties of all mixes show no significant changes in the filling ability and viscosity, whereas, for the passing ability, a decrease of 11.71 % was observed. Similarly, the segregation reduces as the fiber increases up to 186.75 %, which shows a good sign that TWSF is very effective to use in concrete without hampering the fresh properties of concrete. Meanwhile, the compressive strength increased by 31 %. The presence of TWSF can reduce the CO_2 emission by 17 %. From this information, it can be stated that TWSF can be fully utilized in self-compacting concrete because there are insignificant changes in fresh properties, and it enhances the compressive strength. In general, TWSF is a better material to fully use in the construction industry when considering strength, low-cost materials, sustainability, and being environmentally friendly.

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