Sustainable Structures
ISSN: 2789-3111 (Print); ISSN: 2789-312X (Online)
http://www.sustain-dpl.com/journal/sust
DOI: 10.54113/j.sust.2025.000064

ORIGINAL ARTICLE

Behavior of eco-friendly concrete reinforced with hybrid recycled fibers

Radwa Defalla Abdel Hafez1[a,*], Raghda Osama Abd-Al Ftah[b], Bassam Abdelsalam Abdelsalam[c], Ibrahim Saad Agwa[d]

[a,*]Civil and Architectural Constructions Department, Faculty of Technology and Education, Sohag University, Egypt. Radwa_abdalhafz@techedu.sohag.edu.eg

[b] Properties & Strength of Materials, Housing, and Building National Research Center, Egypt. eng.fahdhana@gmail.com.

[c] Department of Civil and Architectural Constructions, Faculty of Technology and Education, Suez University, P.O.Box: 43221, Suez, Egypt. bassam.abdelsalam@suezuniv.edu.eg

[d] Department of Civil and Architectural Constructions, Faculty of Technology and Education, Suez University, P.O.Box: 43221, Suez, Egypt. Ibrahim.agwa@suezuniv.edu.eg

* Corresponding: Radwa Defalla Abdel Hafez, Radwa_abdalhafz@techedu.sohag.edu.eg

Abstract: Recycling waste materials is a crucial strategy to reduce landfill disposal. The emission of greenhouse gases like methane and carbon dioxide into the atmosphere by landfills is well-known to be harmful to both people and the environment. Urgent action is required to address the pressing social and environmental issue of how to dispose of used tires. This study aimed to develop an eco-friendly concrete (EFC) mix that uses recycled aluminum cans and tire wire as reinforcement. Examine how EFC's workability and mechanical qualities are impacted by recycled fibers as well. Ten concrete mixes were experimented with in this research and divided into three groups. Three mixes contain 0.5%, 1%, and 2% of the aluminum can fibers (ACF), and three mixes include 0.5%, 1%, and 2% of tire wire fibers (TWF), three mixtures incorporate 0.5%, 1%, and 2% of hybrid recycled fibers (HRF) of both ACF and TWF, in addition, control mix. The workability and mechanical tests of eco-friendly concrete were investigated. The experimental results show that the recycled fiber volume fractions (RFVFs) are inversely proportional to the concrete workability. The recycled fibers don't reveal any significant effects on the compressive strength and the elastic modulus of concrete. All recycled fiber ratios improved the concrete behavior for tensile and flexural resistance. The development ratio of concrete mix containing 1% TWF reached 53.2% and 62.4% for tensile and flexural strengths, respectively. It can be noticed that the recycled fibers are enhancing the failure of the concrete matrix to become ductile failure rather than brittle behavior. However, the recycled fibers have arrested the development of cracks in the internal concrete structure.

Keywords: Aluminum can fiber (ACF), eco-friendly concrete (EFC), hybrid recycled fibers, mechanical behavior, tire wire fiber (TWF).

1 Introduction

The amount of waste produced has been rising over the last several decades. The amount of municipal solid waste generated annually will rise from its current level of around two billion metric tons by 2050, an anticipated 70% increase. Government trash treatment and disposal services that

Received: 24 August 2024; Received in revised form: 4 December 2024; Accepted: 28 January 2025

prioritize environmental sustainability are in high demand due to the exponential growth of rubbish generation in recent years [1, 2]. The environmental and economic challenges are taking priority for production and manufacturing processes, especially the concrete industry. Recycling waste materials into the concrete matrix is a very useful technique to save energy, keep natural resources, reduce costs, be environmentally friendly, and enhance concrete behavior [3, 4]. Concrete has a low resistance to cracking and is weak in tension but somewhat robust in compression. The fiber reinforced concrete (FRC), when used, has a wide range of uses as a reliable building material with better response characteristics than regular concrete [5-7]. Steel, polyester, glass, organic materials, and a variety of other materials in a wide range of shapes and sizes are just a few of the materials used to make fibers. Global energy consumption encourages researchers to recycle waste materials through concrete manufacturing processing [8-10]. Concrete's shear resistance and flexural bearing capacity are frequently enhanced by the addition of waste tire steel fibers (WTSF) [11, 12]. In previous studies, the researchers were interested in the fiber impacts on the concrete behavior and the failure performance and discovering the optimum fiber volume fractions [13, 14]. Concrete reinforced with WTSF has the ability to resist the shear performance rather than concrete without fibers [12, 15]. There are many advantages to using steel fibers (SF) in concrete production, as follows, reduce the steel reinforcement, construction duration, and labor costs [16, 17]. Moreover, the SF extracted from tire waste becomes a method for overcoming a problem or limitation in resisting the internal cracks in the concrete microstructure. Also, overcoming the structure weak to tensile and flexural behavior [18, 19]. It can be proved that the toughness and ductility of concrete will increase when the WTSF volume in the concrete matrix is at the maximum ratios, then reducing after this ratio. The previous investigation by Chen Le et al. [20] discovered that the inclusion of waste tire steel fibers decreased the compressive strength. Utilizing these wastes as fibers would assist in lessening the negative effects on the environment caused by the annual disposal of between 1 and 1.8 billion worn tires [21, 22]. As a result, research into and discussion of the characteristics of concrete containing both steel and waste tire fibers. The efficiency of fiber hybridization in altering the cementation material's properties has already been covered in earlier studies [23, 24]. Four waste products were used in concrete by Murali et al. (2012) [25] at a dosage of 1% of the total weight of concrete as fibers: lathe debris, soft drink bottle tops, empty trash tins, and waste tire steel fibers from workshops. According to the findings, adding waste tire steel fibers boosts concrete's compressive strength by 41.25% more than using regular concrete. However, the strength of the split tensile has improved by 40.87%. In addition, when waste material from soft drink bottle caps is included, the flexural strength rises by 25.88%. In conclusion, the authors only used three tests: compressive, split tensile, and flexural strengths, and one mixed percentage. Towards achieving the efficiency of concrete behavior, Ravinder (2016) [26] conducted an experimental study on recycling soda soft drink cans after being treated and cut to be a reinforced fiber in a concrete matrix. The fiber volume fractions (FVFs) mean the fiber ratio from the concrete volume, which was 0%, 0.5%, 1.0%, and 1.5%. There is a reduction in compressive strength by the ratio of 8.6%, corresponding to the FVFs of 1.5%. However, the proportions of 1.5% FVFs increase the tensile strength to 6% compared to concrete without fibers. The spiral shape of recycling soft drink cans' fiber may be the main reason for the reduction of the compressive result and a few enhancements of the tensile behavior. The two most important batching requirements for describing fiber are volume fraction and aspect ratio [27, 28]. The behavior of concrete, especially mechanical performance, was controlled by the ratio of length to diameter (L/D) of fiber. The L/D that ranges between 10 to 150 becomes a better performance of concrete. The FVF is the secondary factor that affects concrete behavior by adding the fibers from the concrete volume [29, 30]. Some studies suggest that 1% of the concrete volume should be made of fibers; any higher additions reduce the concrete strengths, but only for low-modulus fibers [7, 9, 31].

The fiber volume contents have been selected according to the recommendations of the previous related studies that not more than 2% by concrete volume. Although increasing fibers improve the tensile and flexural behaviors, the compressive strength was negatively effected by increasing fiber contents by more than 1% by concrete volume. The primary aim of the study is to combine industrial waste, such as steel fibers from tire waste, with aluminum fibers from cans waste to a degree ranging from 0% to 2%. In addition, it produces ecologically friendly, long-lasting concrete with improved mechanical characteristics using recycled solid industrial waste. An additional critical undertaking is the identification of the best component combinations for green fiber-reinforced concrete.

2 Research Significance

Energy consumption is high due to the large amount of electricity required for producing the primary aluminum process. Therefore, the carbon footprint of primary aluminum, which may vary from 4 to 20 kg CO_2e/Kg, is partly determined by the carbon intensity of the electricity generation used for smelting [32]. Among engineering materials, steel is both the most popular and widely used. Additionally, it ranks first in terms of greenhouse gas emissions. Traditional steelmaking processes release around 2.2 metric tons of carbon dioxide gas for every metric ton of steel produced. By 2050, the steel sector is expected to generate more anthropogenic emissions than any other process industry, thanks to a 25-30% increase in output [33].

This study interests the viability of recycling leftover aluminum cans and tire wires as a sustainable reinforcing fiber to produce eco-friendly concrete (EFC), while lowering the energy absorption associated with the use of synthetic conventional fibers. Aluminum can fiber (ACF) and tire wire fiber (TWF) were gathered from Sohag City, Egypt. This investigation aimed to study the behavior of concrete containing ACF, TWF, and hybrid recycled fibers. Hybrid recycled fibers (HRF) mean a combination of ACF and TWF. The recycled fibers were used by volume up to 2% fiber volume fractions (FVFs). The workability and mechanical behavior of EFC were carried out.

3 Experimental work

In addition to the control mix, nine different EFC mixtures were intended for this investigation. The stronger concrete mixtures were made by using recycled fibers to improve the EFC's behavior.

3.1 Materials

The cement type CEM I with grade 42.5N was employed. ASTM C150-07 was followed for conducting cement tests [34], and the chemical compositions of cement are tabulated in **Table 1**.

Before being utilized as a fiber for concrete, the collected aluminum can and tire wire waste had to be cleansed to remove dirt and other contaminants from their surface. Each recycled ACF and TWF was dried at room temperature after cleaning. **Fig. 1** displays the use of scrap wire from aluminum cans and tires as a fiber in the concrete matrix. TWF was extracted from tire waste and executed with an aspect ratio of 62.5, whereas ACF was made from waste from soft drink cans, cleaned, and cut into a 2.5 × 25 mm cross-section. To enhance the EFC behavior, recycled FVFs were used at concentrations of 0.5, 1, and 2 % by volume of concrete. In terms of specific gravities, ACF came in at 2.7 and TWF at 6.9.

(a) Aluminum can fibers (b) Tire wire fiber

Fig. 1. Fiber used

Natural siliceous sand was the fine aggregate employed in this experimental work. This sand had a specific gravity of 2.66 and had a 1680 kg/m^3 unit weight. The coarse aggregate in this experiment, the dolomite has been used as a coarse aggregate with a particle size of 20 mm and 2.68 specific gravity. The aggregates conformed with the standard specifications [35].

Performance super-plasticizer (SP) admixes were used to enhance the concrete workability.

Viscocrete-3425 (ASTM-C- 494 Types G and F) has a specific gravity of 1.08 and is especially well-used to enhance concrete workability, reduce water content, and get high early strength [36].

Table 1. Chemical compositions of cement (% by weight)

CaO	Fe_2O_3	Al_2O_3	SiO_2	MgO	SO_3	Na_2O	K_2O	LOI
62.52	3.81	6.47	21.12	2.28	2.13	0.87	0.78	1.64

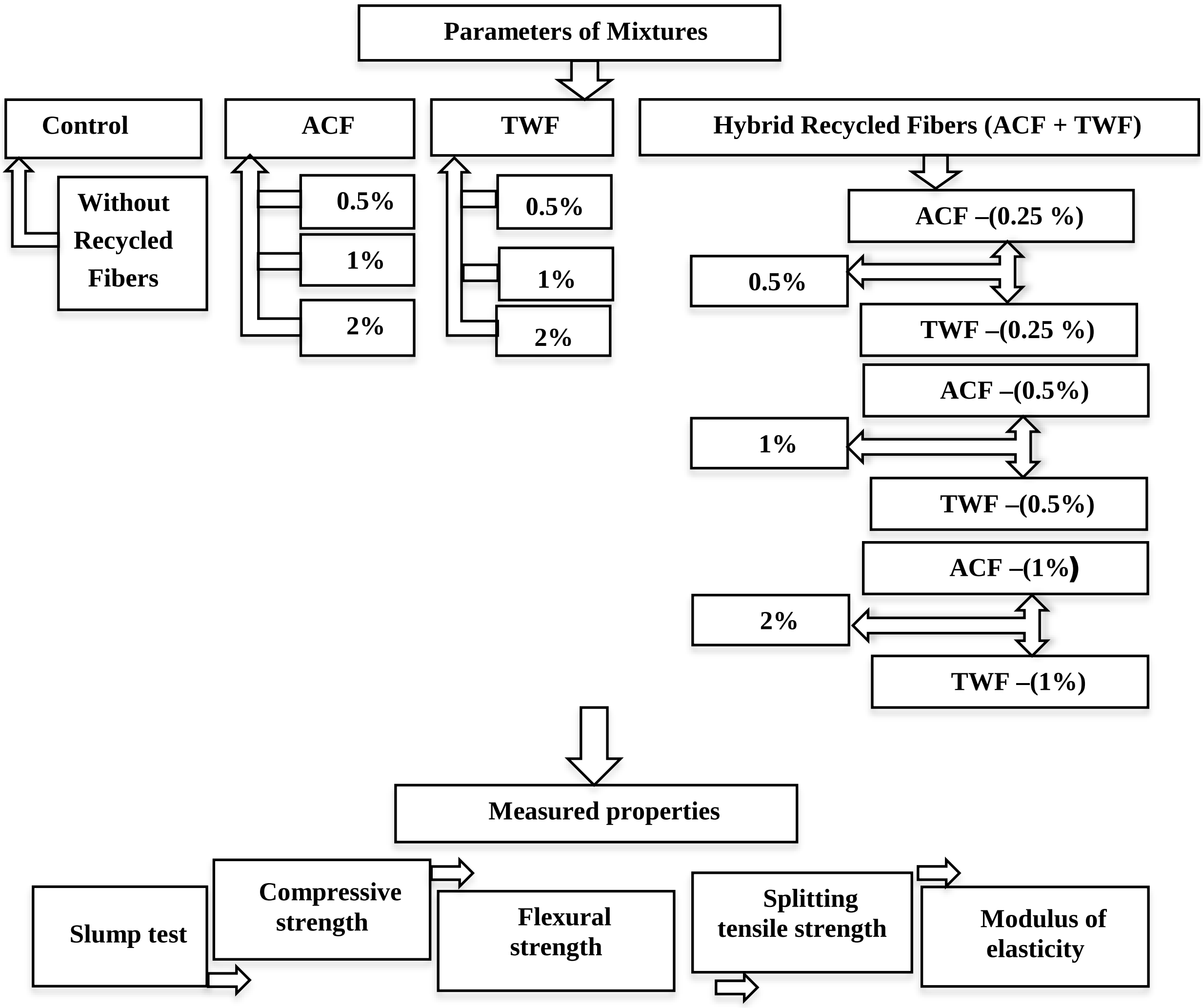


Fig. 2. Schematic diagram of experimental details

3.2 Mixing procedure

The control mixture was designed to be moderately strong. The EFC mixes that use recycled fibers may be grouped into three distinct types. The first group includes three matrixes that include FVFs with different amounts of ACF:0.5%, 1%, and 2%. The second group contains the three mixtures using TWF by 0.5%, 1%, and 2% FVFs. The third group involves three mixes with HRF at concentrations of 0.5% (0.25% ACF + 0.25% TWF), 1% (0.5% ACF + 0.5% TWF), and 2% (1% ACF + 1% TWF). **Fig. 2** displays the experimental schematic flowchart. The ratio of fine to coarse aggregate was 1:1.5, and the constant weight of the cement was 400 kg/m^3. The super-plasticizer made approximately 2% of the weight of the cement. The water-to-cement ratio was 0.4. **Table 2** shows the mixture proportions of EFC reinforcing with recycled fibers. The mixing procedures were carried out as follows. First, 3 minutes were spent mixing natural sand with coarse aggregates (saturated surface dry). Next, add the components of cement and recycled fiber, then mix for an additional 3 minutes. After that, add water and super-plasticizer and stir for 5 minutes before casting into the forms.

3.3 Testing procedure

The EFC mixtures' qualities were assessed in both fresh and hardened states. The slump test was done following ASTM specifications [37]. The compressive of EFC mixes was experimented with. According to [38], a compression test was conducted on a cubic form of 150 mm on the seventh and twenty-eighth days (See **Table 2**). After 28 days, an indirect tension test was conducted on cylinder moulds 150 × 300 mm by ASTM standards [39]. Prism samples with a cross-sectional of 100 × 100 mm and span of 500 mm were cast to a flexural test conforms with [40]. On the 28th day, the elasticity modulus of specimens of cylinders 150×300 mm was calculated according to ASTM C469/C469M [41].

Table 2. Mix proportion of eco-friendly concrete (EFC) (kg/m^3)

	Mix ID	Cement	Aggregate		Recycled Fibers		SP	Water
			Fine	Coarse	ACF	TWF		
	MC	400	751.1	1126.7	0	0	8	160
G1	M1-0.5%ACF	400	751.1	1126.7	13.5	0	8	160
	M2-1%ACF	400	751.1	1126.7	27.0	0	8	160
	M3-2%ACF	400	751.1	1126.7	54.0	0	8	160
G2	M4-0.5%TWF	400	751.1	1126.7	0	34.5	8	160
	M5-1% TWF	400	751.1	1126.7	0	69.0	8	160
	M6-2% TWF	400	751.1	1126.7	0	138.0	8	160
G3	M7-0.5%HRF	400	751.1	1126.7	6.3	17.3	8	160
	M8-1%HRF	400	751.1	1126.7	13.5	34.5	8	160
	M9-2%HRF	400	751.1	1126.7	27.0	69.0	8	160

ACF: Aluminum Cans Fibers; TWF: Tire Wire Fibers; HRF: Hybrid Recycled Fibers; SP: Super-plasticizer

4 Results and discussion

Fresh and hardened tests for EFC mixtures resulted, discussed, and analyzed in this study. Fresh properties such as the slump test are a guide to knowing the workability performance of EFC and to understanding the effects of using recycled fibers (ACF, TWF, and HRF) with different ratios. On the other hand, the hardened behavior of concrete, such as compressive, splitting tensile, and flexural strengths, in addition to modulus of elasticity, were studied and resulted in **Table 3**.

Table 3. Experimental behavior results of the eco-friendly concrete (EFC)

Mix ID		Slump (mm)	Compressive strength (MPa)		Splitting tensile strength (MPa)	Flexural strength (MPa)	Modulus of elasticity (GPa)
			7 days	28 days			
	MC	135	30.6	42.4	4.55	4.60	26.9
G1	M1-0.5% ACF	131	31.1	43.9	5.12	5.50	30.5
	M2-1% ACF	129	28.8	39.2	6.30	6.70	29.1
	M3-2% ACF	127	25.1	35.5	6.42	6.81	27.9
G2	M4-0.5%TWF	129.5	34.2	46.3	5.87	6.22	32.7
	M5-1% TWF	126.5	30.1	42.6	6.97	7.47	31.3
	M6-2% TWF	126	29.4	40.5	7.18	8.10	30.5
G3	M7-0.5% HRF	130	32.5	44.4	5.60	5.80	31.7
	M8-1% HRF	127.5	29.3	40.7	6.60	7.10	30.9
	M9-2% HRF	126	27.9	38.3	6.82	7.42	28.5

4.1 Fresh properties

4.1.1 Slump test

The slump test of concrete mixtures plays the main role in evaluating the workability and flowability performance. As shown in **Fig. 3**, all combinations with various ACF and TWF had slumps that varied from 126 mm to 135 mm. Although the fraction of fibers increased, the concrete workability decreased. Slump values for mixes MC, M1-0.5%ACF, M2-1%ACF, and M3-2%ACF were 135, 131, 129, and 127 mm, respectively. On the other hand, slump values for mixes M4-0.5%TWF, M5-1%TWF, and M6-2%TWF were 129.5, 126.5, and 126 mm, respectively. Due to the fiber shape and low water absorption, the EFC mixes with ACF had slightly higher workability than those mixes with TWF and HRF [11, 42, 43]. When comparing the control mix MC to one that included recycled fiber at a high level of 2% FVFs, the decreased ratio of concrete workability reached 7%. Because the concrete matrix and fibers experience internal friction in a fresh state, it is not surprising that EFC mixes reinforced with recycled fibers have poor workability. Two more major components that influence the workability of concrete are the FVFs and the shape of the fibers. The super-plasticizer had little to no impact on increasing the mix's workability [44, 45].

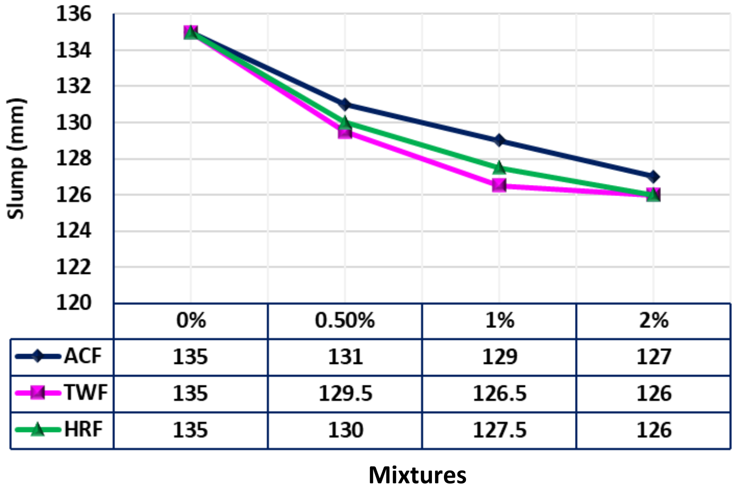


Fig. 3. Slump results for concrete mixtures

4.2 Hardened properties

4.2.1 Compressive strength

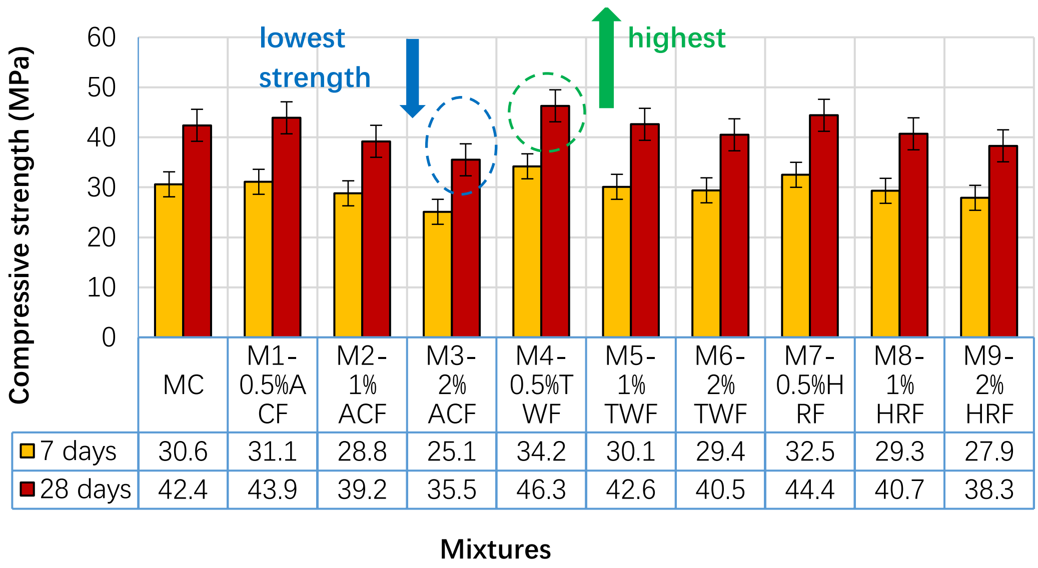


Fig. 4. Compressive strength for concrete mixtures

At 7 and 28 days, the compressive strength was evaluated of concrete mixtures reinforced with recycled fibers. The experimental results of the compressive strength at 7 and 28 days are shown in **Fig. 4**. The compressive strengths at 28 days of the concrete include ACF with 0.5%, 1%, and 2% FVFs were 43.9, 39.2, and 35.5 MPa, respectively. The increment ratio was 3.5% when using 0.5% ACF from the control mix MC, but the compressive strengths were decreased when increasing ACF to more than 0.5% FVFs. The reduction in the compressive strength may be due to the engineering shape and size of ACF and its weak bonding with concrete paste. On the other hand, the use of TWF with ratios 0.5% developed the compressive strength up to 9.2% compared to the control matrix; then the 2% TWF reduced the compressive strength to 4.5% from concrete without recycled fibers. **Fig.5** shows the effects of recycled fibers ACF, TWF, and HRF with different FVFs on the compressive strength of EFC.

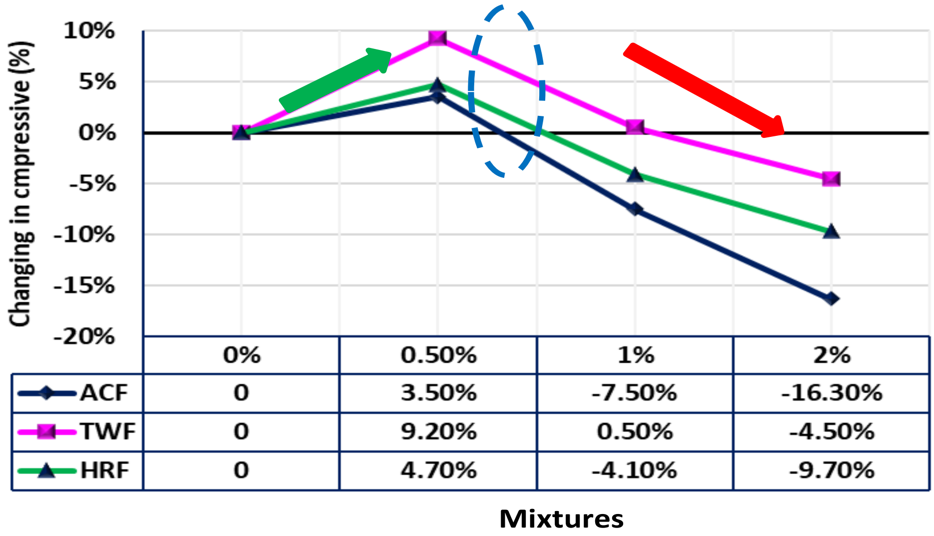


Fig. 5. Changing in compressive strength at 28 days for concrete mixtures

(a) TWF (inside the concrete)

(b) ACF (inside the concrete)

(c) MC

(d) M2-1% ACF

(e) M5-1% TWF

(f) M8-1% HRF

Fig. 6. Failure behavior of concrete cubes after the compression test

All strengths (mechanical characteristics) considerably decreased when the fiber ratio addition was higher than 1% [46-49]. Furthermore, the recycled TWF enhanced the transitional zone between gravel and sand; due to TWF's high strength, cement paste, and jelly are capable of effectively covering all of the constituents of the concrete mix [50, 51]. The concrete contained 0.5%, 1%, and 2% HRF recorded a compressive strength at 28 days of 44.4, 40.7, and 38.3 MPa, respectively. The HRF represents that the strength was better than those of the control mix and concrete with ACF at any FVF level. Whereas the improvement ratios of mixes with 0.5%HRF, 1% HRF, and 2% HRF were 1.14%, 3.83%, and 7.89%, compared to 0.5% ACF, 1% ACF, and 2% ACF, correspondingly. Depending on the composite amount of each ACF and TWF added to the concrete mixtures, the compressive strength increased at 0.5% FVFs.

Compared to concrete without fibers, the fibers generated a robust failure plane [52-55]. However, the recycled fibers ACF, TWF, and HRF at every FVF enhanced the failure behavior of

EFC under the compression test, as presented in **Fig. 6**. The concrete with recycled fibers revealed ductile failure than the concrete without fibers [56-58].

Glavind and Aare [59] investigated the effects of synthetic fibers like polypropylene and steel (PPF and SF) on the performance of ordinary and high-strength concretes. The synthetic PPF and SF were placed by volume to the mix with 0.6% and 1.0% FVFs. One concrete mix contained a hybrid fiber (50%:50%) that consisted of PPF and SF with 1% FVFs. This technique can be proven to increase the compressive strength of normal-strength concrete. Kazemian and Shafei [60] demonstrated that the low FVFs could improve concrete behavior under mechanical tests. Qiang Fu et al. [61] experimented with the combination of PPF and basalt fiber (BF) stirred with the concrete mix and then studied its impacts on the dynamic compressive performance. The strain rate during the dynamic compressive test was raised with an increase in the FVFs of hybrid PPF and BF from 0.1% to 0.2%. On the contrary, the strain rate decreased as concrete strength increased at the same FVFs [61]. The concrete resistance increased with an increase in the fiber volume from the concrete volume. The concrete reinforced with SF displayed better performance comparable to concrete reinforced with sisal fiber, but the concrete reinforced with hybrid fibers SF beside PPF by 1.5% FVFs is better than those [62].

4.2.2 Splitting tensile strength

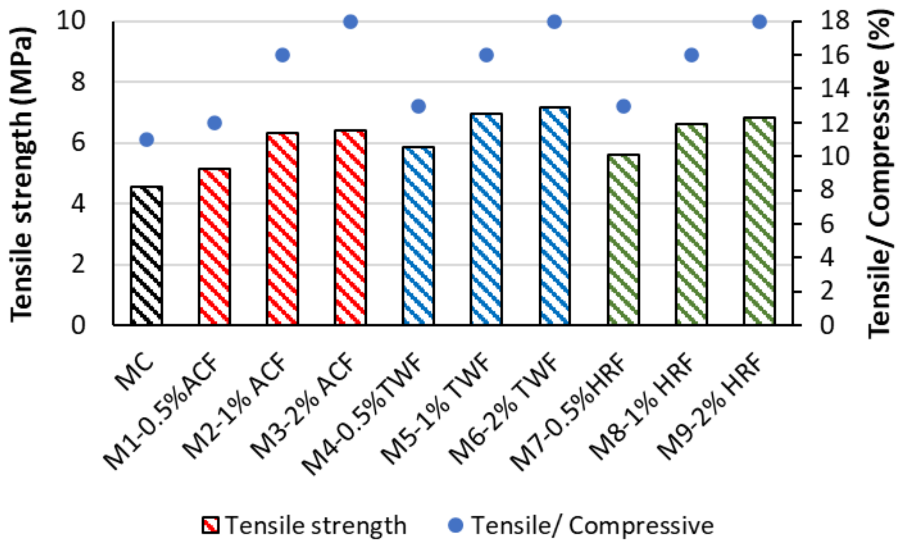


Fig. 7. Splitting tensile strength and ratio of Tensile/ Compressive for EFC mixes

Testing for splitting tensile was done using typical cylinder moulds. The test results after curing time at 28 days are shown in **Fig. 7**. The concrete matrix incorporated recycled fibers by 0.5%, 1%, and 2% ACF exhibited significant ascending of splitting tensile strength with 5.12, 6.30, and 6.42 MPa when compared to concrete without recycled fibers (4.55 MPa). Compared to MC, the tensile strength of concrete mixes with TWF percentages increased gradually and peaked at 29%, 53.2%, and 57.8% for 0.5%, 1%, and 2% FVFs, respectively. The recycled fibers TWF with 0.5%, 1%, and 2% FVFs have higher tensile strength by 14.6%, 10.6%, and 11.8% than the same FVFs of ACF, whereas the tensile strength was increased with an increase in ACF by 12.5%, 38.5%, and 41.1% for 0.5%, 1%, and 2% FVFs, respectively. The splitting tensile strength started to decrease gradually as the fiber content increased at a maximum value, which was about more than 4% FVFs [63, 64]. The tensile strength of concrete mixes is affected by using 0.5%, 1%, and 2% HRF and being more effective than control mix and ACF mixes. The improvement ratios were 23.1%, 45.1%, and 49.9%, compared to the control mix, and were 9.4%, 4.8%, and 6.2% when compared to the same FVFs of ACF concrete mixes. It can be concluded that ACF's smooth external surface and specific surface area are probably to reasonably weak bonding strength with cement paste compared to TWF. As a result of their ideal bond with the concrete mixture, the 2% TWF displayed the highest effectiveness in tensile strength compared with fiber volume in other concrete mixes. As shown in **Fig. 8**, the increasing rate of tensile strength decreased when using FVFs more than 1% by concrete volume. The tensile/compressive ratios of concrete mixes, including recycled fibers ranged between 11% and 18%, whereas the mix M3-2% ACF has the highest tensile/compressive strength ratio, which reached about 18%, as presented in **Fig. 7**. In comparison to ACF mixes and the control mix, the TWF mixes showed a superior mode of failure due to the better bonding of concrete matrix with recycled fibers than control specimen, which the cylinder was split up after tensile test conducted, as shown in **Fig. 9**.

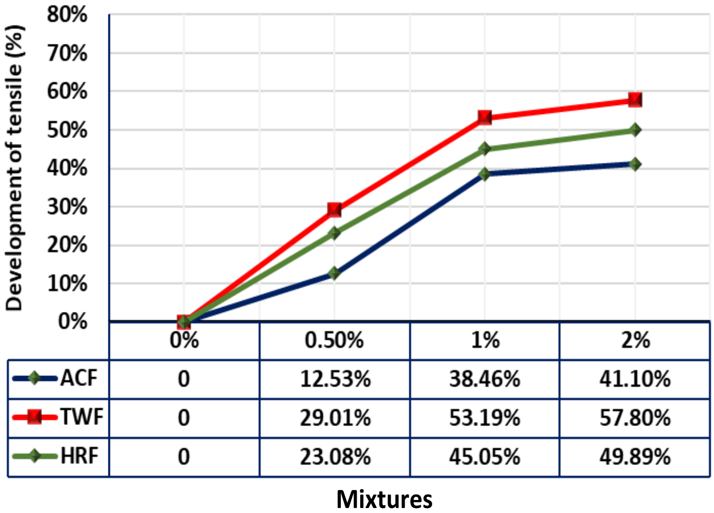


Fig. 8. Development of tensile strength for concrete mixtures

All mixes had an increment ratio between 12.5% and 57.8%. These outcomes can be attributed to the TWF structure's EFC mix bonding being stronger than the control concrete [65, 66]. While cylinders with fibers demonstrated a successful form of failure without separating the cylinder, the control cylinder without fibers fractured into two half-cylinders, see **Fig. 9**. When exposed to tension, mixtures containing TWF and ACF strengthened the connection between the two cylinders and created thin cracks. The results of [67-69] are consistent with the failure shapes caused by the tensile strength for all combinations.

(a) Without fiber (b) with fiber

Fig. 9. Failure mode for concrete with and without recycled fiber

4.2.3 Flexural strength

The experimental results of the flexural test for mixes M1-0.5% ACF, M2-1% ACF, and M3-2% ACF were 5.50, 6.70, and 6.81 MPa, respectively, whilst for concrete mixes M4-0.5% TWF, M5-1% TWF, and M6-2% TWF were 6.22, 7.47, and 8.10 MPa, respectively. The flexural strength of concrete using TWF is significantly increased by 35.2%, 62.4%, and 76.1% for different FVFs when compared to the control mix, as approached in **Fig. 10**. The recycled TWF exhibited higher development in the flexural behavior of EFC than the recycled ACF, which reached 76.1% for TWF corresponding to 48% for ACF at the same level of FVFs. The bond between TWF and concrete may be to blame for these outcomes, which referred to the fiber size and shape as having a significant role in enhancing the bond with the concrete matrix [70-73]. On the other hand, the utilization of HRF with 0.5%, 1%, and 2% FVFs revealed a better flexural strength when compared to concrete with

ACF and without fibers. The rising ratios were 26.1%, 54.4%, and 61.3% from the control concrete mix and were 3.9%, 6.2%, and 2.2%, comparable with the 0.5%, 1%, and 2% ACF mixes, respectively. As can be seen in **Fig. 11**, the recycled fibers TWF and HRF present the linearity of increasing the flexural strength with increasing FVFs up to 2% from concrete volume [74-77].

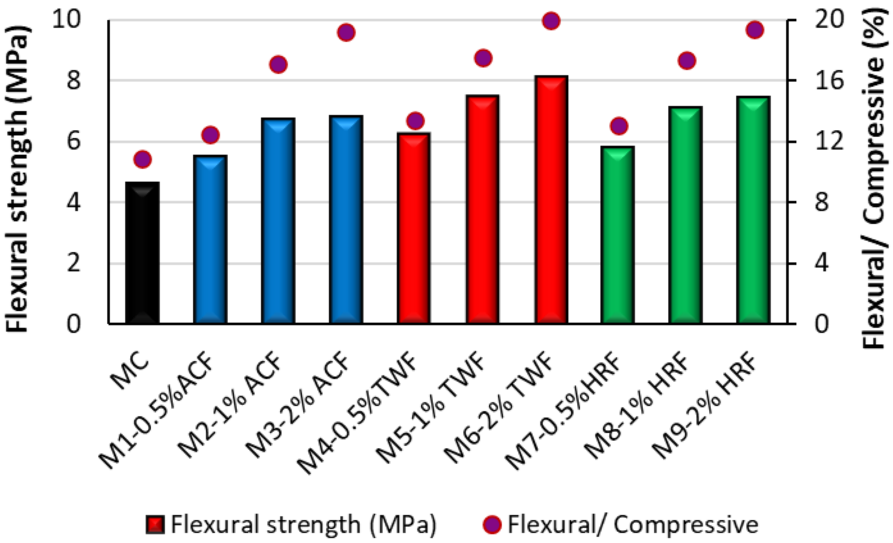


Fig. 10. Flexural strength and Flexural / Compressive (%) for all mixtures

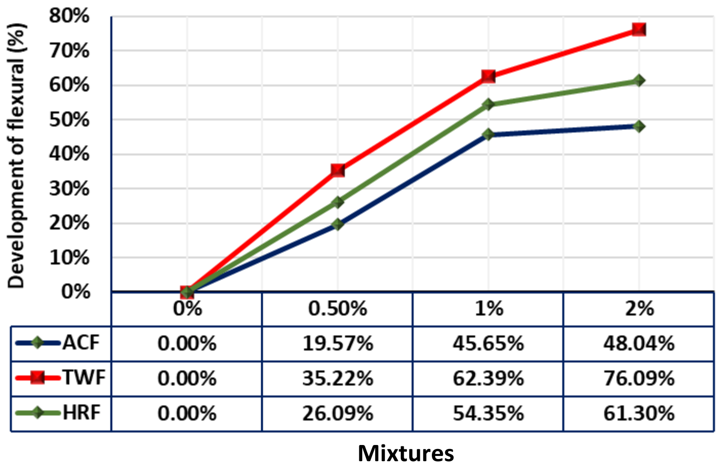
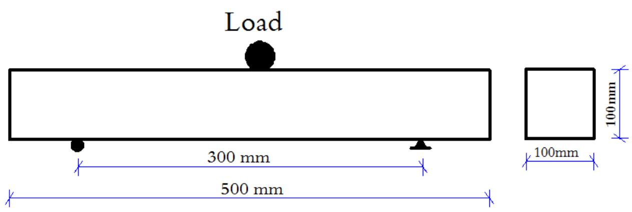


Fig. 11. Development of flexural strength for concrete mixtures

The flexural to compressive strength ratios (*F*/*C*) and flexural strengths of EFC mixes with and without fibers are shown in **Fig. 11**. The *F*/*C* ratios of mixtures including 0.5%, 1%, and 2% ACF were 12.5%, 17.1%, and 19.2%, respectively, whereas mixtures containing TWF with FVFs of 0.5%, 1%, and 2% TWF were 13.4%, 17.5%, and 20%, respectively. In addition, the *F*/*C* ratios for concrete with 0.5%, 1%, and 2% HRF achieved 13.1%, 17.4%, and 19.4%, correspondingly. The amount or kind of fiber has almost no impact on the F/C ratio, See **Fig.12**. However, the addition of recycled fibers ACF, TWF, and HRF clearly reduced the brittle behavior of EFC and attenuated the failure behavior of prisms during the flexural test; this conclusion is consistent with references [78-81].



a) Flexural strength test on machine test

b) Non-separation of the sample(with fiber) c) Separation of the sample(without fiber)

Fig. 12. Development of flexural strength for concrete mixtures

4.2.4 Modulus of elasticity

The elastic modulus of EFC with and without recycled fibers was measured to analyze the deformation behavior. The results were contrasted with the control mix MC. According to **Fig. 13**, the modulus of elasticity of EFC mixtures with ACF, TWF, and HRF exhibits a similar upward trend as the compressive strength trend by roughly 8.2%, 16.4%, and 14.9%, respectively, until the peak is reached at a ratio of 1% FVFs by concrete volume [82-84]. After reaching its peak, the curve started to increase as the fiber ratio continued to rise until a ratio of 1 %. Concrete mixtures with recycled fibers were positively impacted on the elastic modulus of concrete. The reason for the elasticity modulus transition at 0.5% fiber may refer to the internal hair fractures surrounding the recycled fiber structure, which can lead to poor adhesion between the recycled fiber and concrete matrix [85-87] and thought to be the cause of the low modulus of elasticity of EFC combinations with varied 1% and 2% of ACF and TWF. Due to the high compressive capacity of TWF mixes, the concretes exhibit better elasticity than concrete mixes with ACF [79, 88]. The weak influence of ACF on the modulus of elasticity may be the result of the ACF structure's inflection, which results in weak interfacing transaction zones between the ACF and cement paste [89-91]. The Young's modulus of EFC with recycled TWF was higher than the concrete with other recycled fibers ACF and HRF. The concrete mixes contained HRF show a good modulus of elasticity comparable with concrete using ACF at different recycled fiber ratios, which recorded 31.7, 30.9, and 28.5 GPa. The increment ratios were 3.9%, 6.2%, and 2.2%, respectively, for FVFs of 0.5%, 1%, and 2%.

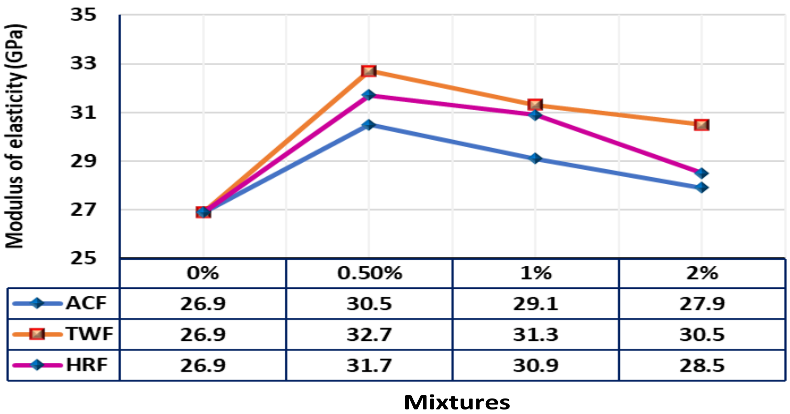


Fig. 13. Static modulus of elasticity (GPa) for all mixtures

5 Conclusions

A safe and efficient approach is proposed in this study to recycle the wastes like aluminum can and tire wire as fibers for use in the concrete industry:

Recycling waste into the concrete matrix is a very useful technique for saving energy, conserving natural resources, reducing costs, being eco-friendly, and improving the behavior of concrete.

Due to the shape of the fiber and not absorbing water, EFC mixes with recycled fibers ACF had a higher workability than those utilizing TWF and HRF; the superplasticizer had little effect on increasing the mix's workability.

The compressive strength of the concrete continuously increases until it reaches its maximum strength with 0.5% FVFs of each recycled fiber, which recorded 43.9, 46.3, and 44.4 MPa for mixes with ACF, TWF, and HRF, respectively. Once the FVFs of recycled fibers were more than 0.5%, the strength decreased up to 16.3%, 4.5%, and 9.7% for concrete using ACF, TWF, and HRF, correspondingly.

The TWF particularly enhances the transitional zone between gravel and sand. Due to TWF having a high strength, jelly is capable of effectively covering all the constituents of the concrete mix.

For the mixture M5-2% TWF, the split tensile strength increased gradually and peaked at 57.8% of concrete without recycled fibers. Also, the mixture includes 2% ACF and has a higher tensile strength than the control mix by 41.1%. Whereas the mix M9-2% HRF achieved a 49.9% increase in tensile strength compared to MC.

The smooth external surface of ACF is probably to blame for the weak bonding compared to TWF due to its size and shape and its ideal bond with the concrete mixture.

Flexural strength rises by 48%, 76.1%, and 61.3% for 2% FVFs of ACF, TWF, and HRF, respectively. However, the addition of recycled fibers ACF, TWF, and HRF clearly reduced the brittle behavior of EFC and attenuated the failure behavior of prisms during the flexural test.

The modulus of elasticity of EFC mixtures with ACF, TWF, and HRF exhibits a similar upward trend as the compressive strength trend by roughly 8.2%, 16.4%, and 14.9%, respectively, until the peak is reached at a ratio of 1% FVFs by concrete volume.

All recycled fibers with 0.5%, 1%, and 2% FVFs developed concrete's tensile and flexural behavior. Especially TWF is the best-recycled fiber compared with other recycled fibers. There is a positive relationship between recycled fiber FVFs and the tensile properties and the flexural strength of concrete.

Funding Statement

The author(s) received no specific funding for this study.

CRediT authorship contribution statement

Radwa Defalla Abdel Hafez: Conceptualization, Methodology, and Writing – original. **Raghda Osama Abd-Al Ftah:** Conceptualization, Methodology, and Writing – original draft. **Bassam Abdelsalam Abdelsalam:** Investigation, Writing – original draft, and write – review & editing. **Ibrahim Saad Agwa:** Supervise, Investigation, Writing – original draft and write – review & editing.

Conflicts of Interest

The authors declare that they have no conflicts of interest to report regarding the present study.

Data Availability Statement

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

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