



RESEARCH ARTICLE

Influence of Locally Sourced Recycled Tire Steel Fibers and Waste Aluminum on the Strength and Absorption Properties of Fiber-Reinforced Concrete

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ABSTRACT

The study looks at how adding locally sourced recycled tire steel fibers (SF) and waste aluminum (WAL) affects the strength and absorption capacities of fiber-reinforced concrete (FRC). FRC is a popular choice in sustainable construction because it improves strength, durability, and cracks resistance. However, the performance of FRC is influenced by fiber type, volume, and distribution. In this research, three SF volume fractions (0.5%, 1.25%, and 2%) and 10% WAL as a partial replacement for fine aggregate were incorporated into eight concrete mixes, including plain concrete, SF-enhanced concrete with varying fiber contents, WAL concrete, and combined SF-WAL mixes. Workability, density, compressive strength, splitting tensile strength, and water absorption were determined after 28 days by the experimental program. Mechanical properties were found to increase by 1.25% SF, but strength decreased when the SF content was raised to 2%, as it caused fiber clumping. The experiment showed that when WAL is used alone, its effect is to boost workability, but it lowers the strength in compression and tension. Still, using 1.25% SF together with 10% WAL brought about a good balance, preserving the concrete's strength. Using a moderate amount of SF limited water absorption, but when the concrete contained WAL, water absorption went up somewhat. According to this study, adding recycled SF and WAL to concrete improves its strength and supports sustainable construction.

Keywords: Fiber-reinforced concrete, steel fibers, waste aluminum, compressive strength, splitting tensile strength

BACKGROUND

Most structures are built using concrete, made up of cement, water, gravel or coarse aggregate, sand, and fine aggregate, as well as additional substances known as admixtures or additives. The world uses around 25 gigatons of concrete in a single year.^[1] Even so, the extraction process for concrete is damaging to the environment, mainly because it relies on aggregates and exploitation of natural resources.^[2,3] Moreover, concrete's inherent limitation is its low tensile strength, leading to the formation of cracks under tensile stress, which compromises the structural integrity of concrete structures.^[4,5] To mitigate these issues, researchers have explored incorporating industrial waste and recycled materials as substitutes for traditional concrete components.^[6]

Advanced construction composite materials like fiber-reinforced concrete (FRC) have drawn a lot of interest in contemporary construction because of their improved mechanical qualities, adaptability, and durability.^[7] In order to enhance the concrete's performance in its hardened states, different fibers-such as steel, glass, synthetic polymers, or natural materials-are randomly distributed and mixed into the concrete.^[8] Fibers affect the performance of concrete

by improving its strength, toughness, resistance to cracks, energy absorption, the ability to still function under tension after a crack, burst failure capacity and resistance to impact. As concrete fractures easily when in tension but is strong in compression, experts decided to add reinforcement and make FRC to solve these issues. The stiffness of concrete often leads to cracks due to stress which could impact the future safety of the building structure. When fibers are present in the concrete, they provide support and keep cracks from expanding too far. Therefore, FRC components are more resistant to changes in heat, shocks, cycling and cracks.^[9-11]

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For these reasons, FRC systems are being used in many parts of the world. It is now widely used for things such as precast concrete, industrial floors, pavements, bridges, tunnels and more.^[8,11,12] Properties such as size and shape of the different fiber types influence the hardened concrete. It is also necessary that the amount of fiber in concrete be restricted depending on its length, form and the kind being used, even if enough fiber is used for the required strength. To maximize the concrete's strength and durability and minimize its loss in flexibility, the best number of fibers should be chosen.^[13-16]

Steel fibers (SF) in concrete enhance compressive strength, but their effectiveness depends on fiber content and treatment. According to Centonze *et al.*,^[17] 0.46% yielded stronger samples at day 28, but the strength became lesser with more fiber in the concrete. Additionally, it was found by Slimane and Hadj Mostefa^[18] that 1.5% fiber reached the greatest compressive strength, whereas adding more fibers decreased workability. Another study Leporace-Guimil *et al.*^[19] carried out experimental work with waste steel scrap in concrete. It was found that compressive strength increased by 26.8–0.5% of fiber and reached a peak gain of 30.7% at 0.75%, yet it declined by 5.3% with 1.5% due to the poor workability. It is clear from these results that maximizing fiber in concrete can help maintain a good balance between how strong it becomes and how it's toughness can be improved.^[19,20]

The use of recycled melted furnace slag improves the tensile strength of cement. According to Shewalul^[20] only 2% volume of tire-recycled SF improved the tensile strength at the 28-day mark, whereas 3% content made the concrete more difficult to work with. Researchers Zeybek *et al.*^[21] found that tire SFs added at 1% boosted the tensile strength by 15% and the strength increased by 35% with the addition of 2.5% of fibers^[22] study revealed that SFs from waste tires added 25% to the tensile strength of high-strength concrete when used at 1.5% and 33% when used at 2.0% content, proving these values are the maximum efficient rate. The way SFs are shaped influences the structural strength of concrete. The study by Zeng *et al.*^[5] indicated that corrugated fibers gave the largest gain in strength by 122% and both hooked-end and straight fibers caused improvements from 33% to 93% at the end of 28 days, all compared to plain concrete.^[23-25]

With SFs in concrete, the ease of delivering and shaping the material is often reduced. Increasing SF content lessened slump, resulting from the increased difficulty of compacting due to fiber interlocking, according to Ali *et al.*^[23] and Fauzan^[24] suggest that with 1% SF, the concrete has enough workability and durability. A study conducted by Zheng *et al.*^[25] demonstrated that adding more SF to concrete made the workability of the mixture lower.

The use of waste aluminum (WAL) as an alternative part of concrete, together with sand, is also being studied. Aluminum is light and can be recycled, making it possible to decrease the weight of concrete projects. Some studies Elzaroug,^[26] Mubeen *et al.*^[27] reported that incorporating aluminum waste as a partial replacement for fine aggregates improved concrete's lightweight characteristics while maintaining satisfactory compressive strength^[28] observed that using aluminum waste reduced the cost of concrete production while retaining adequate mechanical properties. Besides,

using aluminum waste as a substitute for fine aggregates in concrete may enhance its performance and help lower production expenses.^[29] Since aluminum does not rust easily, carries electricity, and can be recycled, it is used in sustainable projects by many builders.^[26-35]

The objective of the research is to investigate if using tire steel wire as fibers and WAL can be a good alternative for fine aggregate in concrete. Dealing with industrial waste in a sustainable manner has led the researchers to examine material efficiency. During the investigation, attention is given to the properties of concrete after 28 days, for example, its workability, density, strength when and after compression, resistance to splitting and how much water it soaks up.

EXPERIMENTAL METHODOLOGY

Raw Materials

Cement

The binder utilized in this experiment was CEM I 42.5 Portland cement not plane concrete, Table 1 list its physical properties, Table 2 lists its chemical components, and the scanning electron micrograph (SEM) is shown in Figure 1.

Fine aggregate

The fine aggregate used in the test was river sand, with the maximum aggregate size being 4.75 mm. The gradation range is given in Table 3. Physical properties are in Table 4.

Coarse aggregate

The coarse aggregate is crushed stone with a particle size of 4.75 mm–16 mm. The gradation is given in Table 5, and the physical properties are in Table 4.

WAL

The WAL used for this study was obtained from a door and window manufacturing factory in Soran, Kurdistan, Iraq. Was used to substitute the natural sand in cement mortar. The substitution ratios were (10%) by volume of sand. It was screened on the sieve number (4.75 mm) and (150 μ m) to be close to the sizes of natural fine aggregates. Therefore, any material retaining on the 4.75 mm sieve and passing the 150 μ m sieve is discarded. The wastes are irregular in shape, gray in color, and light in weight [Figure 2], before using the. Its chemical component shown in Table 2 and is grains in the SEM picture seem to consist of smaller plates [Figure 3] sieve analysis show in Table 3 and Physical properties are shown in Table 4.

SF

Wires obtained from tires were utilized as fiber to investigate the influence of fiber amount on the mechanical and durability

Table 1: Physical properties of cement

Properties	Results
Standard consistency (%)	26.5%
Specific gravity	3.15
Initial setting time (min)	65
Final setting time (min)	168

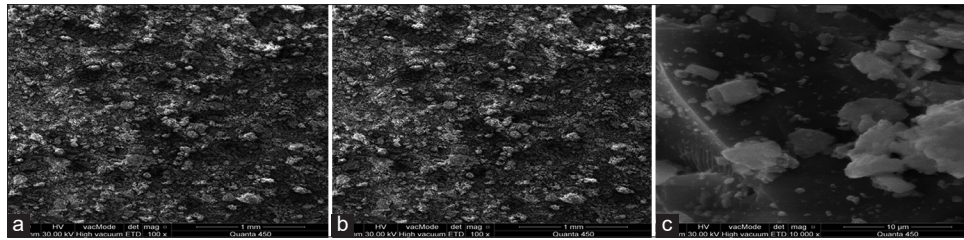


Figure 1: Scanning electron microscope images of cement at (a) 1 mm, (b) 10 μm, and (c) 100 μm magnification, showing microstructural variations and hydration products



Figure 2: (a) Waste aluminum from factory. (b) prepared waste aluminum for mix

Table 2: Chemical composition of cement and aluminum waste (% by element)

Element	Cement %	Aluminum waste %
MgO	4.6585	-----
Al ₂ O ₃	4.4078	92.2303
SiO ₂	16.0302	1.7403
P ₂ O ₅	0.0708	-----
SO ₃	4.6103	0.9358
K ₂ O	2.6345	-----
CaO	63.4096	1.2252
TiO ₂	0.0625	0.5973
Vanadium	0.0002	0.0135
MnO	0.0225	0.0329
Fe ₂ O ₃	3.5793	0.9226
Cobalt	-----	0.0058
Nickel	0.0064	0.0201
Copper	-----	0.2994
ZnO	-----	0.1176
Strontium	0.1189	0.0564
Yttrium	0.0041	0.0077
Zirconium	0.0416	0.0521
Niobium	0.0089	0.0627
Molybdenum	0.0581	0.0993
Silver	0.0046	0.0114
Cadmium	-----	0.008
Tin	0.2675	0.5788
Lead	0.0038	0.0556
Barium	-----	0.9134
Tantalum	-----	0.0138

performance properties in terms of compressive strength, split tensile strength, and water absorption and density of concrete. The utilized steel wires are shown in Figure 4 provided, Kurdistan, Iraq. Table 6 lists the Performance parameters of SF

Super-Plasticizer

The superplasticizer (Hard-cone-16) with a density of (1.03–1.035 g/cm³) with (3.5–5) of PH and without chloride content was used while mixing concrete according to (ASTM C-494) to provide workability and to improve the properties of hardened concrete.

Mix Proportion

Three different fiber volume ratios, including 0.5% SF, 1.25% SF, and 2% SF, were studied according to modelling and programming for previously studied and optimization process. 1.25% SF was founded as optimum value, 0.75% higher and 0.75% lower based on trial mixing were used as minimum and maximum volume fractions. The second waste that used is aluminum by product waste as partial replacement of fine aggregate by 10%. In this study 8 mixes were designed mixes including plain concrete (PC), plain concrete with 0.5% of steel wire (SF 0.50), Plain concrete with 1.25% of steel wire tiers (SF 1.25), plain concrete with 2% of steel wire tiers (SF2), plain concrete with 10% of aluminum waste (WAL 10), plain concrete with 0.5% of steel wire with 10% of aluminum waste (HB 0.5), plain concrete with 1.25% of steel wire with 10% of aluminum waste (HB 1.25) plain concrete with 2% of steel wire with 10% of aluminum waste (HB2). The water to cement ratio was kept constant at 0.5. Concrete mix design was selected for 40 MPa at 28 days for the optimum value of SF ± 10% error, the mix design obtained from the modelling and optimization process shown in Table 7.

Mix Procedure, Workability, and the Slump Test

As indicated in Table 7, eight FRC concrete mixes, including a control mixture devoid of fiber, were created for this investigation. All the PC and aggregates utilized in the concrete mixes were combined with two-thirds of the mixing water over the course of 3 min. After that, SP was combined with the remaining water for a further 2 min. When the materials were properly disseminated, SFs were finally added and gradually blended into the mixture to ensure uniform distribution in fiber-reinforced mixes. Slump tests were conducted and measured in order to adjust the similar workability [Figure 5]. Workability was significantly decreased after a 2% fiber

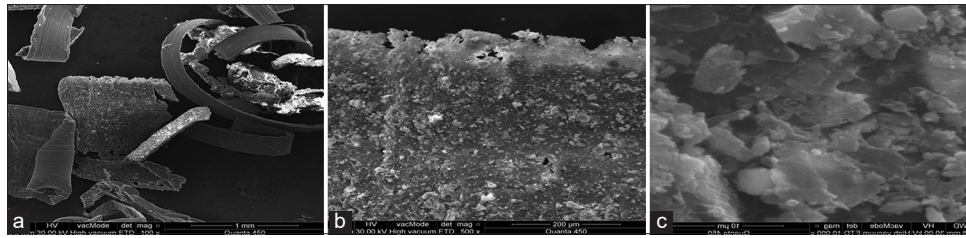


Figure 3: Scanning electron microscope images of waste aluminum at (a) 1 mm, (b) 10 μm, and (c) 200 μm magnification, showing microstructural variations and hydration products



Figure 4: (a) Waste tire (b) steel wire extracted from waste tires. (c) Steel fiber waste tire with 30 cm length

Table 3: Fine aggregate and waste aluminum sieve analysis

Opening (mm)	Fine aggregate (1000 g)		Waste aluminum (500 g)	
	Retained weight (g)	% Passing	Retained weight (g)	% Passing
4.75	45.7	95.43	46	90.8
2.36	100	85.43	0	90.8
1.18	180	67.43	264	38
0.6	200	47.43	154	7.2
0.3	190	28.43	32	0.8
0.15	170	11.43	4	0
Pan	114.3	0	0	

Table 4: Physical properties of aggregate

Description	Fine aggregate	Coarse aggregate	Waste aluminum aggregate
Type of fine aggregate	River sand	Crushed stone	By product waste
Specific gravity	2.65	2.67	-----
Absorption (%)	1.07	0.87	-----
Unit weight (kg/m ³)	1690	1549	381.2
Fineness modulus (%)	2.64		

Table 5: Coarse aggregate sieve

Opening (mm)	Retained Weight (g)	% Passing
16	5	99.5
12.5	503	49.2
9.5	407	8.5
4.75	83	0.2
Pan	2	0

content ratio. The values fell between 40 and 65 mm. After that, they vibrated after being placed into molds. To prevent

moisture loss, plastic sheets were placed over the specimens after the concrete was formed. Following a 24-h period at room temperature, the samples were kept at room temperature for 24 h after casting. Then the samples were tested after 28 days of curing in saturated water.

Test Procedure

Three different tests were conducted to evaluate the influence of recycled steel wire types and fiber ratio. These tests, including compressive, splitting tensile, and total water absorption tests, three specimens were tested for each designed mixture, and the mean value of the tests was given

as the hardened characteristics. In accordance with ASTM C39/C39M, 100 × 100 × 100 mm³ cube specimens were used in [Figure 6a] for the compressive strength tests. 3000 N/s was the loading rate. Until it lost its ability to carry all loads, the test was kept going. Cubes of 100 mm were also used

for the total water absorption capacity of concrete specimens and density in accordance with ASTM C642-97 [Figure 6b]. Cylindrical specimens of 100 mm in diameter and 200 mm in height were used for the splitting tensile strength test according to ASTM C496-96 [Figure 6a]. A loading rate of 333N/s was set up. The specimen's length was marked with a thin plywood bearing strip to evenly distribute the diametral compressive force.



Figure 5: Slump test

RESULTS AND DISCUSSION

Workability

Workability conducted to determine the effect of incorporating SF and WAL on the workability of concrete. The results of the slump test for all eight mixes are shown in Figure 7, It can be seen that the control mix (with no SF or WAL) recorded a slump of 56 mm. However, with the addition of SFs at 0.5%, 1.25%, and 2% by volume of concrete, the slump values progressively decreased to 53 mm, 49 mm, and 40 mm, respectively which the percentage reduction in slump compared to the control was approximately 5.36% for 0.5% SF, 12.5% for 1.25% SF, and 28.57% for 2% SF. This trend shows that the addition of SFs induces a decrease in workability that can be attributed to



Figure 6: (a) Samples for total water absorption and density test and (b) samples for compressive and splitting tensile strength test

Table 6: Performance parameters of steel fibers

Type	Tensile strength (MPa)	diameter (mm)	Length (mm)	Aspect ratio	Manufacturing process	shape	Remark
Recycled SF	1380	1.00	30	30	Cutoff	straight	Uniform, neat cuts, and a small amount of rubber adhesion on the surfaces

Table 7: Mix design for (1 m³)

Mix type	Cement (kg/m ³)	Fine aggregate (kg/m ³)	Coarse aggregate (kg/m ³)	Water (kg/m ³)	WAL Kg/m ³	SF (kg/m ³)	Admixture (kg)
Control (PC)	366	708	1099	183	----	---	2.08
SF0.50	366	708	1099	183	----	36	2.08
SF1.25	366	708	1099	183	----	90	2.08
SF 2	366	708	1099	183	----	144	2.08
WAL10	366	601.8	1099	183	31.84	----	2.08
HB0.5	366	601.8	1099	183	31.84	36	2.08
HB1.25	366	601.8	1099	183	31.84	90	2.08
HB2	366	601.8	1099	183	31.84	144	2.08

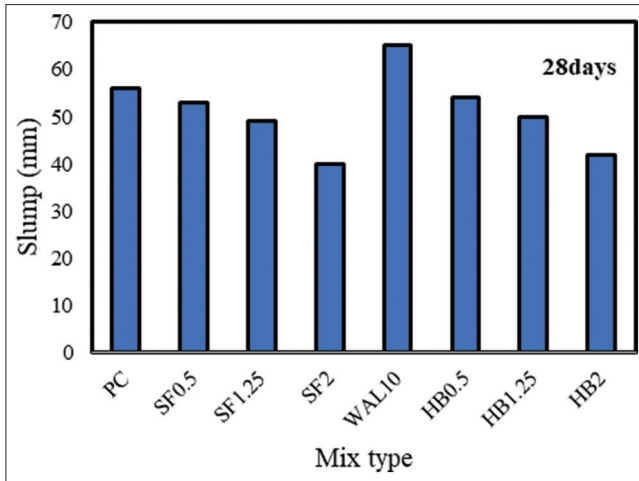


Figure 7: Slump values for concrete mixes

the increased surface area and interlocking properties of the fibers that impede the free movement of concrete.

On the contrary, the blend using 10% WAL as a partial fine aggregate replacement displayed a slump value of 65 mm, which was a 16.07% improvement in workability over the control. This enhancement can be related to the smoother texture and lighter weight of WAL than natural sand, leading to reduced internal friction and easier flow of the mix and less water absorption as compared to fine aggregate.

When used in combination, there were observed intermediate values for SF and WAL. The blends with 0.5% SF and 10% WAL obtained a slump of 54 mm, which is less than the control, but greater than the respective SF-only. In the same way, the mixes containing 1.25% and 2% SF and admixed with 10% WAL gave slump values of 50 mm. and 42 mm respectively. Based on these results, though the addition of WAL fortifies the workability of a mixture of FRC, it cannot completely neutralize the stiffening influence that is imparted to the concrete through increased values of SFs. It can therefore be concluded that inclusion of SFs negatively impacts on the workability of concrete because of the obstruction caused by the fibers in the pour of fresh mix. On the other hand, aluminum waste improves workability and can be efficiently used for compensation of the reduction in slump due to the introduction of SFs.

Compressive Strength

The compressive strength results for the 28-day curing time show in Figure 8 that the control mix achieves a compressive strength of 39.93 MPa, serving as a baseline for comparison. Adding 0.50% SF increases the compressive strength to 42.90 MPa, indicating that a small amount of SF enhances the concrete's mechanical properties by bridging cracks, delaying crack propagation, and improving tensile resistance, which collectively enhance load-bearing capacity. A further addition of SF to 1.25% gives the maximum compressive strength of 44.57 MPa, which implies that this quantity distributes the fibers best and creates a stronger, more unified structure. At a 2% SF content, the compressive strength falls to 35.80 MPa, mostly because the fibers cluster together instead of spreading

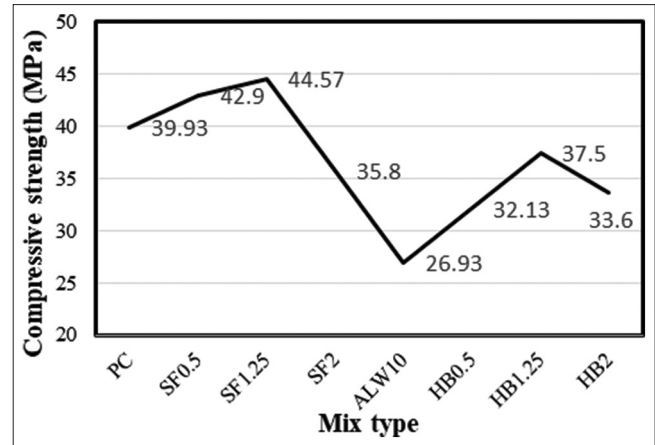


Figure 8: Compressive strength result of concrete mixes

evenly in the matrix. The presence of fibers in clusters makes the matrix less connected and weaker overall. When 10% WAL is added, the compressive strength drops to 26.93 MPa mainly because WAL has a porous structure and is weaker than normal aggregates. Incorporating WAL into the concrete may reduce its density and internal bonding, causing less bonding between particles and leading to lower strength as can be explained by the SEM images' details shown in the Figure 3. The compressive strength goes up to 32.13. The use of 1.25% SF and 10% WAL raises the compressive strength to 37.50 MPa, which means that the best fiber level can help balance the reduction in strength caused by WAL by spreading stress and limiting cracks. Even so, when 2% SF is combined with 10% WAL, compressive strength drops slightly to 33.60 MPa, pointing to the fact that too much fiber content in the presence of WAL causes fiber clumping and the formation of more voids, harming the structural matrix.

The highest compressive strength is achieved with just 1.25% SF, thanks to better dispersion of fibers and improved stress, but the use of 1.25% SF and 10% WAL together is the most effective way to incorporate WAL particles into concrete, as it provides a good balance between fiber reinforcement and waste utilization, while reducing the problems caused by each.

Splitting Tensile Strength

When looking at [Figure 9] for the 28-day strengths, the control mix provides a tensile strength of 3.32 MPa, which is used as a reference. At 0.50% SF, the splitting tensile strength rises to 4.20 MPa, which means that small amounts of SFs improve the tensile properties. Such an improvement is caused by the fibers spanning between cracks, delaying when they form and keeping cracks from widening, improving the sample's crack-resistance and tensile strength. Raising the SF content to 1.25% results in a tensile strength of 4.57 MPa, the best among all mixes, which suggests fibers are optimally spread, allowing better stress transfer and improved crack control, resulting in increased toughness and strength.

Once the SF content gets to 2%, the splitting tensile strength drops to 3.84 MPa. Fiber agglomeration and uneven distribution probably because this decreases, as they result

in spots of high stress rather than even reinforcement of the matrix. On the other side, the addition of 10% WAL lowers the splitting tensile strength to 2.38 MPa, which is the minimum value. This weakness is mainly caused by the low strength and many pores in WAL, which make it hard for the WAL to bind well with the concrete matrix, thereby reducing the tensile strength.

Mixing 0.50% SF with 10% WAL results in a slight increase in tensile strength to 3.36 MPa, suggesting that the fibers reduce some of the bad effects of WAL by bridging cracks. The addition of 1.25% SF and 10% WAL increases the tensile strength to 3.44 MPa, which shows the fiber content's usefulness for supporting structure despite the presence of weaker WAL. However, increasing the SF content to 2% along with 10% WAL results in a slight decrease to 3.40 MPa, reinforcing the observation that excessive fiber content may cause clumping, reducing the expected improvement in tensile strength. Moreover, the splitting tensile test showed clear differences in crack behavior between plain, WAL, and FRC. Plain concrete exhibited wide, continuous cracks, indicating brittle failure. In contrast, SF-reinforced specimens showed narrower, shorter cracks and remained more intact. This demonstrates that SFs improve tensile performance

by bridging cracks and enhancing ductility, as shown in Figures 10 and 11.

Water Absorption

The water absorption results are shown in Figure 12. The control mix recorded 5.29% absorption. Incorporating 0.5% and 1.25% SF reduced the values to 5.02% and 4.86%, reflecting 5.1% and 8.1% reductions, respectively. This suggests that moderate SF addition refines the internal structure and decreases porosity. When 2% SF was used, absorption went up to 5.55%, giving a 4.9% increase over the control, possibly because of poor compression and fiber bunching. The mix using 10% WAL on its own reached an absorption value of 5.60%, which is 5.9% higher than the control, mainly due to how porous and absorptive WAL is. When SF was combined with WAL, the 0.5% SF + 10% WAL and 1.25% SF + 10% WAL mixes recorded 5.36% and 5.09%, respectively, close to the control, indicating a balanced effect. However, the 2% SF + 10% WAL mix rose again to 5.72%, an 8.1% increase, demonstrating that high fiber content with WAL significantly raises porosity.



Figure 9: Compressive strength test

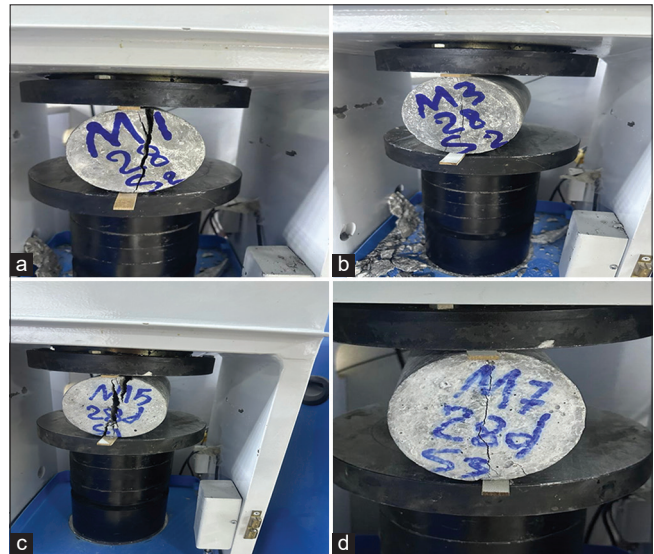


Figure 11: (a-d) Crack occurrence type of samples

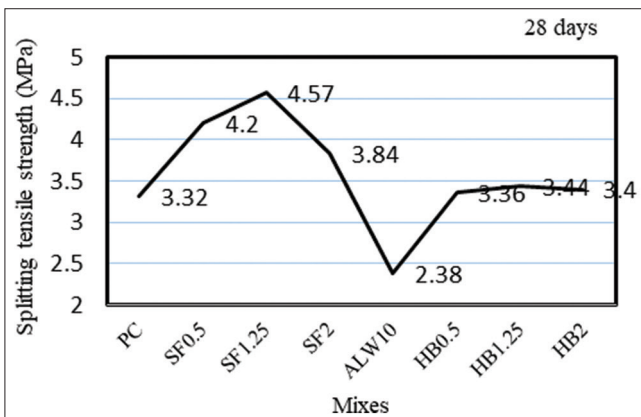


Figure 10: Splitting tensile strength results of concrete mixes

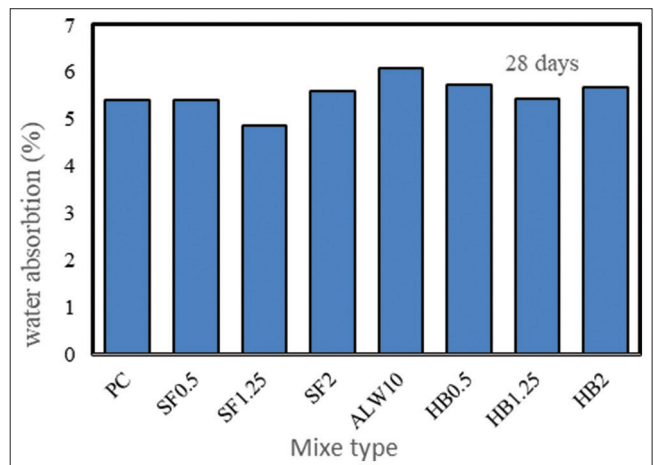


Figure 12: Water absorption of concrete mixes

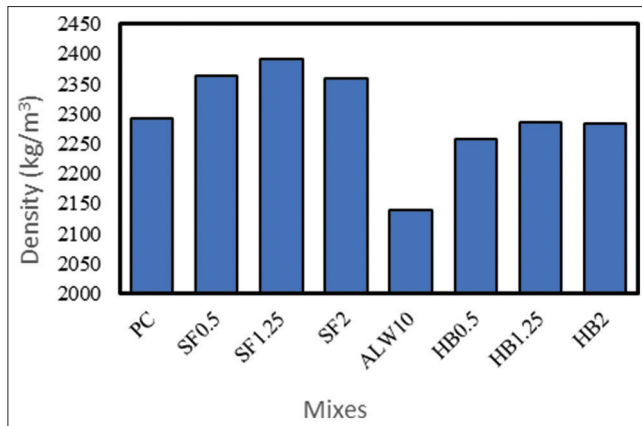


Figure 13: Density of concrete mixes

In short, moderate SF lowers absorption and raises durability, but WAL has the opposite effect. To keep pores from connecting and reduce water movement, it is necessary to find the best mix.

Density

The presence of SF from waste tires resulted in a significant change in the dry density, Figure 13 shows this. The density of concrete with SF was respectively found to be 2363.8 kg/m³. These values show an increase in values of 3.17%, 4.36% and 2.91% respectively, which means that the presence of SFs compacts the matrix more closely corresponding to enhanced packing effects and the higher specific gravity of steel with respect to other concrete constituents.

On the other hand, when 10% WAL was mixed with SFs, the densities went up again: For 0.5% SF, the density was 2256.3 kg/m³, notching down by 1.52%; for 1.25% SF, density dropped slightly to 2284.3 kg/m³ at -0.30%. This improved density after adding SFs shows that they can at least partially make up for the loss brought by WAL, supporting their benefit for the composite's packing and strength.

CONCLUSION

- Optimal SF content: With the inclusion of 1.25% SF, compressive strength increased the most, while tensile strength remained high, leading to the top performance.
- Effect of excess fiber: As SF increased to 2%, the strength of the concrete increased, but its workability decreased due to fiber clustering.
- Aluminum waste impact: Although the use of 10% WAL in concrete improved workability and surface smoothness, its strength in both compressive and tensile states decreased.
- Combined Use: Combining 1.25% SF and 10% WAL resulted in a mix that is strong, controls water absorption and is considered an environmentally friendly pick.
- Water absorption: Using medium SF allows the concrete to absorb less water and WAL allows water to pass through more easily. Increasing SF (2%) when using WAL results in better absorption and pore structure.
- Density trends: Concrete in SF was made denser, but WAL made it less dense. The combination of both additives maintained acceptable performance thresholds.

- Sustainability contribution: Reusing steel and aluminum waste for concrete is eco-friendly since it supports sustainability and deals with industrial byproducts.

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