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Sustainable High-Performance Concrete Reinforced with Hybrid Steel Waste Fibers

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HIGHLIGHTS

- Using recycled fibers as a substitute for commercial fibers was investigated.
- The effect of fibers volume fraction and aspect ratio on the mechanical properties of concrete were studied.
- The possibility of producing sustainable high-performance concrete using recycled coarse aggregate and recycled fibers was investigated.

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ABSTRACT

This research aims to study the benefit of using fibers made from waste materials in concrete and evaluate the ability to use these fibers as a substitute for commercial fibers. Different aspect ratios of alternative fibers formed from cut steel tied wire waste were utilized. This material is selected because of its low price and wide availability. Two concrete mixes with 15% waste crushed clay brick coarse aggregate reinforced with different volume fractions of 1.0 and 1.5% and an aspect ratio of 40 were prepared. Also, three concrete mixes reinforced with a hybrid aspect ratio of 40 and 65 of tied wire waste steel fibers (TWWSF) with different volume fractions of 1.0% and 1.5% were prepared. The compressive, splitting tensile, flexural strengths, and ultrasonic pulse velocity (UPV) of all prepared concrete mixes were tested. The results illustrate that the inclusion of tied wire waste steel fibers significantly enhances the strength of concrete with 15% waste crushed clay brick coarse aggregate, and high-performance concrete with compressive strength of up to 85 MPa can be produced. The enhancement in compressive, splitting, and flexural strengths were 29%, 42.8%, and 38%, respectively, for concrete reinforced with a fiber aspect ratio of 40 and volume fraction of 1.5%. In comparison, for the same volume fraction, the percentage was 22%, 48%, and 44%, respectively, for equal content of hybrid aspect ratio of 40 and 65.

1. Introduction

The building industry consumes a large number of natural resources and, at the same time, a waste generator, as well as the competitive costs needed to finish these projects. As a result, the sustainable construction concept was established in response to growing concerns about our planet's future [1,2].

Because it is one of the most extensively used building materials, the concrete industry utilizes many natural resources. Because of its composite form (a cement, fine and coarse aggregate, and water) and wide use, concrete is frequently viewed as a potential waste disposal option. This means that if waste can be utilized in concrete, it can almost likely be recycled in huge amounts. Because aggregate makes up roughly 70% to 80% of the entire volume of concrete, any decrease in using natural aggregates will have a major environmental impact. Consequently, alternative materials such as construction and destruction waste from other industries are increasingly being evaluated and employed in concrete as environmentally friendly natural aggregates substitutes [3,4]. Since world war II, recycled aggregate concrete has continuously grown in Europe. Large quantities of waste clay bricks are produced during the production, building, and destruction. These wastes are disposed of in landfills or illegally dumped, presenting a significant environmental threat [5,6]. Waste clay bricks were employed as a source binder and coarse aggregate in the manufacture of sustainable geopolymer concrete, with clay bricks in the proper dosage improving pulse velocity and reducing void content, resulting in enhanced thermal insulation performance [5]. Waste aggregate concrete absorbs about 20% more water than natural aggregate concrete, while the amount varies depending on the kind and composition of waste aggregate [4,7]. Using recycled crushed clay bricks as aggregate in concrete manufacturing would help protect natural aggregate

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sources while minimizing the quantity of waste transported to landfills [8,9]. The inclusion of crushed clay brick as aggregate in concrete affects its strength, density, and thermal conductivity, according to previous studies [10,11].

Fibers, a small piece of reinforcing material, can provide a mechanism that decreases crack spread, limits useful crack bridges, and gives strength, durability, and ductility to concrete [12]. Many studies have been conducted in recent decades to investigate steel fiber reinforced concrete characteristics [13]. Incorporating steel fibers into concrete has been shown to prevent macro cracks from forming and reduce the breadth of micro cracks, resulting in increased resistance to dynamic, impact, and unexpected loads. Also, steel fibers help increase concrete's tensile strength [13,14]. The aspect ratio (l/d ratio) and the volume fractions (VF) are the most critical elements impacting the characteristics of steel fiber reinforced concrete. The aspect ratio is critical during concrete manufacturing's mixing and replacement phases [15]. Multiple fiber types, such as a mix of short and long fibers, should be used to produce both durability and ductility. Rossi was the first to propose using multiple types of fibers in a concrete mixture, named multi-modal fiber reinforced concrete [16]. Even though concrete reinforced with steel fibers has been the topic of numerous research studies, it is somewhat expensive composite material. As a result, waste fibers collected from various industries such as mills, manufacturing, and the textile sector could be deemed a successful alternative to the original materials from both an economic and environmental standpoint [14]. The feasibility of employing discarded steel fibers as concrete reinforcement was investigated by Aghaee et al.[17]. According to the findings, waste steel wires could be a viable option for steel fiber reinforcement. Askar et al. studied alternative fibers (tied wires and discarded plastic bottles) to improve the mechanical characteristics of concrete and their effectiveness. When 2% tied wire fibers were added to the mix, the compressive strength increased by 22%, whereas when only 1% steel fibers were added, the compressive strength increased by 16%. When 2% steel fibers are employed, the flexural strength increases to 52% [18]. Vandewalle [19] examined the mechanical characteristics of hybrid steel fiber reinforced concrete and hybrid steel fiber (long and short) with an optimum fiber dosage of 0.75 percent. The findings demonstrate that hybrid fiber concrete's flexural strength and ductility are considerably better than plain concrete for small fracture widths. Hussein et al. [20] studied the properties of (HPLWACs) reinforced with mono fibers, double fibers, and triple fibers in many aspect ratios. The incorporation of fibers in HPLWAC improves ultimate failure and initial crack impact resistance for hybrid and mono fiber specimens relative to reference specimens.

Using crushed brick waste as aggregate in concrete contributes to long-term sustainability and reduces the waste materials' negative environmental impact. Waste materials can be used as fibers to reinforce concrete with crushed brick aggregate to make it more sustainable and improve its properties. There hadn't been any research done on the combined effect of crushed brick waste aggregate and waste fibers. This study investigates the mechanical properties of sustainable high-performance concrete utilizing crushed brick wastes as a volumetric replacement to natural coarse aggregate and reinforced with various volume fractions and hybrid aspect ratio of tied wire waste steel fibers.

2. Experimental Program

2.1 Materials

Ordinary Portland cement (Type I) was used in this research with the trademark Al- Mass. The chemical composition and physical characteristics of the cement utilized in this investigation show that it follows the standards of Iraqi Specification No.5/1984 [21]. Natural crushed coarse aggregate from Basrah region with 12 mm maximum size and natural sand zone (2) from Al-Ukhaider region with 4.75mm maximum aggregate size were used. The results demonstrate that fine and coarse aggregate grading and all other properties were governed by Iraqi Specifications No. 45/1984 [22]. Table 1 demonstrates the characteristics of the coarse aggregates, while Table 2 displays the characteristics of fine aggregates utilized in this study. Waste clay bricks were collected from the building sector and crushed into small pieces in the Building Research Center's laboratories. They were prepared with the same grading of natural coarse aggregate used in this study. It had a maximum particle size of 12mm, a density of 940 kg/m^3, absorption of 24%, and specific gravity of 1.57. Table 3 illustrates the properties of crushed clay brick coarse aggregate. High range water reducing admixture (HRWRA), which conforms to ASTM C494 type F & G [23], has been used. Table 4 shows the details of this superplasticizer (HRWRA). Galvanized tie wire was gathered from the construction industry's waste and used as a steel fiber with a 1.00 mm diameter. As indicated in Figure 1, tied wire waste steel fibers with two lengths of 40 and 65 mm and aspect ratios of 40 and 65 were prepared and used to reinforce the concrete.

Table 1: Properties and Grading of natural coarse Aggregate

Sieve Size, (mm)/ as Stated by IQS, No.23 [24]	%, Cumulative Passing	Limitation of IQS, No. 45/1984 with (5-14)mm[22]
14	100	90-100
12.5	100	………..
10	64.23	50-85
5	1.9	0-10

Table 1: Continued

Physical and Chemical Characteristics		
Dry Rodded Density, kg/m^3	1670	-
Specific Gravity, SSD	2.67	--
Sulphate Content, %	0.063	≤ 0.1
Absorption, %	0.85	--

Table 2: Properties and Grading of natural fine Aggregate

Sieve Size, (mm)/ as Stated by IQS, No.23 [24]	%, Passing	Limitation of IQS, No. 45/1984 Zone(2)[22]
10	100	100
4.75	97	90-100
2.36	90.6	75-100
1.18	84	55-90
0.6	57	35-59
0.3	18	8-30
0.15	5	0-10
Physical Properties and Others		
Material Passing Sieve75µm, %	3.3	≤5%
Sulphate Content, %	0.5	≤ 0.5%
Fineness Modulus	2.32	--
Absorption, %	2.4	--
Specific Gravity, SSD	2.65	--
Bulk Density, kg/m^3	1601	--

Table 3: Properties and Grading of Waste Clay Brick Aggregate

Sieve size (mm)	%, Passing	Limitation of IQS, No. 45/1984 with (5-12)mm [22]
14	100	90-100
12.5	100	………..
10	56.23	50-85
5	2.33	0-10
Other Properties		
Density (kg/m^3)	1570	
Dry Roded density, (kg/m^3)	940	
Absorption, (%)	24	
Specific Gravity	1.57	
Thermal Conductivity[W/(m.K)]	0.7406	

Table 4: Properties of Superplasticizer (Master Glenium 54)*

Physical and Chemical Characteristics	Description [25]
Appearing	Liquid with whitish to straw color
Specific Gravity	1.07
Content of Chloride	free
PH	5-8

*According to the manufacturer.

2.2 Mix Proportions and Concrete Mixes

The nominal mixing proportion used for casting the specimens was 1:1.4:1.8 (cement: sand: coarse aggregate) by weight with 0.27 W/C ratio and variable HRWRA dosage to achieve the same workability of 120 mm slump for all mixes. After being submerged in water for 24 hours, The crushed bricks were dried until they had a saturated, dry surface. Table 5 indicates the details of concrete mixes prepared in this study and the mass of the materials for 1m^3 of concrete.

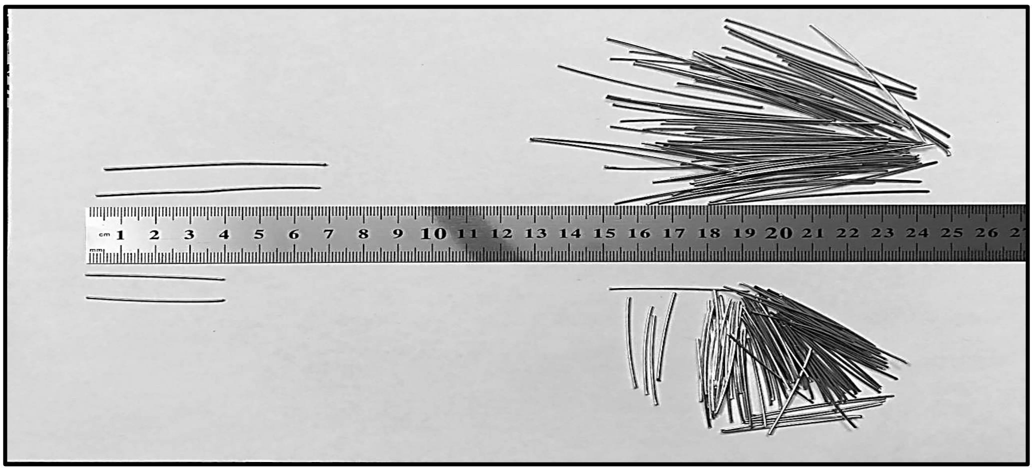

Figure 1: Tied wire waste steel fibers

Table 5: Details of Concrete mixes

Groups	Concrete mix symbol	Crushed Clay Brick Waste(%) by Volume	Vf (%)	Cement (kg/m3)	Sand (kg/m3)	Gravel (kg/m3)	Crushed Clay Brick Waste (kg/m3)	Water (kg/m3)	HRWRA (%) by weight of cement	Fiber with Aspect Ratio 40 (kg/m3)	Fiber with Aspect Ratio 65 (kg/m3)
1	R_0	15	0	500	700	765	79.08	135	1.17	0	0
2	W1	15	1	500	700	765	79.08	135	1.32	78.59	0
	W2	15	1.5	500	700	765	79.08	135	1.4	117.84	0
3	WH1	15	1(0.5+0.5)	500	700	765	79.08	135	1.35	39.295	39.295
	WH2	15	1(0.25+0.75)	500	700	765	79.08	135	1.39	18.82	58.94
	WH3	15	1.5(0.75+0.75)	500	700	765	79.08	135	1.5	58.92	58.92

2.3 Preparation of Specimens

An electric rotary mixer with a capacity of $0.1m^3$ was used in the mixing process. The inner face of the mixer pan was cleaned to remove any stuck concrete and then wetted with water before putting the materials in it. Initially, the cement, coarse and fine aggregate was mixed for one minute, then the largest amount of mixing water (about 70%) was added to the dry mixture, which was then mixed for approximately one minute. Next, the adopted quantity of superplasticizer was blended with the remaining mixing water (30%) before being added to the mixture and then finished the process by mixing for two minutes. The whole mixing time was approximately 4-5 minutes. The superplasticizer amount in concrete mixes containing tied wire waste fibers was adjusted to achieve the same workability (120mm). The fibers were sprayed over the mixture carefully and mixed with it for two minutes throughout the mixing process. All molds were thoroughly cleaned, and the inside surfaces lightly lubricated before casting. All the molds were filled with layers of concrete and compacted to be compatible with the requirements of each specimen. Mould's top surfaces were leveled and covered with nylon sheets to avoid moisture loss. Twenty-four hours later, the specimens were demolding, marked, and cured fully submerged in water until testing at 28 days.

2.4 Experimental Tests

At the age of 28 days, a series of experimental tests were conducted. These tests are as the following:

1) Compressive strength test performed in accordance to BS EN 12390 1881: part 116 [26] on cubes of 100 mm. A universal testing machine with a capacity of 2000 kN and a loading rate of 15 MPa per minute was used to compress and test the specimens.
2) The splitting tensile strength test was carried out in compliance with ASTM C496 [27] on 200 mm in height and 100 mm in diameter cylindrical concrete samples.
3) Flexural strength test performed according to ASTM C78 [28] using prism specimens (100 x 100 x 400 mm).
4) Ultrasonic pulse velocity test is conducted using 100 mm cubes with placing grease on the surfaces of the concrete specimens to ensure good contact according to ASTM C597 [30].

3. Results and Discussion

3.1 Compressive Strength

The influence of tie wire waste steel fibers on the compressive strength of concrete is indicated in Table 6 and Figure 2. It can be noticed that the incorporation of tie wire waste steel fibers in concrete specimens containing 15 % crushed clay brick enhances the compressive strength at 28 days of age. For concrete fiber specimens with an aspect ratio of 40, the compressive strength increases with increasing the volume fraction. The observed increase was about 27% and 28% for the volume fraction of 1.0% and 1.5%, respectively, compared to reference concrete. This increase in compressive strength is because of the ability of fibers to bridge fissures and stop their progression, alter the orientation of cracks, and slow the rate of crack formation [18,31]. Concrete mix WH1 with hybrid fibers (0.5% l/d 40 + 0.5% l/d 65) shows the highest compressive strength. The compressive strength increases by around 3.2% compared to concrete mix with mono fibers of an aspect ratio of 40 and volume fraction of 1% (mix W1). Including fibers with an aspect ratio of 65 causes a slight reduction in compressive strength for other concrete mixes (WH2 and WH3). This could be attributable to the formation of air pores and voids in these mixes, both of which lower compressive strength [32].

Table 6: Mixes results at age of 28 day

Concrete mix symbol	Compressive Strength (MPa)	Splitting Tensile Strength (MPa)	Flexural Strength (MPa)	UPV (km/sec)
R_0	64.86	4.5	6.2	4.75
W1	82.63	6.4	8.35	5.05
W2	83.36	6.43	8.55	5.15
WH1	85.3	6.50	8.75	5.23
WH2	82.30	6.55	8.9	5.02
WH3	79.26	6.66	8.95	4.90

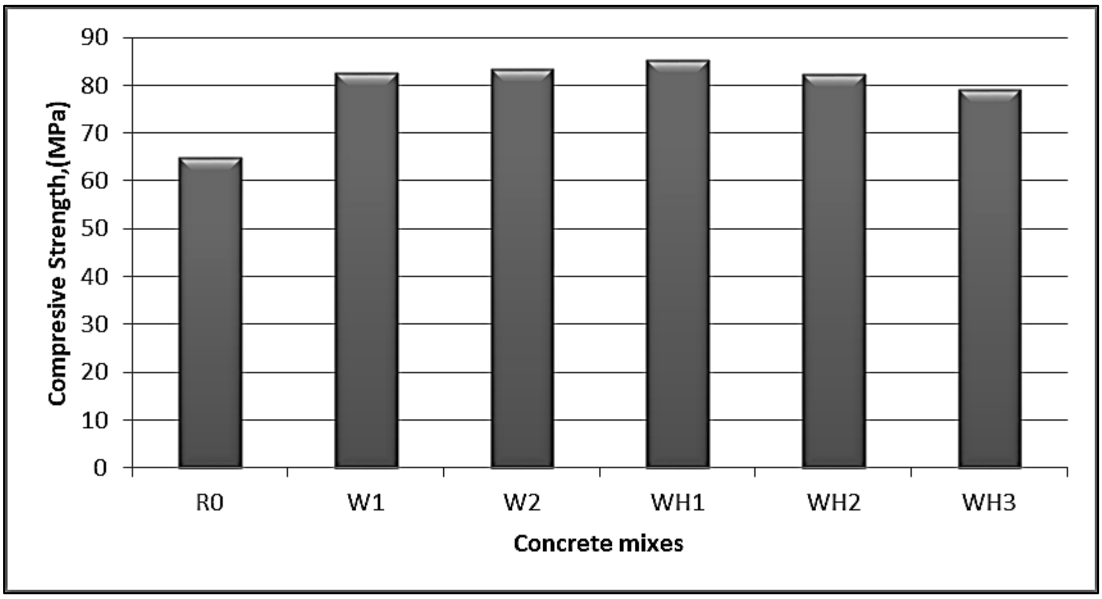

Figure 2: Compressive Strength at 28 days for all concrete mixes

3.2 Splitting Tensile Strength

Table 4 and Figure 3 represent the splitting tensile strength results for all concrete specimens. According to the results, including tied wire waste steel fibers in concrete specimens containing 15% crushed clay brick greatly improves the splitting tensile strength. For example, for concrete specimens reinforced with tied wire waste steel fibers with l/d = 40, the enhancement percentages were 42% and 42.8% for volume fractions 1.0% and 1.5%, respectively, relative to reference concrete (R_0). This is because of fiber's ability to stop crack propagation by acting as bridges between the fissures and the high tensile strength of steel fibers [33,34]. In addition, the results indicate that when using tied wire waste steel fibers with a hybrid aspect ratio (40 and 65), the splitting tensile strength is slightly enhanced compared to concrete samples with corresponding fiber volume fraction and fibers aspect ratio 40. This increase is because hybrid fibers of various sizes offer distinct restrain conditions. It is also attributed to the enhancement of the mechanical bond strength when the two sizes of fibers cause crack forming delay and their propagation to be stopped [35,36].

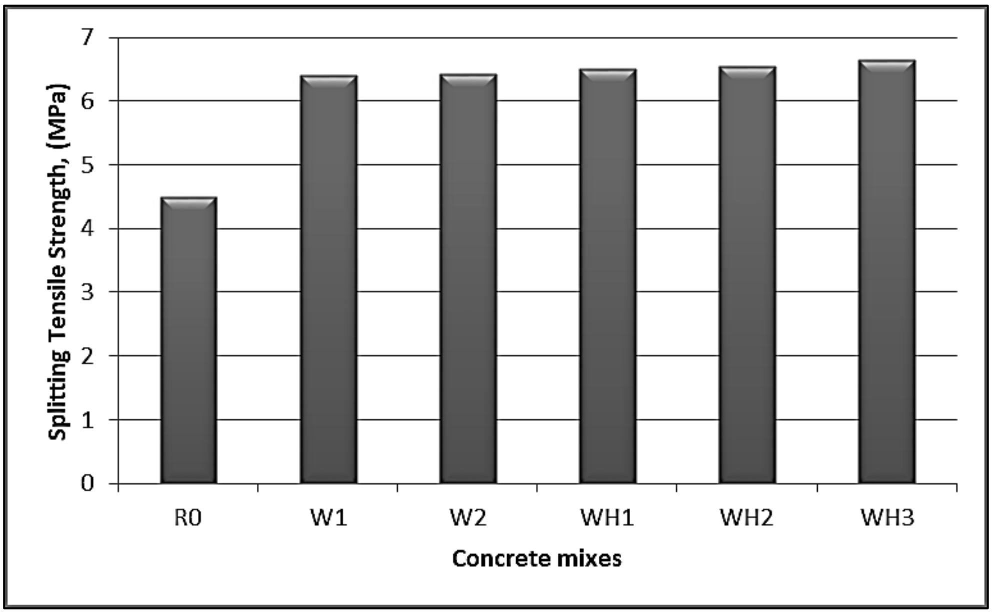

Figure 3: Splitting Tensile Strength at 28 days for all concrete specimens

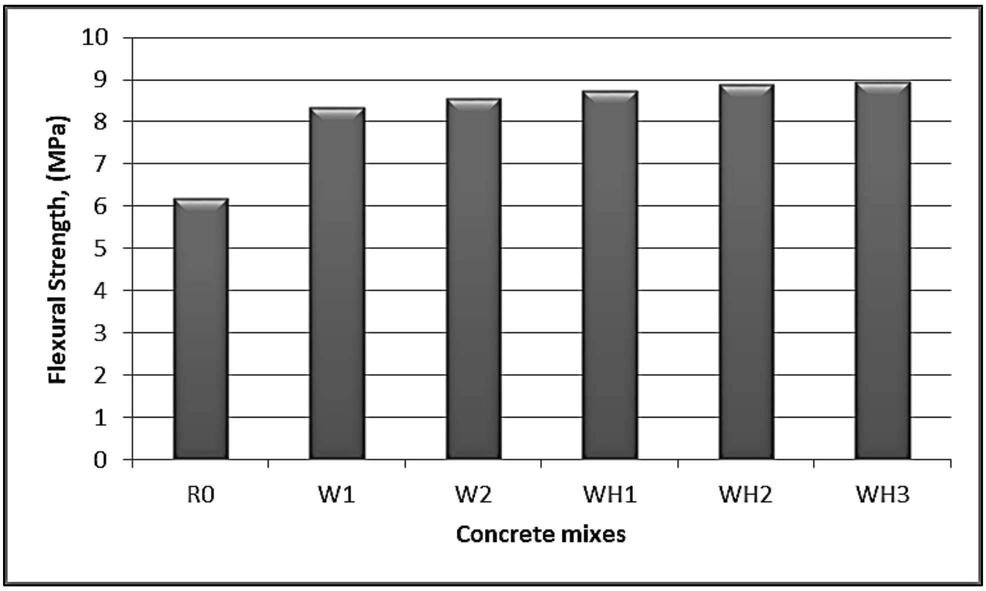

Figure 4: Flexural Strength at 28 days for all concrete specimens

3.3 Flexural Strength

Table 6 and Figure 4 display the influence of fiber reinforcement on the flexural strength of concrete samples. The results demonstrate that adding tied wire waste steel fibers to concrete specimens containing 15% crushed clay brick increases the flexural strength for both fiber aspect ratio mixes relative to the plain concrete mix. For mixes reinforced with fibers aspect ratio 40, the percentages of increase in flexural strength were 34.6% and 37.9% for volume fractions of 1.0% and 1.5%, respectively, compared to reference concrete. These results also show that increased percentages are developed with increasing

fiber's volume fractions and aspect ratio. For concrete samples reinforced with hybrid tied wire waste steel fibers generally, the concrete mix samples that are reinforced with hybrid fibers showed a slight increase in flexural strength compared to concrete mixes with fiber aspect ratio 40 and corresponding fiber volume fraction. Concrete mixes WH1 and WH2 have a flexural strength of 4.8% and 6.6% higher than that of concrete mix W1, while concrete mix WH3 show a 4.7% increase in flexural strength relative to mix W2. This increase in flexural strength is attributed to the fact that the fibers help to limit the development, propagation, and widening of cracks, hence increasing the crack resistance of the composite [37,38]. Figure 5 illustrates the crack pattern of concrete flexural specimens containing 15 percent crushed brick aggregate with and without tied wire waste fibers. The plain specimen is divided into two parts because it is obvious that concrete without tied wire waste fibers (reference) fails brittle under flexural loads. Including fibers in concrete alters the flexural failure mode from brittle to a ductile failure, and the increase of fiber volume fraction from 1 to 1.5% reduces the crack width.

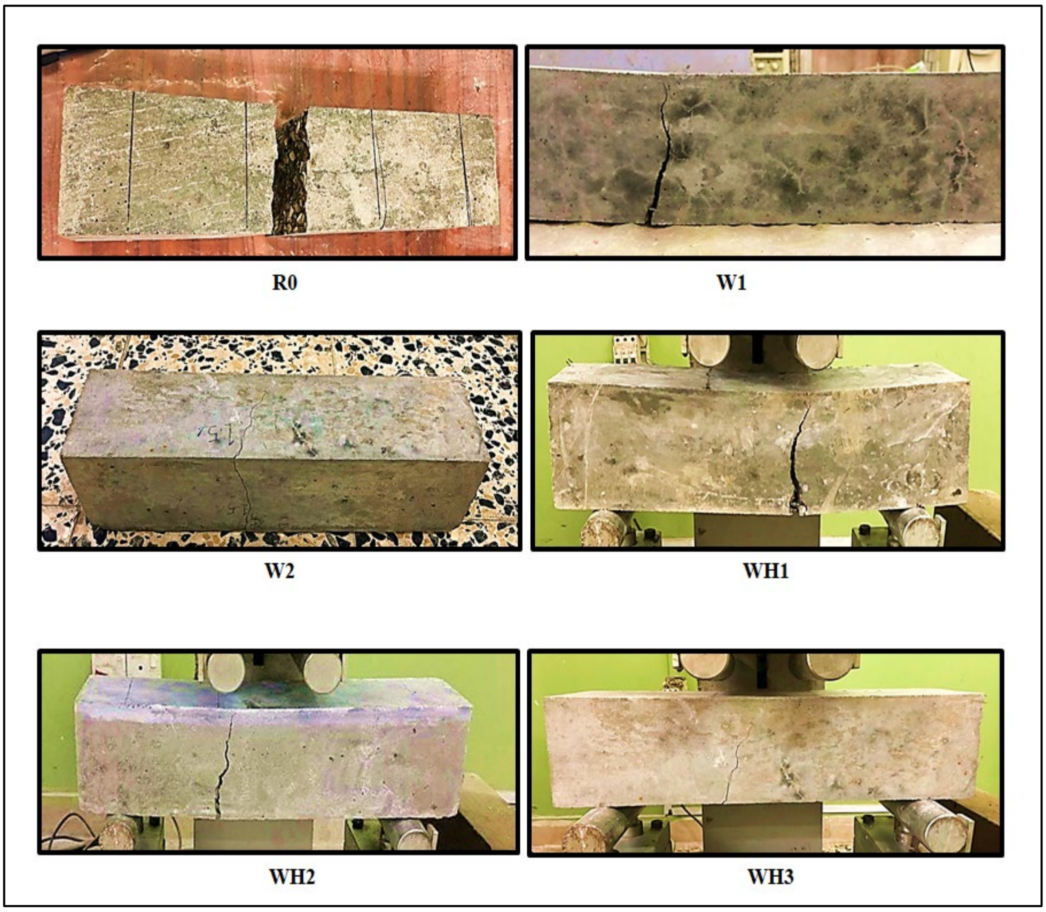

Figure 5: Flexural failure of concrete specimens with and without tied wire waste steel fibers

3.4 Ultrasonic Pulse Velocity

The ultrasonic pulse velocity results for concrete specimens containing 15% crushed clay brick and reinforced with tied wire waste steel fibers are illustrated in Table 6 and Figure 6. The results illustrate an enhancement in UPV with tied wire waste steel fibers, which means there is a reduction in the presence of voids and cracks. For volume fractions of 1 and 1.5% and aspect ratio of 40, the results range from 4.75 to 5.15 km/sec, while for concrete specimens with hybrid aspect ratio fibers (40 and 65), the results reach 5.23 km/sec. These values are considered good quality concrete [39].

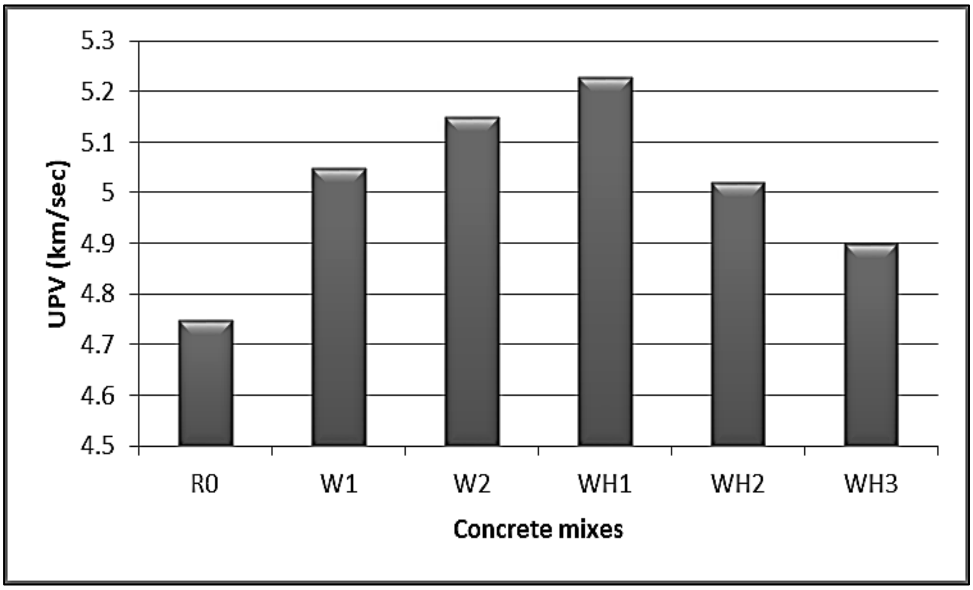

Figure 6: UPV test at 28 days for all concrete mixes

4. Conclusion

Based on the investigation's results, the following conclusions have been reached:

1) The addition of tied wire waste steel fibers with an aspect ratio of 40 to concrete containing 15% crushed brick aggregate significantly increases the compressive strength by about 27% and 28% for volume fractions of 1% and 1.5%, respectively.
2) Using hybrid aspect ratios (40 and 65) of tied wire waste steel fibers with an equal volume fraction of 0.5% enhances the compressive strength by about 33% relative to plain concrete. Still, increasing the fiber content with an aspect ratio of 65 decreases the compressive strength compared to the corresponding samples with the same fiber content of 40 aspect ratio.
3) The splitting tensile strength developed by about 42% and 42.8 % with the incorporation of tied wire waste steel fibers of an aspect ratio of 40 and volume fractions of 1.0 and 1.5 % compared to plain concrete. In contrast, using a hybrid aspect ratio (65 and 40) fibers results in a slight enhancement in the splitting tensile strength compared to the corresponding mixes with the same fiber volume fraction of a 40 aspect ratio.
4) Tied wire waste steel fibers enhance the flexural strength of concrete containing 15% crushed clay brick to 34.6% and 37.9% for volume fractions of 1 and 1.5 percent and aspect ratio of 40. Still, the inclusion hybrid aspect ratio (40 and 65) slightly enhances the flexural strength compared to the corresponding mixes with the same fiber volume fraction of the 40 aspect ratio.
5) Adding various amounts and aspect ratios of tied wire waste steel fibers to concrete containing 15% crushed brick as coarse aggregate by volume significantly improves the compressive, splitting tensile, and flexural strengths. This allowed to produce high-performance, sustainable concrete with compressive, splitting tensile and flexural strengths of about 85, 6.7, and 9 MPa, respectively, that can be used in different construction projects.

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Author contribution

All authors contributed equally to this work.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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