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Khaled Elsayed
Department of Civil Engineering, Benha Faculty of Engineering, Benha University, Egypt, khaled.mohamed@bhit.bu.edu.eg

mohamed Makhlouf,
Assistant Prof., Department of Civil Engineering, Benha Faculty of Engineering, Benha University, Egypt, mohamedmakhlouf83@yahoo.com

Manar Ali
New Banha Banha, manaradly5@gmail.com

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Impact Resistance of Concrete with Recycled Steel Fibers and Crumb Rubber

K. M. Elsayed, *M. H. Makhlouf* and M. A. Ali*

KEYWORDS:
Waste steel fibers.
Industrial steel fibers.
Rubber concrete.
Drop weight test.
Impact load.

Abstract— **Concrete with waste steel fibers and crumb rubber (WSFCR) was primarily created using components that are extracted from the scrap tires recycling process. Crumb rubber particles of size (1- 4) mm and relative density 1.0 gm/cm3 were included as a partial replacement (10% by volume) of natural sand. Recycled or waste steel fibers were used in four percentages from the total mass of the concrete (0.5%, 1.0%, 1.5%, and 2.0%). The efficiency of WSFCR has primarily been studied to evaluate its performance against impact loads, compared to the performance of traditional concrete (CR 0), rubber concrete (CR 10%), and rubber concrete reinforced with industrial steel fibers (ISFCR). Also, the influence of recycled steel fibers on the different strengths of the rubberized concrete was presented. A total number of eleven slabs (1000×1000×100 mm) were subjected to 10.738 Kg cylindrical steel weight falling from a 1.5 m distance concerning the number of blows at the first crack formation and complete failure. Both WSFCR and ISFCR showed outstanding performance under impact loads compared to CR0 and CR 10% control mixtures. Although ISFCR resulted in a higher impact energy resistance than WSFCR, which showed convergent results and a similar crack pattern; therefore, it is a strong candidate as a low-cost alternative to industrial steel fibers.**

I. INTRODUCTION AND LITERATURE REVIEW

EGYPT'S vision 2030 is to achieve sustainable development in the society, economy, and the environment. Changing the urban map of Egypt, creating large transportation systems considering crucial environmental problems as global climate change, natural resources preservation, rationing water use, and seeking clean, cheap, renewable energy are sustainable achievement goals [1].

The development of the transportation system is presented by implementing high-standard projects to connect the Egyptian cities for commercial and economic purposes, providing safety and security. In 2020, a total length of 625 km of new roads was constructed at the cost of 10.2 billion Egyptian pounds, 500 km of roads were rehabilitated at the cost of 1.5 billion Egyptian pounds, and a total number of 156 bridges and tunnels were implemented [2].

Transportation structures are highly subjected to impact loads compared to ordinary structures that are primarily designed to resist compression, tension, and bending stresses. Highway sub and superstructures such as roads and bridges are used by heavyweight vehicles and trucks that cause severe losses in lives, structures, and the environment when accidents happen [3, 4].

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Khaled Mohamed Elsayed, Professor of Properties and Strength of Materials, Department of Civil Engineering, Benha Faculty of Engineering, Benha University, Egypt (e-mail: khaled.mohamed@bhit.bu.edu.eg).

Mohamed Hussien ali Makhlouf, Assistant Prof., Department of Civil Engineering, Benha Faculty of Engineering, Benha University, Egypt (e-mail: mohamedmakhlouf83@yahoo.com).

****Corresponding Author:** Manar Adly Abbas Ali, Civil Engineer, The General Authority of Educational Buildings, Benha, Qalubia, Egypt- MSc Student at Department of Civil Engineering, Benha Faculty of Engineering, Benha University, Egypt (e-mail: manaradly5@gmail.com).*

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Concrete is a stress/strain sensitive material; its behavior when subjected to dynamic loads is entirely different from static loads [3, 5]. Under static loads, equilibrium equations are applied to calculate reaction forces resulting from the structure's loads. The bending moment and the shear forces are then determined by either the applied or the reaction force. In contrast, under impact loads, supporting reaction forces are insignificant and do not equal the applied impact force because impact load is not resisted by reaction forces only, but impact force and structure's inertial force are also principles in achieving the structure's equilibrium state [6].

Rubber concrete, an effective solution for dumped waste tires problem, is recommended for highway concrete slabs because of its high ductility, toughness, energy absorption, dry shrinkage cracking resistance, post cracking resistance, and durability [7-10]. Also, fiber inclusion in concrete mixtures showed significant toughness and impact resistance [11, 12].

The initial researches that studied rubber concrete performance as a construction material recommended its use in non-structural elements because of its reduced mechanical properties compared to the traditional concrete [13, 14]. Nevertheless, the excellent performance of rubber concrete under impact loads, besides its slow, gradual failure pattern accompanied by alarming cracks widespread in contrast to sudden brittle failure in ordinary concrete, was reported [15, 16]. That encouraged researchers on further studies to improve the mechanical behavior of rubber concrete. Different strategies were applied to find solutions to the causes of rubber concrete's reduced strength, for example, using particular types of cement, adding silica fume, or treating rubber granules before adding to the concrete mix [17-20]. Most importantly, controlling rubber percentage, type, and particle size was the vital solution to restrict rubber concrete's negative performance, which was attributed to the rubber particle characteristics [21]. The maximum rubber percentage was recommended at (15-20%) by volume of the natural aggregate [19, 21, 22]. Valente et al. [23], suggested the maximum rubber percentage at 15% and 8% by the fine and coarse aggregate weight, respectively. Because of the significant effect of the mechanical and physical properties of rubber on the performance of rubber concrete, the major of researchers tended to use rubber particles as a partial replacement of the fine aggregate [7, 24-27].

Further studies were conducted with adding fiber reinforcement to the rubber concrete elements to study their influence on the performance of the rubber concrete [28-30]. Moreover, The dispersed matter of fibers in concrete mixtures encouraged its use as an altering option for conventional reinforcement in high-impact loading applications or sensitive cracking projects such as transportation systems and industrial facilities [31]. Steel fibers have proven their effectiveness in resisting impact loads due to their influence in increasing the durability of concrete, developing the brittle behavior of concrete to a more ductile performance, and controlling the width of the resulting cracks by their bridging effect [32-34].

Elavenil et al. [35], studied the effect of the slab's thickness, the fiber aspect ratios, and percentages on the impact response of concrete. Three thicknesses of 20, 25, and 30 mm and three fiber percentages by volume 0.5, 0.75, and 1.0% of three different aspect ratios (50, 75, and 100) were the main variables for eighteen slabs (600×600 mm) tested under dynamic loads. The impactor of a 4.5 kg cylindrical weight ends with a 0.5 kg steel ball, and the dropping distance of 750 mm was kept fixed for all test trials. Regardless of the slab's thickness, the impact resistance was greatly enhanced by increasing fiber contents and aspect ratio, but the fiber's aspect ratio effect was evident with higher fiber percentages. Also, the crack widths were restricted by increasing fibers' percentage and aspect ratio. The enhanced performance against crack propagation and post-loading resistance was attributed to the dispersed fibers inside the concrete. Regardless of the fiber content, the thickness of the slab affected the crack width as increasing the thickness reduces the crack width.

Murnal et al. [36], studied the effect of end-hooked steel fibers with an aspect ratio of 60 and five different percentages by weight of cement (0.5, 1.0, 1.5, 2.0, and 2.5%) on three different grades of concrete M20, M30, and M40 subjected to impact loads. The increase of impact strength due to using end-hooked steel fibers was ascertained. Also, the dependent relationship between increasing fiber contents and increasing ductility, impact resistance, and energy absorption was proved.

Noaman et al. [28], analyzed the performance of rubber concrete samples reinforced with steel fibers (SRC), compared to ordinary specimens (NC without rubber or fibers), rubber concrete samples (RC), and plain concrete reinforced with steel fibers (SFC). Crumb rubber particles (1 – 2) mm with a specific gravity of 0.73 were partially replaced fine aggregate with a specific gravity of 2.64 by two volumetric replacement ratios (17.5% and 20%). End hooked steel fibers, with a 0.75 mm diameter and an aspect ratio of 80, were used in a fixed percentage of 0.5% by volume. The impacted samples were exposed to a 5.1 kg weight falling from a 0.17 m distance. The impact resistance was enhanced for each RC and SFC at each first and ultimate crack compared to NC; however, the performance of SFC was better than RC. Nevertheless, the combination of rubber and steel fibers significantly enhanced the samples' performance due to their characteristics' integration, as rubber is responsible for the ductility improvement, while steel fibers increased concrete toughness properties and improved its cracking formation resistance.

Girskas et al. [37], concluded that fiber-reinforced concrete is superior in resisting cracks formation, impact loads; therefore, it has high durability, fatigue, and toughness characteristics besides compressive and flexural strengths improvement. Three types of mixtures were manufactured by replacing (1.5%, 3.0%, and 4.5% mass percentages) sand with steel cord scrap that reduced water absorption, open porosity, and increased closed porosity. Consequently, it improved durability and freeze-thawing resistance. A dependent relationship between the substituted scrap cord steel and the increased compressive strength rate was also observed. The estimated cost saving because of using recycled steel fibers instead of industrial steel fibers ranges from 7% to 33% per cubic meter of concrete.

Adding industrial steel fibers to rubber concrete mixtures showed promising results to improve their properties. However, the high cost of the manufactured steel fibers (estimated at 90% increment than plain concrete when used by 1.5% by volume) still limits their use in practical fields. Therefore, cheap alternative sources for manufactured fibers with comparable mechanical properties are necessary to study [38].

Tire waste steel fibers are produced by recycling tires process considering that 15% of a vehicle tire's weight is high-grade steel cords while contributing about 25% of a truck tire's weight [39]. Massive numbers of waste tires are dumped annually due to their short service period (about five years), in addition to accumulated numbers in landfills [40].

A global vision is moving towards sustainability and a healthy environment, and laws enacted by many countries prohibit dumping out-of-date tires in landfills. Therefore, waste tires recycling is growing; consequently, their extracted materials are constantly increasing as rubber and steel fibers [38]. These materials should be exploited effectively; otherwise, they will be wastes.

Despite their irregular geometries, disparity of their lengths and diameters, particularly fibers recycled by shredding scrapped tires, also their undefined physical and mechanical properties, according to the defined properties of steel beads used in the tire industry, recycled steel fibers from waste tires can be described to have high tensile strength (1600-2000 MPa) and aspect ratio higher than 100, grooved surface texture enhances their bond with the cement matrix over the industrial steel fibers of smooth surface [38, 41-43].

The efficiency of tire steel fibers on the compressive strength and freeze-thaw resistance of the conventional plain concrete was reported by Girskas [44]. Also, Dehghanpour et al. [45], reported an increase in the compressive strength, flexural strength, toughness, and the absorbed energy under impact loading compared to plain cement mortars. Bdour et al, [41] confirmed the privileged role of waste steel fibers similar to industrial steel fibers in controlling crack, and increasing post-failure resistance, consequently converting the brittle nature of concrete to ductility performance.

According to the concluded results of the privileged role of industrial steel fibers on improving the properties of rubber concrete but their high-cost values, and the promising results obtained by tires recycled steel fibers of low cost. Furthermore, the coalescence effect of tires recycled steel fibers and crumb rubber particles on the performance of concrete is studied.

This research studies the main characteristics and the impact resistance of rubberized concrete with recycled steel fibers extracted from used tires as a low-cost alternative material to industrial steel fibers and excellent solutions for several economic and environmental issues.

II. EXPERIMENTAL PROGRAM

Eleven slabs (1000×1000×100 mm) were tested under impact load: two control slabs were made of plain concrete (CR0), one slab was made of rubber concrete mixture prepared by 10% by volume of crumb rubber (CR10%), four slabs (one slab for each fiber's ratio) were made of Waste Steel Fibers Reinforced Rubber Concrete (WSFRC), and another four slabs were made of Industrial Steel Fibers Reinforced Rubber Concrete (ISFRC).

Each slab was accompanied by six cubes (150×150×150 mm), three cylinders (150×300 mm), and three beams (100×100×500 mm), except for the two slabs made of the plain concrete mixture, they both were accompanied by six cubes, three cylinders, and three beams. These specimens were tested to study the mechanical properties of each mixture.

A detailed description of the different prepared mixtures, the number of slabs for each type of concrete, and the number of companion specimens are presented in Table 1.

TABLE 1
THE NUMBER OF TESTED SPECIMENS

Mixture Type	**Cube 150×150×150 (mm)**	**cylinder 150×300 (mm)**	**Beam 100×100×500 (mm)**	**Slab 1000×1000×100 (mm)**
Traditional Concrete				
CR0 (Control)	6	3	3	2
Rubber Concrete				
CR 10%	6	3	3	1
Waste Steel Fiber Rubber Concrete				
WSFCR 0.5%	6	3	3	1
WSFCR 1.0%	6	3	3	1
WSFCR 1.5%	6	3	3	1
WSFCR 2.0%	6	3	3	1
Industrial Steel Fiber Rubber Concrete				
ISFCR 0.5%	6	3	3	1
ISFCR 1.0%	6	3	3	1
ISFCR 1.5%	6	3	3	1
ISFCR 2.0%	6	3	3	1
Total	60	30	30	11

A. *Materials*

All the used materials are locally available natural resources (sand, dolomite) and Egyptian manufactured (cement, industrial steel fibers, rubber, and waste steel fibers). Samples of the recycled materials (crumb rubber and steel fibers) and the industrial steel fibers are presented in Figure 1. The physical properties of the natural aggregates were experimentally assigned, and the properties of the manufactured materials were provided by their producers.

a) Ordinary Portland cement with a specific gravity of 3.15, manufactured according to the European standard (EN 197-1:2011/CEM I 52.5 N) and the Egyptian standard (ES 4756-1 /2013), was the binding material. The properties presented in Table 2 were assigned experimentally.

TABLE 2
ORDINARY PORTLAND CEMENT PROPERTIES

Property	Test Result	Standard Limits
Fineness of Cement	1.6%	≤ 10%
Specific Gravity	3.15	-
Setting Time (hr.: min) *Initial* *Final*	 1:45 7:30	 ≥ 45 min. ≤ 10 hr.
W/C for consistent cement paste	27%	-

b) Dolomite coarse aggregate with a nominal maximum size aggregate of 19mm, a specific gravity of 2.67, known commercially as Attaka No 1. Its properties are recorded in Table 3. Dolomite is strongly suggested by the Egyptian Code of Practice for Urban and Rural Roads [46] in producing concrete for road paving, bridge decks, and airport runways due to its high physical and mechanical properties; high hardness and abrasion resistance, and low porosity.

TABLE 3
COARSE AGGREGATE CHARACTERISTICS

Property	Test Result	Standard Limits
Max Grain Size (mm)	19	Compatible with Egyptian Code of Practice for Urban and Rural Roads[46] recommendation
Specific Gravity	2.67	-
Bulk Density (kg/m^3)	1350	-
Absorption	1.9%	≤ 2.5%
Crushing Value	17%	≤ 25%
Abrasion Resistance (Los Angeles machine)	28%	≤ 30%

c) Natural sand aggregate with a nominal maximum size of 4.75 mm, a fineness modulus of 3.77, and a specific gravity measured as 2.67. Its properties are presented in Table 4.

TABLE 4
FINE AGGREGATE CHARACTERISTICS

Property	Test Result	Standard Limits
Max Grain Size (mm)	4.75	-
Specific Gravity	2.67	(2.50-2.75)
Bulk Density (kg/m^3)	1570	-
Fineness Modulus	3.77	-
Fine Materials (by weight)	2.4%	≤ 3%

d) Recycled rubber aggregate with particle size range (1-4) mm and relative density 1.0 gm/cm^3. It was derived from wasted automotive and truck tires and recommended for construction and asphalt applications.

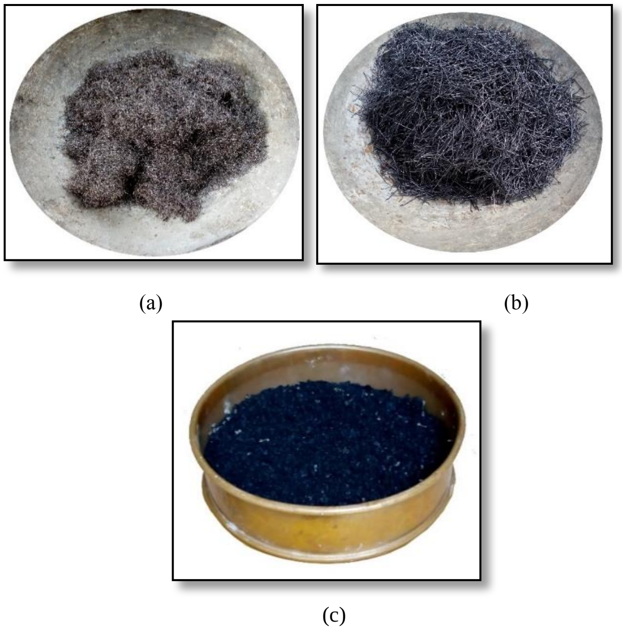
Two different sources and types of steel fibers were used:

e) Recycled fine scrap steel fibers of irregular random shapes because they are by-products of waste truck tires shredding and separated by magnetic tools (98% free from rubber particles). It was recommended by the manufacturer to be incorporated in the steel industry and concrete slab reinforcement.

f) End hooked steel fibers made of cold drawn wire (35 mm length× 0.80 mm diameter, length of hook 4-6 mm) with an aspect ratio of 43.75 and have a tensile strength of 1100 N/mm^2 (±10%). It was recommended for flooring, roads, pavements, and shotcrete applications. The data provided by the producer are presented in Table 5.

TABLE 5
INDUSTRIAL STEEL FIBERS CHARACTERISTICS

Type	Length (L) (mm)	Diameter (D) (mm)	Tensile Strength (MPa)	Aspect Ratio (L/D)	Surface Texture
End-Hooked Steel Fibers	35 (± 3 mm)	0.80 (± 0.05 mm)	1100 (± 10%)	43.75	Clear, bright, and loose


(a) (b)

(c)

Figure 1. (a) Recycled Steel Fiber; (b) Industrial Steel Fiber; (c) Crumb Rubber

B. Mixing Proportion and specimens preparation

Plain concrete with a 28-day target strength of 30 MPa was designed based on the Egyptian Code for Urban Roads specifications to simulate the concrete pavement decks [46].

Four percentages by concrete mass (0.5%, 1.0%, 1.5%, and 2.0%) of recycled and industrial fibers were mixed with rubber particles which were partially replaced fine aggregate in a percentage of 10% by volume, namely as (WSFCR 0.5%, 1.0%, 1.5%, and 2.0%), and (ISFCR 0.5%, 1.0%, 1.5%, and 2.0%). The constituents of the used mixes are presented in Table 6. Recycled steel fibers were specified by concrete mass percentage to avoid undesired problems as balling or non-uniformly dispersed pattern due to their irregular shapes and higher aspect ratio [29].

The materials were mixed dry for a minute, then half the water amount was added, and the mixing continues for another minute. After that, the second half of the water was added, and the mixing continued for another three minutes. The fibers were progressively added while the mixer mixes the other ingredients to avoid the conglomeration problem [47].

The mechanical properties of each mixture in compression, tensile, and flexural strengths were assigned according to the Egyptian Code of Practice 203 [48]. The obtained results are shown in Table 7.

TABLE 6
THE COMPOSITION OF WASTE/INDUSTRIAL STEEL FIBER RUBBER CONCRETE

Materials (Kg/m^3)	***Cement***	***Water***	***Coarse Aggregate***	***Fine Aggregate***	***Crumb Rubber***	***Fibers***
CR0 (Control)	400	200	1159	636.5	0	0
CR10%				573	23.8	0
WSFCR 0.5%						12.10
WSFCR 1.0%						24
WSFCR 1.5%						36.29
WSFCR 2.0%						48.39
ISFCR 0.5%						12.10
ISFCR 1.0%						24
ISFCR 1.5%						36.29
ISFCR 2.0%						48.39

III. IMPACT LOAD TEST

A simple low-velocity impact load test setup was applied at the materials lab at Banha Faculty of Engineering. A cylindrical flat-ended steel mass weighs 10.738 Kg was manually dropped from a height of 1.5 m to hit simply supported 1.0 m squared slab of 100 mm thickness, as illustrated in Figure 2. This test aims to calculate the impact energy of each slab using Eq (1).

$$E_{imp} = (mgh).n \qquad (1)$$

Where;

m is the weight of the cylindrical mass (10.738 Kg).

g is the acceleration of gravity (9.81 m/s^2).

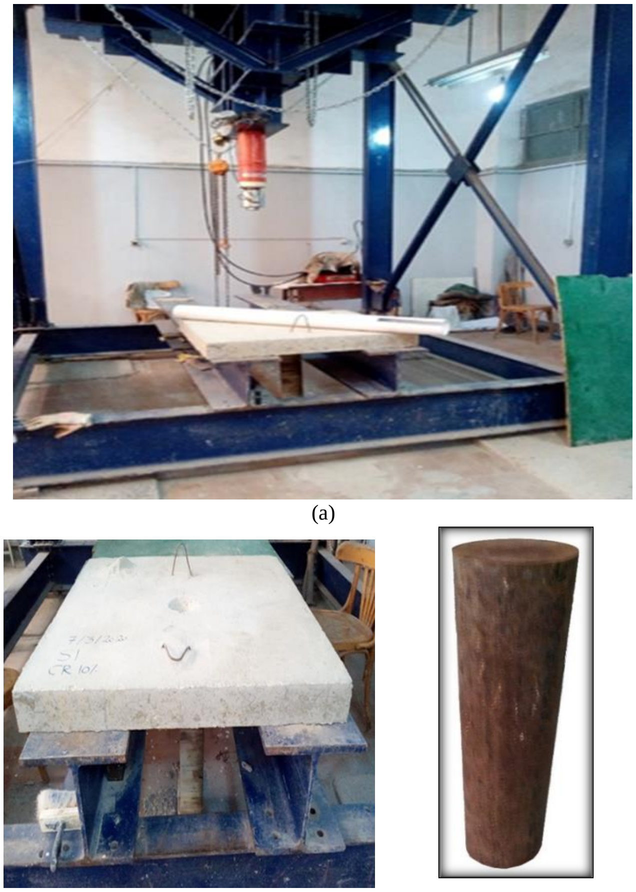
h is the fall distance (1.50m).

n is the number of hits at (first crack/failure).

The main parameters for analyzing the performance of the impacted slabs are; the number of blows responsible for the first crack formation, and those causes the specimen's complete failure and the corresponding impact energy, the effect of different fiber types, and percentages on the absorbed energy, and the pattern of cracks and the failure type.

Each slab was visually checked after each impact to investigate the cracks produced on the top and bottom surfaces. Each crack was tracked by a marker and numbered according to the number of blows responsible for its appearance. Therefore, an error percentage may be attributed to the author's estimation of the first crack appearance.

The absorbed energy, the crack initiation, growing and width, the failure pattern (local or global or combined), and the severity of damage at the impacted zone are the main parameters that were studied to evaluate and compare the effect of different steel fiber contents and types (Industrial/Waste) on the performance of each slab under impact loading.


(a)

(b) (c)

Figure 2. Impact test (a) Test set-up; (b) The impacted slab; (c) The drop-weight

IV. RESULTS AND DISCUSSION

The properties of each mixture at fresh and hardened phases are shown in Table 7.

TABLE 7
TEST RESULTS

Slab	Slump value (mm)	Fresh density	Compressive Strength (MPa)		Splitting Tensile Strength (MPa)	Flexural Tensile Strength (MPa)
			7 days	28 days		
CR0 (Control)	55	2194	29.467	38.8	3.3	5.44
CR 10%	30	2150	29.13	33.73	1.6	4.98
WSFCR 0.5%	45	2162	21.67	32.2	2.4	5.49
WSFCR 1.0%	65	2141	17.4	25.83	2.3	4.20
WSFCR 1.5%	28	2164	25.03	31.63	2.5	5.14
WSFCR 2.0%	25	2188	27.46	35.76	2.8	5.03
ISFCR 0.5%	60	2164	20.6	30.5	2.7	5.02
ISFCR 1.0%	70	2186	22.33	30.23	2.8	4.93
ISFCR 1.5%	40	2211	25.3	33.16	2.4	5.44
ISFCR 2.0%	22	2233	25.23	35.16	3.2	5.38

A. Slump Test Results

Substituting 10% by volume of natural sand with rubber particles reduced the slump value by 45%. The rubber content-slump reduction relationship was proved in previous works and attributed to rubber particles' nature that causes friction between the particles resulting in low flowable mixtures.

The effect of fiber addition (Waste or Industrial) in small ratios (0.5 and 1.0%) on the slump values was unpronounced; however, increasing these ratios to (1.5 and 2.0%) significantly reduced the slump values.

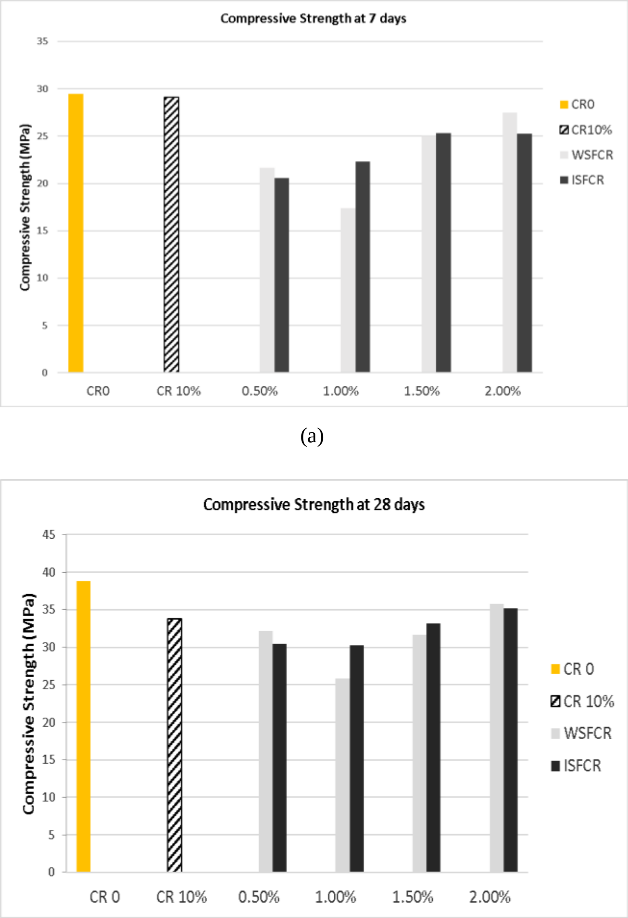
The lowest slump values were recorded for WSFCR 1.5%, WSFCR 2.0%, and ISFCR 2.0% with a reduction rate of 49%, 54%, and 60% respectively. However, these mixes were workable and efficiently compacted and molded using a vibrator. This reduction was interpreted to fiber conglomerations, especially with higher contents.

B. The compressive strength

A slight reduction was observed in the compressive strength of CR10% by 1.0% at seven days, but, at 28 days, the compressive strength reduced by 13% (see Figure 3). This reduction was attributed to rubber properties; its tendency to entrap air, besides its compressibility nature, produces high void percentages in concrete which act as zero-strength aggregate particles. In addition, its elasticity and compressibility nature act as springs that cause internal tensile stresses responsible for crack initiation.

A noticeable decline in the compressive strength was observed due to fiber addition (Waste or Industrial) by a maximum reduction value of 40%, and 23%, at 7 and 28 days, respectively; but the reduction rate was lesser at 28 days, and both WSFCR2.0% and ISFCR2.0% specimens achieved a maximum strength of 35 MPa by an increase up to 6% compared to CR10%.

A slight effect of fibers on the compressive strength was reported in previous research; moreover, increasing fiber length reduces the compressive strength due to increasing entrapped air.



(a)

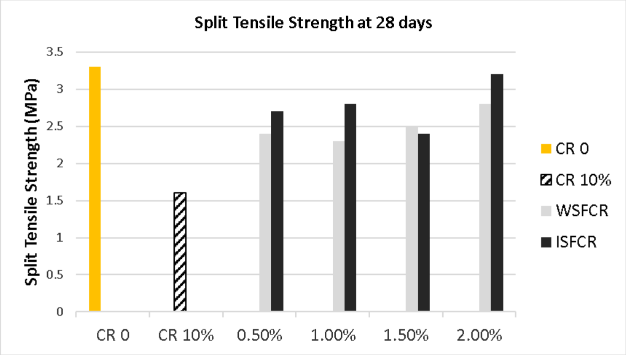
(b)

Figure 3. Compressive strength results (a) at 7 days; (b) at 28 days

C. *The splitting tensile strength*

The splitting tensile strength decreased by 51% for CR 10% compared to CR 0. Adding fibers also reduced the splitting tensile strength compared to CR 0; however, it significantly enhanced the strength of CR10%, as presented in Figure 4. Increasing fiber percentages increased the splitting tensile strength significantly except for specimen ISFCR 1.5%, which showed an illogical strength drop. The best value was recorded for ISFCR 2.0%, which nearly achieved the strength of the control sample. Compared to CR 10%, the splitting strength increased by 50%, 44%, 56%, and 75% for WSFCR (0.5%, 1.0%, 1.5%, and 2.0%, respectively) and increased by 69%, 75%, 50%, and 100% for ISFCR (0.5%, 1.0%, 1.5%, and 2.0%, respectively).

This reduction has been interpreted to the lower modulus of elasticity for crumb rubber particles in addition to the weak bond between rubber particles and the cement paste. The addition of steel fibers (waste/industrial) enhanced the strength reduction resulted from rubber particle addition because of the crack bridging effect of steel fibers.

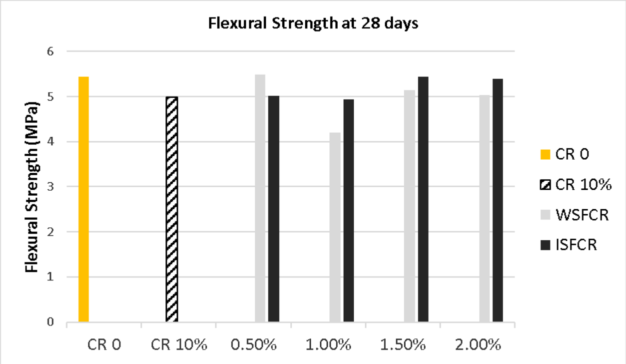


(a)

Figure 4. The splitting tensile strength at 28 days

D. *The flexural strength*

The flexural strength slightly decreased for CR 10%, but by 8.5%, then the strength slightly enhanced by adding fibers up to 8% compared to specimen CR 10%, except specimens WSFCR 1% and ISFCR 1%, which showed a slight reduction in flexural strength compared to specimen CR 10%, by 16% and 1%, respectively, see Figure 5. Adding fibers to rubberized concrete has an unclear effect on flexural strength enhancement as on the splitting tensile strength.



(b)

Figure 5. The flexural strength at 28 days

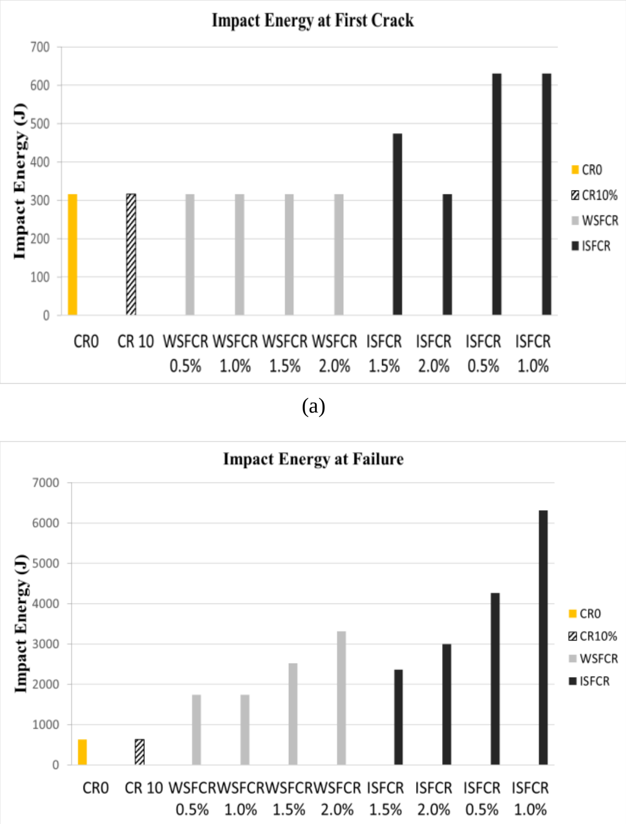
Fibers positively improve the splitting tensile and flexural strengths of crumb rubber mixtures, contrary to compressive strength, due to their bridging effect. Which controls cracks, preserves structure integrity, and resists internal tensile stresses.

V. IMPACT TEST RESULTS

A. *Impact Resistance*

Both the impacted concrete structure and the impactor are responsible for collision energy dissipation. Therefore, soft and hard impact situations are differentiated considering the distortion extent regarding the impactor and the compacted structure. Soft impact results in deforming the impactor, while hard impact causes cracking the impacted body [49].

As illustrated in Figure 6, both CR 0 and CR 10% were first cracked by the second blow and exhibited a brittle failure pattern after four blows. The addition of fibers did not enhance the number of blows responsible for first crack initiation, but it significantly increased the number of blows that caused the complete failure compared to CR 0 and CR 10%. The impact resistance increased by 175% for both WSFCR 0.5% and WSFCR 1.0%, which have the same number of blows at both first crack and failure; however, the cracks pattern and failure type were different as explained in the next section (see Figures 9-10).



(a)

(b)

Figure 6. Impact Energy (a) at first crack; (b) at failure

ISFCR achieved a higher number of blows than WSFCR and improved the impact resistance at the ultimate load by 275% and 375% for ISFCR 0.5% and ISFCR 1.0%. The positive relationship between the fiber percentages and the impact resistance was assured. Increasing fiber percentages to 1.5% increased impact resistance by 300% and 575% for WSFCR and ISFCR, respectively. Moreover, the impact resistance for WSFCR 2% and ISFCR 2% was increased by 425% and 900%.

ISFCR specimens revealed higher impact resistance than WSFCR specimens by 100%, 100%, 275%, and 475% and showed better performance before failure at fiber percentages of 0.5%, 1.0%,1.5%, and 2.0%, respectively. Nevertheless, the impact resistance of WSFCR 2.0% was approximately similar to that of ISFCR1%; therefore, recycled steel fibers in higher percentages can simulate the effect of synthetic steel fibers.

The difference between the number of blows required for the first crack formation (N_1) and those at the complete failure of the specimen (N_2) was increased with increasing fiber percentages. That represents the increasing ductility and toughness of fiber reinforced concrete compared to the brittle behavior of normal concrete with a humble difference in the number of blows at first crack and failure occurrence. In addition, (N_2-N_1) was higher for samples contain industrial steel fiber than those made of waste steel fiber. That was attributed to the strong bond between the industrial fibers and the concrete matrix, their superior absorption capacity, tensile strength, and high pullout resistance. The Impact test results are presented in Table 8.

TABLE 8
MPACT TEST RESULTS

Slab	Number of Blows at First Crack (N_1)	Number of Blows at Failure (N_2)	Impact Energy At first crack (J)	Impact Energy at Failure (J)	N_2-N_1	Absorbed Energy (J)
CR0 (Control)	2	4	316	631	2	315
CR 10%	2	4	316	631	2	315
WSFCR 0.5%	2	11	316	1736	9	1420
WSFCR 1.0%	2	11	316	1736	9	1420
WSFCR 1.5%	2	16	316	2526	14	2210
WSFCR 2.0%	2	21	316	3315	19	2999
ISFCR 0.5%	3	15	474	2368	12	1894
ISFCR 1.0%	2	19	316	2999	17	2683
ISFCR 1.5%	4	27	631	4262	23	3631
ISFCR 2.0%	4	40	631	6314	36	5683

B. Failure Pattern

The response of concrete structures subjected to impact loads is differentiated to local and global cracking mechanisms, considering the most affected region due to the collision. Local failure is defined as the majority of cracks are concentrated around the impacted area; its styles are categorized as penetration, cone cracking and plugging, spalling, radial cracking, scabbing, and perforation. In contrast, global failure typically happens in the whole structure due to bending and shear stresses. Structures may respond locally, globally, or in combination. The local response is typical in impacted slabs and shells, whereas the global response is typically tested in beams [49, 50].

A brittle failure pattern was dominant in the control specimens (CR0 & CR10%); the first slab was divided into two parts after four strikes, and the second slab broke down into three parts after four strikes (see Figures 7-8).

The slabs were supported against vertical and horizontal movements, but the free rotational movement was allowed.

The number of blows at the first crack was nearly constant at the second impact for all specimens except for the two specimens with industrial steel fibers of 1.50% and 2.0%, which first cracked at the fourth impact. Also, the first crack was repeatedly shown in the thickness of the slab, then advanced cracks displayed at the top and bottom faces, except for ISFCR 1.5% and 2.0%, which first cracked at the bottom and top sides, then cracking at slab’s thickness was displayed. The most predominant cracks at the top and bottom sides were directed from the slab's center to its four sides, making a star shape.

A local failure pattern was dominant at lower fiber percentages (0.5% and 1.0%), but a combining local and global response was evident at higher ratios (1.5% and 2.0%).

All specimens were perforated and scabbed except for specimens ISFCR 0.5% and 1.5%, which were intentionally skipped from the last impact to investigate cracks pattern at the bottom side of the impact zone before scabbing. The equivalent diameter of the perforation at the slab's top surface was approximately constant at (8.8-9.5 cm), but the scabbed area was varied, corresponding to fiber contents. The substantial effect of adding steel fibers on crack width controlling was evident for industrial and recycled fibers. However, industrial fibers showed superiority over recycled fibers.

Although both WSFCR 0.5% and WSFCR 1.0% recorded the same number of strikes at first and failure cracks, WSFCR 1.0% showed slower and more gradual crack propagation. Also, the perforated part of the slab was kept attached to it by the fibers. Moreover, the scabbing area decreased compared to WSFCR 0.5% (see Figures 9-10). For ISFCR, a similar crack and failure pattern was observed for specimens with (0.5, or 1.0% fiber ratios) (see Figures 13-14), but the number of strikes at failure increased; consequently, the impacted energy slightly increased by 27%. WSFCR 1.50% showed similar behavior to ISFCR 1.0%, as the cracks were gradually extended with small cracks width compared to the previous percentages (see Figures 11-14).

In contrast to previous surface crack patterns spread from the center of the slab to its four sides, a tangled crack network was created for ISFCR 1.5% at the top and the bottom of the slab, as presented in Figure 15. WSFCR 2.0% and ISFCR 2.0% showed similar performance to those with 1.5% fiber (see Figures 12-16), but the number of blows to break the slab was elevated.

All slabs with fibers (Industrial or Waste) were intact after failure due to the fiber bridging effect that sews cracks and restricts their opening. Although ISFCR recorded a higher number of blows than WSFCR, their value was convergent, representing a solid candidate as an alternative to industrial fibers.

The privilege results from combining rubber concrete with steel fibers of both types were achieved due to exploiting both materials advantages', the distinguished ductility of rubber accompanied by cracking control of steel fibers.

Figure 7. The control slab (CR 0) -Top surface

(a) Top Surface (b) Complete Failure

Figure 8. The crumb rubber concrete slab(CR 10%)

(a) (b)

Figure 9. WSFCR 0.5% (a) Top surface; (b) Bottom surface

(a) (b)

Figure 10. WSFCR 1.0% (a) Top surface before penetration; (b) Bottom surface at failure

(a) (b)

Figure 11. WSFCR 1.5% (a) Top surface; (b) Bottom surface

(a) (b)

Figure 12. WSFCR 2% (a) Top surface; (b) Bottom surface

(a) (b)

Figure 13. ISFCR 0.5% (a) Top surface; (b) Bottom surface

(a) (b)
Figure 14. ISFCR 1.0% (a) Top surface; (b) Bottom surface

(a) (b)
Figure 15. ISFCR 1.5% (a) Top surface; (b) Bottom surface

(a) (b)
Figure 16. WSFCR 2.0% (a) Top surface; (b) Bottom surface

VI. CONCLUSION

This paper mainly studies the efficiency of recycled steel fibers from tires as an alternative for industrial steel fibers, particularly under impact loads, by applying a low-velocity impact load test. Four fiber percentages by the total mass of concrete (0.5%, 1.0%, 1.5%, and 2.0%) were combined separately with a fixed rubber content of 10% by volume replaced from the fine aggregate.

The comparison between these two fiber types was evaluated regarding the number of blows at first crack and specimen's failure, the effect of fiber content on the concrete performance, and the specimen's crack propagation and failure pattern. Also, the influence of using recycled steel fibers on the different strengths of the rubberized concrete was studied. The most significant results are as follows:

- The slump value of the control specimen decreased by 45% due to partial replacement of sand with 10% by volume of crumb rubber; however, the CR10% mixture was still workable.
- The addition of fibers (Waste or Industrial) to the rubberized concrete mixture has an insignificant effect on its workability. Even for the lowest slump values recorded for mixtures with 2.0% by weight fibers, the mixes were workable and easily compacted by a mechanical vibrator.
- The influence of (Waste or Industrial) fibers on the mechanical properties (compressive or flexural strength) of concrete (CR0 or CR10%) was unpronounced compared to their influence on the splitting tensile strength which was increased by 75% and 100% for WSFCR2.0% and ISFCR2.0%, respectively, compared to CR10%.
- The effect of substituting 10% by volume of sand with crumb rubber on the compressive strength was null; conversely, fibers addition (Waste or Industrial) badly reduced the compressive strength compared to both the plain CR0 and the crumb rubber CR10% mixtures.
- There is a positive relationship between the fiber percentages and the impact resistance, as increasing fiber percentages increased the number of blows; the tested slabs containing 2.0% of fibers recorded the highest numbers at failure for both waste and industrial fibers. Although ISFCR specimens recorded a higher number of blows than WSFCR specimens, their value was convergent, representing that waste steel fibers are a strong candidate as an alternative to industrial fibers.
- The influence of fiber type and properties (material, geometrical characteristics, and aspect ratio) are evident in the performance of slabs made of the fine recycled fiber with irregular shape and those made of the end-hooked industrial steel fibers with an aspect ratio of 43.75 and a tensile strength of 1100 N/mm^2. About the double percentage of recycled steel fibers is required to achieve the same impact resistance of industrial steel fibers.
- Opposing to the brittle failure pattern mostly happened in slabs made from both plain and rubber concrete mixtures, other slabs made from rubber with fibers concrete mixtures exposed a ductile failure pattern. The ductile failure pattern was evident in an increased cracking pattern, slowly and progressive cracks growth, reducing cracks widths, significant deflection, the intact body of the punched slabs.
- Energy absorption capacity was increased by increasing fiber percentages, particularly at higher fiber ratios (1.5 and 2.0%), as the gap between the number of blows required for the first crack and those that caused slab's failure increased. Fiber ratios of (0.5, 1.0, 1.5, and 2.0%) increased the energy absorbed by 351, 351, 602, and 852; and 501, 752, 1053, and 1704, for WSFCR and ISFCR, respectively. That was attributed to the cracks bridging role that preserves the structure's integrity and consequently increases its post-cracking load resistance.
- Increasing fiber content has a potential influence on crack propagation and widths. A progressive pattern was observed for crack formation. It firstly appeared in short lengths and hairline widths and continued to extend and open with consecutive blows. Also, the

crack spread was more evident with high fiber percentages making a sufficient warning to the sample failure and indicating the failure pattern change from brittle to ductile mode.

AUTHORS CONTRIBUTION

K. M. Elsayed

He substantially contributed in approving the research topic and the concept of work, including the experimental program's supervision (samples preparation and testing), and final revision of the research paper to be published.

M. H. Makhlouf

He substantially contributed in the research review, investigation, submitting feedback, and following the publishing requirements.

M. A. Al

She determined the tools of Data collection, Data analysis and interpretation, Resources and writing the literature review, Methodology of the experimental program (samples preparation and testing), and Drafting the article.

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Title Arabic:

مقاومة الصدم للخرسانة ذات ألياف الصلب المعاد تدويرها وحبيبات المطاط

Arabic Abstract:

يعتمد إنتاج الخرسانة بإستخدام نفايات ألياف الصلب وحبيبات المطاط (WSFCR) على المواد التى يتم إستخراجها من عملية إعادة تدوير الإطارات التالفة. تم إستخدام حبيبات المطاط ذات مقاس (١-٤) مم وبكثافة ١.٠ جم / سم٣ كنسبة (١٠٪) من حجم الرمل الطبيعى المستخدم. تم تسليح الخرسانة بألياف الصلب المعاد تدويرها بإستخدام أربعة نسب مئوية من الكتلة الكلية للخرسانة (٠.٥٪ ، ١.٠٪ ، ١.٥٪ ، ٢.٠٪). تمت دراسة كفاءة (WSFCR) بشكل أساسي لتقييم سلوكها ضد أحمال الصدم، مقارنة بسلوك الخرسانة التقليدية (CR 0) ، الخرسانة المطاطية (CR 10%) ، والخرسانة المطاطية المسلحة بألياف الصلب الصناعية (ISFCR) . كما تم دراسة تأثير الألياف الصلب المعاد تدويرها على مقاومة الخرسانة المطاطية تحت تأثير مختلف الاحمال. تم إختبار ١١ لوح بأبعاد (١٠٠٠ × ١٠٠٠ × ١٠٠ مم) بتعريضهم للصدم بجسم اسطوانى من الفولاذ يزن ١٠.٧٣٨ كجم ،يسقط من مسافة ١.٥ متر لتسجيل عدد الضربات المسئولة عن ظهور الشرخ الأول وكذلك عدد الضربات المسئولة عن الانهيار الكامل للبلاطة المختبرة. أظهرت كل من عينات الخرسانة المطاطية المسلحة بالألياف المعاد تدويرها (WSFCR) والخرسانة المطاطية المسلحة بالألياف الصناعية (ISFCR) أداءً متميزًا في مقاومة أحمال الصدم مقارنةً بعينات الخرسانة التقليدية CR0 والخرسانة المطاطية CR 10٪ . وبالرغم من تفوق العينات المسلحة بالألياف الصناعية (ISFCR) فى مقاومة أحمال الصدم مقارنة بمثيلتها من العينات المسلحة بالألياف المعاد تدويرها(WSFCR) ، إلا أن نتائج مقاومة الصدم للمجموعتين (WSFCR) و (ISFCR) كانت متقاربة وكذلك نمط الانهيار ؛ لذلك فإن الألياف المعاد تدويرها بمثابة مرشح قوي كبديل منخفض التكلفة لألياف الصلب الاصطناعية