Influence of Crumb Rubber and Recycled Steel Fibers on Hybrid Layered Reinforced Concrete Columns under Compression Load

Hasan A. Alasmari
Civil Engineering Department, Faculty of Engineering, Taif University, Saudi Arabia
h.alasmari@tu.edu.sa (corresponding author)

Received: 7 January 2024 | Revised: 2 February 2024 | Accepted: 4 February 2024

 DOI: https://doi.org/10.48084/etasr.6876

ABSTRACT

Waste tires pose an environmental issue that causes health problems when discarded by either land burial or burning. The current study investigated the properties and characteristics of different-length hybrid layered columns of Recycled Steel Fibers (RSF) at a fixed ratio (0.6%) of the volume fraction with utilized fixed content (15%) of Crumb Rubber (CR). Nine square column specimens were prepared and tested under axial compression load to reveal the effect of RSF and CR content on hybrid layered reinforcement columns. The results revealed that as the RSF content increased concrete's properties were enhanced. However, the inclusion of CR at the top layer resulted in performance reduction. Additionally, the layered structure with CR and RSF has higher characteristic properties, including higher load capacity and displacement. Moreover, adding 0.6% RSF to both layers and CR at the top led to a 120% increase in the toughness of the concrete loading capacity. This was followed by a reasonable improvement in displacement and ductility.

Keywords-RSF; CR; layered structure; fixed ratio; axial compression

I. INTRODUCTION

Massive numbers of old and damaged tires are typically burned, buried, or disposed of in landfills causing numerous complicated environmental problems [1]. Therefore, many environmental agents have been striving for environmentally sustainable solutions to important issues such as the disposal of rubber from scrap tires. The latter are becoming a major cause of health problems (mosquito-borne diseases, air pollution, etc.). Insufficient dumping areas and hesitancy in using scrap tires have led to huge excesses of scrap tires in many countries. Authors in [1] note that the recycling of waste tires has received growing attention, with engineers trying to find new recycling approaches. Conversely, there is an increasing demand for concrete, which consumes Natural Aggregates (NA) [2]. Consequently, researchers were intrigued by the prospect of reusing old tire components like Crumb Rubber (CR) and Recycled Steel Fibers (RSF) in a variety of disciplines to reduce their environmental impact and natural resource consumption [3]. It has been shown that utilizing steel fiber in concrete leads to an increase in concrete strength, ductility, and toughness. Authors in [4] investigated the mechanical properties caused by the incorporation of waste metallic fibers of different lengths in concrete and reported that this leads to the best load-carrying capacity with improved concrete properties. Authors in [5] experimented with different volume fractions of RSF to assess its impact on compressive, tensile, and flexural strength. The results demonstrated that the highest compressive strength was acquired for 0.4% volume fraction, whereas the lowest strength was acquired for 0.6%. In contrast, incorporating CR in concrete led to a negative impact, as it reduced the concrete compressive strength [6]. The similarities in the mechanical properties of concrete with the same impact were found in [7]. According to [8], there is a major problem when using CR in the mixtures: it tends to segregate as the rubber absorbs water, causing increased air spaces, which leads to a fragile matrix by increasing stress concentration. The density of CR is lower compared to NA, with a weak bond between the cement paste and CR [9]. In contrast, there are positive effects of incorporating CR in concrete, notably enhancing earthquake resistance by dissipating the impact through energy absorption [8]. Another positive effect is that rubber delays crack initiation at the tension zone [10]. Several studies have employed different techniques and trials to reduce the CR effect on concrete properties [11-13], including partial replacement of fine or coarse aggregates. Most studies suggest an ideal replacement of CR between 10% and 15% of fine aggregates to achieve a homogenous interaction with the rest of the concrete composite and thus obtain the best results [11-14]. To minimize the CR effects in concrete structure, a layered structure can minimize the impact [15-16]. Some layered structures can be named as hybrid concrete with different materials inserted in each layer controlling the reduction of load capacity due to the concentration of waste material. Authors in [17] conducted comparative studies of the rubberized and hybrid rubberized concrete with double-layer reinforced concrete beams. At the top layer rubberized reinforcement concrete was placed with sand replacement of 10%, 12.5%, and 15% by CR, while at the bottom normal reinforcement concrete was used. The beam characteristics were evaluated and it was discovered that the performance of the hybrid beams improved in ultimate load, stiffness, and failure pattern. Also, it was confirmed that these applications can be used in sustainable structures. In this regard, authors in [16] investigated the isolated hybrid structure columns with two layers of up to 30% depth in their sections. The normal concrete was on top, and the scrap rubber was at the bottom. This concrete was tested under resonant excitation. The results showed that these kinds of structures can reduce the structure's response when exposed to load. Authors in [18] considered 5%, 10%, and 20% CR as a partial replacement for sand in three kinds of 50×100×400 mm^3 prism beams, namely plain concrete, rubberized concrete, and hybrid rubberized concrete with a double layer (rubberized concrete top and plain concrete bottom) under three-point bending static load. The results disclosed that the peak value of bending load (N) of hybrid rubberized concrete was higher than that of rubberized concrete beams and lower than that of plain concrete. An extensive literature review was conducted; some tests were on RSF and rubberized concrete on different scale specimens. On the contrary, there were limited studies that have investigated the characteristics of layered columns with recycled waste materials (RSF and CR).

In this study, nine columns with RSF and CR in two layers were examined. One layer had rubberized concrete with 15% CR replacing fine aggregates, while the other layer had RSF at 0.6% volume fraction, with different lengths, ranging from 2 cm to 6 cm. The layered concrete columns were subjected to axial compression load until failure. To explore the benefit of using a hybrid approach with CR and mitigate their negative effects, load capacity, displacement, ductility, and failure modes were determined and compared. This investigation will help reduce the cost of structures, ensure the sustainability of buildings through the repurposing of materials, and raise confidence in these applications.

II. MATERIALS AND METHODS

This research investigated the effects of using waste tires having 15% CR as partial replacement of fine aggregates with a fixed ratio of RSF (0.6%) in a hybrid layered structure for columns, cubes, and cylinders. All the specimens, i.e. the control concrete, fibrous rubberized concrete, layered rubberized concrete, fibrous concrete, and layered fibrous rubberized and fibrous concrete were subjected to axial compression tests.

A. Materials

RSF 0.6% (Figure. 1(a)) and CR (Figure 1((b)) were obtained from a local company in Saudi Arabia (Kenzy Rubber Factory). The mix diameter of the CR was 4.75 mm, the computed specific gravity and water absorption for CR were 1.26 and 1.03, respectively, whereas the fineness modulus was 4.5. The RSF was extracted from Recycled Steel Bead Wires (RSBW) and consisted of straight fibers with lengths ranging from 30 mm to 60 mm and diameters ranging from 0.2 mm to 0.3 mm, with specific gravity of 2.08 and strength of 2140 MPa, according to the supplier data sheet. Natural sand with a fineness modulus of 3.0 and crushed sand with a Maximum Nominal Size (MNS) of 12.5" were utilized as fine and coarse aggregates, respectively. For improving the workability of the concrete mixture, superplasticizer (SP), with a specific gravity of 1.06, conplast SP430 was implemented. With an initial settling period of more than 45 min, all prepared concrete mixes were cast using Ordinary Portland Concrete (OPC) Type 1. The main longitudinal steel bars had a diameter of 10 mm, while the stirrups were 8 mm. The properties of the bars are listed in Table I.

(a) (b)

Fig. 1. (a) RSF, (b) CR.

TABLE I. PROPERTIES OF STEEL BARS

Diameter	Yield strength (MPa)	Tensile strength (MPa)	Tensile modulus (GPa)
8	420	580	207
10	425	610	205

B. Column Preparation and Details

The nine fabrication square column specimens utilized in this investigation were intended to have at least a 1% longitudinal reinforcement ratio. The columns have a cross-sectional size of 200 mm and a height of 500 mm. As shown in Figure 2, they are reinforced with longitudinal steel bars (4Ø10 mm) and link bars (6Ø8 mm), placed 75 mm apart.

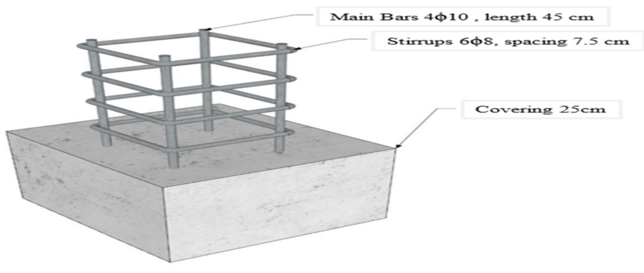

Fig. 2. Reinforcement column 3D sketch details.

C. Mix Design

The columns in Table II are classified into three categories based on RSF and CR with 0.6% and 15% content, respectively. The controlling mixtures (RC) were adopted from previous works with a targeted compressive strength of 35 MP as displayed in Table II [17]. The RC mix properties are 3.15 relative density, 3 fineness modulus, 1% absorption sand, typical OPC (Type 1), and naturally crushed coarse aggregates with a maximum size of 14 mm were utilized. Three mixtures were prepared and tested, and the RC mixtures were prepared without any inclusion of CR or RSF. The H1 and H2 were cast into two equal layers as depicted in Table II. The top layer of H1 was rubberized concrete with 15% CR as a fine replacement, whereas the bottom layer was normal concrete. H2 consisted of rubberized fibrous concrete at the top layer, while the bottom layer contained fibrous concrete at a fixed ratio. Nine square columns, along with 100 mm - edge cubes and cylinders, were cured in water for 28 days and then kept at room temperature until tested.

TABLE II. MIXTURE PROPORTIONS FOR 1 m^3 OF CONTROLLED AND HYBRID LAYER

Mix ID	**CR (%)**		**W/C (-)**	**Fine Aggregates (kg)**		**Coarse Aggregates (kg)**	**RSF (%)**		**Water (kg)**	**Cement (kg)**	**SP430 (kg)**	
RC	0		0.48	713		1060	-		172.8	360	3.6	
Mix ID	**Top layer**	**Bottom layer**	**W/C (-)**	**Top layer**	**Bottom layer**	**Coarse Aggregates (kg)**	**Top layer**	**Bottom layer**	**Water (kg)**	**Cement (kg)**	**Top layer**	**Bottom layer**
H1	15	-	0.48	668	713	1060	-	0.6	172.8	360	2.1	2.7
H2	15	-	0.48	668	713	1060	0.6	0.6	172.8	360	4.8	2.7

III. TEST SETUP AND INSTRUMENTATION

A hydraulic Universal Testing Machine (UTM) with a capacity of 200 tons was used to apply compression stress to the columns, as portrayed in Figure 3. Two steel plates were mounted on the upper and lower surfaces of the columns to distribute the axial force evenly throughout the column surfaces. Before testing, the column's top surface was polished with a Gipson layer (Figure 4). The nine columns were tested under concentric axial compression load until they attained actual axial capacities with failure states at a displacement rate of 0.5 mm/min and until the appearance of hairline cracks. The average of the three-column specimens was considered. The characteristics for all of the columns, such as the axial load and vertical displacement data, were recorded using a computerized system linked to the machine. Additionally, the vertical load-displacement curve was plotted, allowing the three important mechanical properties of the column, i.e. ultimate load, displacement, and ductility, to be determined. Throughout the experiment, the pattern of the cracks and the failure modes were determined.

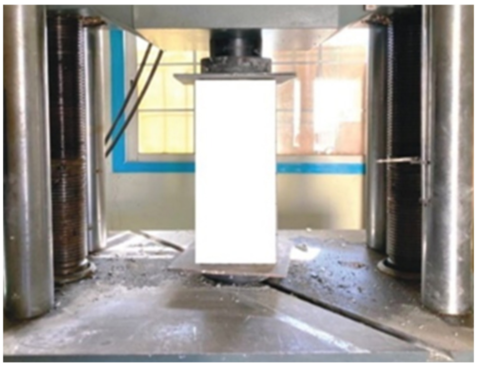

Fig. 3. Testing of concrete columns by UTM load compression.

Fig. 4. Pushing gypsum with a flat glass square.

IV. TEST RESULTS

A. *Concrete Properties*

Table III summarizes the properties of concrete for each mix, including density, compressive, static modulus, and split tensile strength. In the hybrid structure layer (H1 and H2), there was a decrease in the density by 3.55% and 3.35%, respectively, when the fibrous rubberized concrete was placed on the top and the fibrous or normal concrete at the bottom, compared with RC of 2417.67 kg/m³. This occurred because the relative density of sand was double (2.65) the one of CR (1.22) [17]. The compressive strength was obtained by testing three specimens from each mixture after 28 days and calculating the average strength. Regarding H1, the hybrid layered cubical structure containing rubberized concrete on the top and RSF concrete at the bottom, a slight decrease was observed in compression strength (roughly around 2.99%), whereas the changes in the arrangement (swap up) in H2 led to a slight increase of 1.12% compared to RC. This could occur because when at the top, CR with RSF, could absorb more load, causing delayed cracking, whereas when at the bottom, the delayed cracking could be controlled by the addition of RSF in the same ratio. In terms of splitting tensile strength, the average of three cylindrical concrete specimens was obtained. The splitting tensile strength results followed the reductions of compressive strength. For H1, it decreased by 7.08% when the rubber content was placed at the top and fibrous content was placed at the bottom. Conversely, when rubber content was placed at top and fibrous at the bottom (H2), splitting tensile strength increased by 16.14%.

B. *Column Characteristics Results*

Table IV illustrates the column axial characteristics derived by testing the axial load of the columns of all mixtures. Each type of mixture abbreviation represents the average of three specimens. The characteristics considered were first crack load (P_{cr}), cracking displacement (Δ_{cr}), ultimate load (P_u), yield load (P_{yield}), yield displacement (Δ_{yield}), ultimate displacement (Δ_u), total energy (E_{total}), secant stiffness (K), and ductility index (μ). Some characteristics were obtained by naked-eye monitoring during the axial test as well as through the area enclosed by the displacement curve, and others were acquired using calculations from (1) and (2).

$$\mu = \frac{\Delta u}{\Delta yield} \quad (1)$$

$$K = \frac{Pu}{\Delta u} \quad (2)$$

TABLE III. CONCRETE PROPERTIES

Mix. ID	Sp.No.	*dcu* (kg/m³)	*µdcu* (%)	*fcu* (MPa)	*µcu* (%)	*ftu* (MPa)	*µtu* (%)
RC	1	2405	0	48	0	2.01	0
	2	2437		50		3.35	
	3	2411		47		3.25	
	Average	2417		48		2.87	
H1	1	2317	96	45	96	2.2	92
	2	2332		47		3.4	
	3	2346		49		2.4	
	Average	2331		47		2.67	
H2	1	2327	96	47	101	3.4	116
	2	2352		53		4.1	
	3	2329		46		2.5	
	Average	2336		49		3.33	

dcu = cube density, fcu = compressive strength, ftu = tensile strength, μdcu = average ratio of density, μcu = average ratio of compressive strength, μtu = average ratio of tensile strength

The toughness (total energy) for each mixture was obtained by measuring and adding all the area enclosed by the displacement curve of the reinforced concrete during the axial test until failure. There was an increase in the deformability area for H2, which shows an augmentation in toughness, rising to more than 120% of RC's. The stiffness values declined with the addition of rubberized concrete. On average, H1 and H2 columns had 58.67% and 6.93% reductions, respectively, compared to RC, as illustrated in Table IV. The reduction in stiffness increases deformability and enhances the ability of the beams to absorb more energy by making the beams more ductile when exposed to high load [20, 23]. The ductility index (μ) in general increased with the incorporation of CR. Therefore, the ductility of H1 and H2 columns significantly increased to 1.16 and 1.13, compared to control RC samples (1.09), representing a raise of 6.42%, and 3.66%, accordingly. The highest values of the ultimate load (Pu) were observed in H2, which included RSF in both layers.

B. Cracking Behavior and Failure Modes

Table V depicts the characteristics of the cracking patterns (number, angles, width, mix, and minimum spacing) for all the tested columns. In H1, the addition of 15% CR at the top layer led to an average increase of 240% in the number of cracks compared to RC, because the modulus of the rubber aggregate's elasticity is lower than that of the fine aggregates, causing an increase in cracking [15-20]. Conversely, as RSF was included in both layers, the cracking amount in H2 was 15.15% lower than that of H1 columns. In the same line, the widths appeared to be smaller when RSF was used, whether in one or two layers, reduced by 12.5% and 37.5% with wider spacing of about 700% and 877% between cracks, for H1 and H2, respectively, when compared to RC. The presence of fibers helped the cracks bridge, delayed the crack growth, and minimized the effect of rubber inclusion in concrete [19].

TABLE IV. COLUMN CHARACTERISTICS RESULTS

Mix ID	Sp.No.	*Pcr* (KN)	*Δcr* (mm)	*Pyield* (KN)	*Δyield* (mm)	*Pu* (KN)	*Δu* (mm)	*Etotal* (KN.mm)	*K* (KN/mm)	*µ*
RC	1.00	111.00	3.40	1110.00	3.50	1182.00	3.84	1846	307.81	1.10
	2.00	390.00	2.45	560.00	3.70	600.40	4.40	1229	136.45	1.19
	3.00	550.00	2.55	811.00	3.80	890.50	3.79	1640	234.96	1.00
	Average	350.33	2.80	827.00	3.67	890.97	4.01	1571	226.41	1.09
H1	1.00	198.00	1.95	400.00	4.20	453.00	5.00	1185	90.60	1.19
	2.00	245.00	2.37	360.00	3.80	415.00	4.30	983	96.51	1.13
	3.00	170.00	2.10	630.00	4.80	658.00	5.50	1185	119.64	1.15
	Average	204.33	2.14	463.33	4.27	508.67	4.93	1118	93.56	1.16
H2	1.00	615.00	2.75	810.00	3.56	853.10	3.45	1504	247.28	0.97
	2.00	465.00	4.21	1400.00	5.36	1457.90	7.60	7149	191.83	1.42
	3.00	550.00	3.50	810.00	4.50	876.40	4.54	1734	193.04	1.01
	Average	543.33	3.49	1006.67	4.47	1062.47	5.20	3462	210.71	1.13

TABLE V. COLUMN CRACKING PATTERNS

Mix	Specimen no.	No. of spiral	Max crack width (mm)	Angle of crack at failure (deg)	Minimum spacing (mm)	Maximum spacing (mm)	Failure modes
RC	1	2	6	80	1	7	CC
	2	9	5	60	1	35	
	3	6	5	65	1	12	
	Average	5.67	5.33	68.33	1	18	
H1	1	19	4	55	1	125	CC, SB
	2	18	4	55	1	138	
	3	21	6	65	1	175	
	Average	19.33	4.66	58.33	1	146	
H2	1	16	4	65	1	350	CC
	2	17	3	55	1	55	
	3	16	3	45	1	124	
	Average	16.33	3.33	55	1	176.33	

CC= concrete crushing, SB= steel buckling

(a) (b) (c)

Fig. 5. Failure modes: (a) RC, (b) H1, (c) H2.

In terms of failure mode, the specimens cast with normal concrete (RC) were crushed (CC) (Figure 5(a)). In general, the failure modes of columns with crumb rubber showed Concrete Crushing (CC), followed by Steel Buckling (SB) (Figure 5(b)). Conversely, as RSF was included at 0.6%, for both layers, the failure mode was CC only and enhanced due to the increased load capacity of the specimens.

C. Load-displacement Behaviors

Figure 6 presents the curves of the load-displacement response of the reinforced tested columns with and without 15% CR and 0.6% RSF. It was noticed that the slope started increasing by the linear segment before the first cracks occurred when the displacement was recorded and then the nonlinear slope started gradually decreasing. The linear segment was initiated after the cracking and led to a gradual decrease in the slope, coupled with an increase in the number of cracks until failure. In [15, 18], it was reported that the reason for this is that the steel bar began to yield until it exceeded the yielding point by an additional load, after which the slope of the curves crucially decreased to reach the ultimate load through the crushing concrete. In hybrid layered columns, H1 with rubberized concrete on the top and RSF at the bottom exhibited a higher displacement (22.94% average) compared to control (Figure 6). The concentration of CR in one layer close to the load cell limited the stiffness reduction and raised axial strength. Changing the structure of the hybrid layered columns in H2 by adding fiber concrete at the bottom layer and rubberized concrete with RSF on the top increased the displacement and raised the ultimate load. The potential reason for this could be that as RSF and CR were exposed to the load directly on the top, they started the absorbing the load, which might have led to an increased displacement. Meanwhile, at the bottom, RSF helped control the cracks [21, 22].

V. CONCLUSION

In this paper, the mechanical properties and axial behavior of the nine specimens, including control and layered structure columns, were investigated for axial compression loads, and the following conclusions were drawn:

- In comparison with RC, the mechanical properties of H1 slightly decreased by around 2.99% and 7.08% in compression tensile strength. However, when steel fibers were utilized in both layers with CR inclusion at the top in H2, the compressive strength and the tensile strength values were higher by around 1.12% and 16.14%, respectively.

(a) (b) (c)

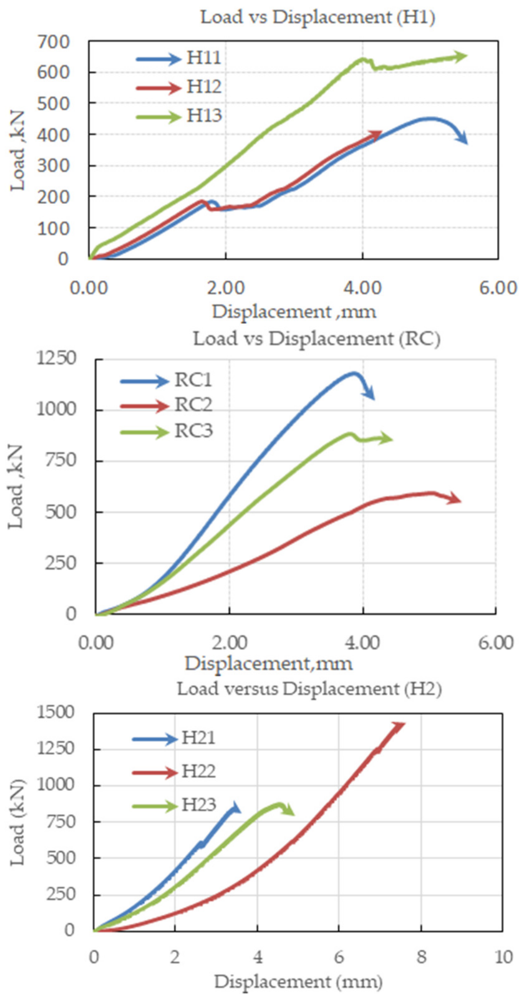

Fig. 6. Load-displacement curves of (a) RC, (b) H1, (c) H2 columns.

- Generally, numerous characteristics of the hybrid layered columns, including toughness, ultimate load and deflection, as well as total energy, seemed to be better than those of the non-layered concrete, especially in H2. The toughness in H2, rising to more than 120% of the control mixtures due to the rubber's ability to absorb the load led to increased values of ultimate load around by 19.32%.
- The maximum crack width of the spiral crack pattern improved with the inclusion of CR. Furthermore, the maximum spacing between spirals increased more than 800 times, which indicates that RSF in both layers of the columns (H2) was able to minimize the effect of CR.

ACKNOWLEDGMENT

The researchers would like to acknowledge the Deanship of Scientific Research, Taif University for funding this work.

REFERENCES

[1] B. S. Thomas and R. C. Gupta, "A comprehensive review on the applications of waste tire rubber in cement concrete," *Renewable and Sustainable Energy Reviews*, vol. 54, pp. 1323–1333, Feb. 2016, https://doi.org/10.1016/j.rser.2015.10.092.

[2] F. M. Z. Hossain, Md. Shahjalal, K. Islam, M. Tiznobaik, and M. S. Alam, "Mechanical properties of recycled aggregate concrete containing crumb rubber and polypropylene fiber," *Construction and Building Materials*, vol. 225, pp. 983–996, Nov. 2019, https://doi.org/10.1016/j.conbuildmat.2019.07.245.

[3] J. Xu, Z. Yao, G. Yang, and Q. Han, "Research on crumb rubber concrete: From a multi-scale review," *Construction and Building Materials*, vol. 232, Jan. 2020, Art. no. 117282, https://doi.org/10.1016/j.conbuildmat.2019.117282.

[4] M. S. Meddah and M. Bencheikh, "Properties of concrete reinforced with different kinds of industrial waste fibre materials," *Construction and Building Materials*, vol. 23, no. 10, pp. 3196–3205, Oct. 2009, https://doi.org/10.1016/j.conbuildmat.2009.06.017.

[5] S. A. Rossli and I. S. Ibrahim, *Mechanical Properties of Recycled Steel Tire Fibres in Concrete*. University of Technology, 2012.

[6] J. Xue and M. Shinozuka, "Rubberized concrete: A green structural material with enhanced energy-dissipation capability," *Construction and Building Materials*, vol. 42, pp. 196–204, May 2013, https://doi.org/10.1016/j.conbuildmat.2013.01.005.

[7] K. Bisht and P. V. Ramana, "Waste to resource conversion of crumb rubber for production of sulphuric acid resistant concrete," *Construction and Building Materials*, vol. 194, pp. 276–286, Jan. 2019, https://doi.org/10.1016/j.conbuildmat.2018.11.040.

[8] K. B. Najim and M. R. Hall, "A review of the fresh/hardened properties and applications for plain- (PRC) and self-compacting rubberised concrete (SCRC)," *Construction and Building Materials*, vol. 24, no. 11, pp. 2043–2051, Nov. 2010, https://doi.org/10.1016/j.conbuildmat.2010.04.056.

[9] R. Alwi Assaggaf, S. Uthman Al-Dulaijan, M. Maslehuddin, O. S. Baghabra Al-Amoudi, S. Ahmad, and M. Ibrahim, "Effect of different treatments of crumb rubber on the durability characteristics of rubberized concrete," *Construction and Building Materials*, vol. 318, Feb. 2022, Art. no. 126030, https://doi.org/10.1016/j.conbuildmat.2021.126030.

[10] A. Y. Kamal, "Ductility of simply supported rubberized concrete beams," *Challenge Journal of Concrete Research Letters*, vol. 12, no. 2, Jun. 2021, Art. no. 49¸https://doi.org/10.20528/cjcrl.2021.02.002.

[11] R. H. Ghedan and D. K. Hamza, "Effect of Rubber Treatment on Compressive Strength and Thermal Conductivity of Modified Rubberized Concrete," *Journal of Engineering and Sustainable Development*, vol. 15, no. 4, pp. 21–29, Jan. 2011.

[12] E. Güneyisi, "Fresh properties of self-compacting rubberized concrete incorporated with fly ash," *Materials and Structures*, vol. 43, no. 8, pp. 1037–1048, Oct. 2010, https://doi.org/10.1617/s11527-009-9564-1.

[13] M. Elchalakani, "High strength rubberized concrete containing silica fume for the construction of sustainable road side barriers," *Structures*, vol. 1, pp. 20–38, Feb. 2015, https://doi.org/10.1016/j.istruc.2014.06.001.

[14] A. M. Rashad, "A comprehensive overview about recycling rubber as fine aggregate replacement in traditional cementitious materials," *International Journal of Sustainable Built Environment*, vol. 5, no. 1, pp. 46–82, Jun. 2016, https://doi.org/10.1016/j.ijsbe.2015.11.003.

[15] H. A. Alasmari, B. H. A. Bakar, and H. M. Akil, "Influence of rubberized-fibrous concrete on flexural behavior of hybrid reinforced beam," *AIP Conference Proceedings*, vol. 2213, no. 1, Mar. 2020, Art. no. 020284, https://doi.org/10.1063/5.0000461.

[16] L. Li, S. Ruan, and L. Zeng, "Mechanical properties and constitutive equations of concrete containing a low volume of tire rubber particles," *Construction and Building Materials*, vol. 70, pp. 291–308, Nov. 2014, https://doi.org/10.1016/j.conbuildmat.2014.07.105.

[17] H. A. Alasmari, B. H. A. Bakar, and A. T. Noaman, "A Comparative Study on the Flexural Behaviour of Rubberized and Hybrid Rubberized Reinforced Concrete Beams," *Civil Engineering Journal*, vol. 5, no. 5, pp. 1052–1067, May 2019, https://doi.org/10.28991/cej-2019-03091311.

[18] M. M. Al-Tayeb, B. H. Abu Bakar, H. M. Akil, and H. Ismail, "Effect of Partial Replacements of Sand and Cement by Waste Rubber on the Fracture Characteristics of Concrete," *Polymer-Plastics Technology and Engineering*, vol. 51, no. 6, pp. 583–589, Apr. 2012, https://doi.org/10.1080/03602559.2012.659307.

[19] A. T. Noaman, B. H. A. Bakar, and H. M. Akil, "Investigation on the mechanical properties of rubberized steel fiber concrete," *Engineering Structures and Technologies*, vol. 9, no. 2, pp. 79–92, Jun. 2017, https://doi.org/10.3846/2029882X.2017.1309301.

[20] A. T. Noaman, B. H. Abu Bakar, H. Md. Akil, and A. H. Alani, "Fracture characteristics of plain and steel fibre reinforced rubberized concrete," *Construction and Building Materials*, vol. 152, pp. 414–423, Oct. 2017, https://doi.org/10.1016/j.conbuildmat.2017.06.127.

[21] B. H. A. Bakar, A. T. Noaman, and H. M. Akil, "Cumulative Effect of Crumb Rubber and Steel Fiber on the Flexural Toughness of Concrete," *Engineering, Technology & Applied Science Research*, vol. 7, no. 1, pp. 1345–1352, Feb. 2017, https://doi.org/10.48084/etasr.854.

[22] N. A. Memon, M. A. Memon, N. A. Lakho, F. A. Memon, M. A. Keerio, and A. N. Memon, "A Review on Self Compacting Concrete with Cementitious Materials and Fibers," *Engineering, Technology & Applied Science Research*, vol. 8, no. 3, pp. 2969–2974, Jun. 2018, https://doi.org/10.48084/etasr.2006.

[23] M. Badawi, A. G. Ahmed, T. A. Eldamaty, and M. M. Helal, "Properties of Recycled Concrete utilizing Waste Rubber," *Engineering, Technology & Applied Science Research*, vol. 13, no. 4, pp. 11451–11458, Aug. 2023, https://doi.org/10.48084/etasr.5918.