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Reference

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ABSTRACT

To enhance the low strain capacity and brittleness of concrete, several researchers have already reported on the mechanical properties of rubberized concrete, which lead to reduced environmental concerns, direct cost reduction, low unit weight, high toughness, and improved absorption of impact. However, to overcome the drawbacks of low flexural strength and the low stiffness of rubberized concrete and to improve the crack resistance, steel, or synthetic (polypropylene) fibers, or both, were added into the rubberized concrete in this study. Based on the flexural performance test according to ASTM C1018 and ASTM C1609, this study investigates the combination of crumb rubber, steel or synthetic fibers, or both, in zero-slump concrete mixtures used in the dry-cast production method for concrete pipes. A series of concrete mixes were examined with the variation of the fiber volume fraction (V_f) (steel: 0.17 % and 0.33 %/synthetic-polypropylene: 0.17 %, 0.33 %, and 0.52 %), and crumb rubber with different replacement ratios of 3 % to 20 % (by volume) for sand (fine aggregate) in the concrete mixture. Seventeen rubberized mixtures were developed by incorporating different dosages of steel and polypropylene fibers and their combinations. The influence of fiber type, dosages of fibers, and rubber are analyzed on the basis of experimental results. Results indicate that the effect of hybrid reinforcement using both steel and polypropylene fiber in rubberized concrete is considerable in terms of increase in both peak load and toughness. The specimen of hybrid fiber-reinforced rubberized concrete (HYFRC) with 44 lb/yd^3 (0.33 %: V_f) of steel fiber, 8 lb/yd^3 (0.33 %: V_f) of polypropylene fiber and 3 % of crumb rubber (replacement with fine aggregates) showed higher peak load, modulus of rupture, and toughness than other mixtures. However, excessive replacement of rubber into the specimens had a negative effect on the flexural properties (strength and toughness).

Keywords

rubberized concrete, steel fiber, polypropylene fiber, toughness, hybrid reinforcement

Introduction

After the natural lifetime of tires, approximately 273×10^6 of them are disposed of each year as stockpile (whole tire) or landfill (shredded tire) in solid waste sites in the United States [1]. There is an environmental risk from the leaching of toxins into the groundwater when placed in wet soils because of heavy metals and other pollutants in tires. This impact on the environment varies according to the *p*H level and conditions of the local water and soil. The use of recycled tire rubber in concrete mixtures has been introduced as a possible alternative for nonconventional concrete mixes to solve the environmental concerns of tire disposal.

Several studies have been carried out to evaluate the effects of recycled rubber, called crumb rubber, from automotive and truck scrap tires in concrete mixes. The effects of crumb rubber, or tire derivative aggregate (TDA), in unreinforced concrete have previously been investigated [2]. It was reported that compressive strengths of up to 4000 psi (27.5 MPa) can be reached by replacing the coarse aggregates in concrete with small amounts of TDA ranging from 7.5 % to 10 %, with a top size of 2 in. (50.8 mm), and using enhanced materials such as silica fume. It was determined that the addition of crumb rubber into the concrete increases the toughness and impact resistance as well. On the other hand, it decreases the modulus of elasticity, splitting tensile strength, and the modulus of rupture. The influence of fine and coarse rubber particles on physical and mechanical properties of concrete has also been studied [3]. Reductions in the compressive strength of cylindrical specimens by 50 % and 60 % were observed when using fine rubber and coarse rubber particles, respectively. Coarse rubber aggregates affected properties of concrete more than fine rubber aggregates. With the addition of rubber, concrete showed more elastic behavior and became more ductile.

The effects of the replacing coarse aggregates by volume contents of 25 %, 50 %, 75 %, and 100 % ground rubber tires were evaluated [4]. The results showed that the use of rubber in concrete reduces both the compressive and flexural strength of concrete, but increases the ductility of the specimens. The reduction in compressive strength was higher than that of the flexural strength. It was found that rubberized concrete with fine rubber particles exhibits an acceptable workability and more ductility with respect to plain concrete [5]. The replacement of mineral aggregates with tire-rubber particles reduces the ultimate strength of concrete significantly. It was recommended to use less than 25 % rubber replacement to lead to less reduction in the ultimate strength. Thus, even though partial replacement of the coarse or fine aggregate in rubberized concrete can enhance qualities of concrete such as low unit weight and high ductility, the reduction of compressive, tensile, and flexural strengths also occur.

Despite the fact that rubberized concrete is considerably weaker than traditional concrete, some research efforts have proposed the use of rubber and fibers in concrete to improve its crack resistance, flexural strength, and toughness. It is well known that the presence of fibers in concrete enhances the materials performance, including post-cracking control, impact resistance, and a higher capacity of energy absorption (defined as a function of the area under the load versus deflection curve) after the initial crack occurs. According to ACI 544.1 R-96 [6] and AASHTO-AGC-ARTBA Joint Committee [7], ultimate flexural strength was found to increase when the volume fraction of steel fibers increased within the practical range, and an increase in the flexural strength may even be possible at higher volume fractions [6,7]. Elavenil and Knight [8] reported that the incorporation of steel fiber reinforcement increased flexural strength, and that the increase in flexural strength was influenced by the increase of the fiber contents. It was also reported that a positive synergy effect was evidenced with regard to the resistance to cracking when rubberized concrete was reinforced with steel fiber [9]. Synthetic fibers do not have as much reported research as steel fibers. However, in general, synthetic fibers have been found to increase mix cohesion, freeze–thaw resistance, impact resistance, and crack control [10,11]. Flexural and impact resistance tests were investigated to optimize the percentage of steel and polypropylene fibers [12]. Hybrid fiber-reinforced concrete with a steel fiber content of 0.75 % (V_f) and a polypropylene fiber content of 0.25 % (V_f) exhibited the highest modulus of rupture and toughness.

Unfortunately, limited studies have been conducted on the combined effect of rubber and fiber (steel or synthetic, or both) on dry concrete mixtures. Most studies on the behavior of rubberized concrete have not emphasized its flexural capacity. Information in this area is still unclear, or needs additional evidence to verify the possibility of producing concrete composites where crumb rubber as a partial replacement of fine aggregates, steel fiber, and polypropylene fiber can interact properly.

Experimental Program

CONCRETE MIXTURE

Two different methods (wet- and dry-cast) are commonly used in precast concrete. Dry-cast concrete, known as zero-slump mix and typically used for precast concrete pipe applications, was employed in this study. The concrete mix design with a 28-day strength of 4000 psi (28 MPa) was: 380 lb/yd^3 (226 kg/m^3) of type I/II Portland cement, 1670 lb/yd^3 (990 kg/m^3) of coarse aggregate, 1700 lb/yd^3 (1010 kg/m^3) of sand (fine aggregate), 125 lb/yd^3 (74 kg/m^3) of fly ash, and 217 lb/yd^3 (129 kg/m^3) of water. The resulting concrete water–cement ratio was 0.43. The materials of coarse and fine aggregates and crumb rubber were dry-mixed for 2 min with half of the fibers before water was added. A further 3 min of mixing was carried out after half of the water along with cement was added to make dispersion of fibers sufficient. Finally, the rest of the water and fibers were added to the mixture and mixed again for 3 min.

CRUMB RUBBER AND MACRO FIBERS

Crumb rubber is obtained from automotive and truck scrap tires and has particles ranging from 0.19 in. (4.75 mm: No. 4 sieve) to 0.003 in. (0.075 mm: No. 200 sieve). Addition of crumb rubber reduces the unit weight of the concrete mixture because the mineral aggregates have a higher unit weight than the crumb rubber particles.

The steel fiber is a low carbon drawn steel wire with hooked ends and glued into bundles. The fibers are 1.3 in. (33 mm) in length, 0.02 in. (0.50 mm) in diameter, and have a Young's modulus of 30 458 ksi (207 GPa), a relative density of 7.85 (13 226 lb/yd^3 or 7847 kg/m^3), and a tensile strength of 174 ksi (1200 MPa).

The synthetic fiber is made from 100 % virgin polypropylene and is a monofilament and embossed fiber (MasterFiber MAC Matrix), which complies with ASTM C1116 [17]. The fiber length was 2.1 in. (54 mm) and the fiber tensile strength was 85 ksi (585 MPa). The mechanical and geometric properties of the fibers are shown in **Fig. 1** and **Table 1**.

MIX PROPORTION

The combination of two different fibers (type and volume contents) and crumb rubber (volume contents) led to 17 test series. Concrete mixes were examined with the variation of the fiber volume fraction (V_f) [steel: 0.17 % (22 lb/yd^3) and 0.33 % (44 lb/yd^3)/synthetic-polypropylene: 0.17 % (3 lb/yd^3), 0.33 % (5 lb/yd^3) and 0.52 % (8 lb/yd^3)] and crumb rubber with different replacement ratios of 3 % (51 lb/yd^3), 8 % (136 lb/yd^3), 10 % (170 lb/yd^3), and 20 % (340 lb/yd^3) by volume for sand (fine aggregate) in the concrete mixture. These composites are termed rubberized concrete (RC), steel fiber–reinforced rubberized concrete (SFRC), polypropylene fiber–reinforced rubberized concrete (PFRC), and hybrid fiber–reinforced rubberized concrete (HYFRC). The nomenclature of test specimens is as follow; the first character, "CR" or "SF" or "PF" or "HY," represents the type of reinforcement for fiber; the second, third, and fourth numbers "0-0-0" represent the amount of the fiber reinforcement and crumb rubber [steel fiber (lb/yd^3)-polypropylene fiber (lb/yd^3)-crumb rubber (volume %)]. For example, HY-44-8-3 represents that the reinforcement consists of 44 lb/yd^3 of steel fiber, 8 lb/yd^3 of polypropylene fiber, and

FIG. 1 Materials: (*a*) crumb rubber, (*b*) steel fiber–end hooked, and (*c*) polypropylene (synthetic) fiber.

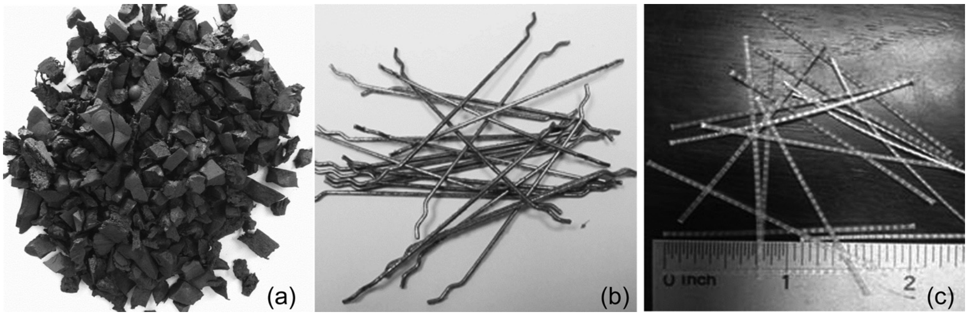


TABLE 1

Mechanical and geometric properties of steel and synthetic fiber.

Fiber Type	Surface Type (cross-section)	Materials	Length	Tensile Strength	Equivalent Diameter
Steel fiber (Stick type)	End-hooked (Circle)	Low carbon steel	1.3 in. (33 mm)	174 ksi (1200 MPa)	0.02 in. (0.5 mm)
Synthetic fiber (Stick type)	Embossed (Rectangle)	100 % virgin polypropylene	2.1 in. (54 mm)	85 ksi (585 MPa)	0.04 in. (1.0 mm)

3 % (by volume of sand) of crumb rubber. Details of the flexural specimens are presented in **Table 2**.

FLEXURAL TEST SETUP AND PARAMETERS

Flexural beam specimens were prepared for each mix design and tested in accordance with ASTM C1609 [13]. The dimensions of the beams were 6 by 6 by 20 in. (150 by 150 by 500 mm). The geometry of flexural specimens and test setup is described in **Fig. 2**. The pure span length was 18 in. (450 mm). Linear variable

TABLE 2

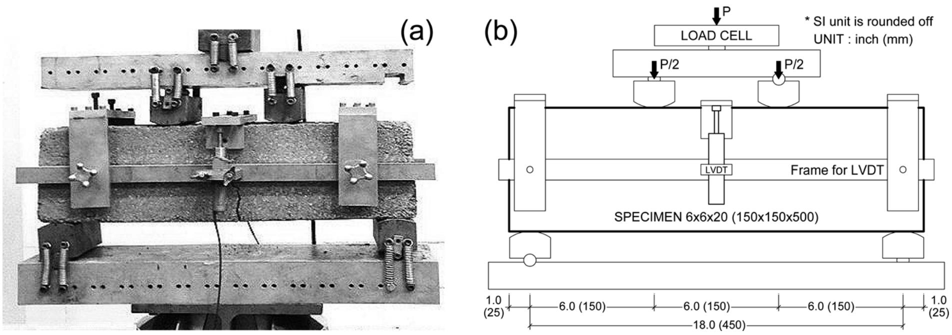
Details of test specimens.

	Specimen ID	Fiber Reinforcement and Rubber Contents		
		Steel (lb/yd^3 (kg/m^3))	Synthetic (lb/yd^3 (kg/m^3))	Rubber (%) by Volume for Sand
1	Control beam	—	—	—
2	CR-0-0-8	—	—	8
3	CR-0-0-10	—	—	10
4	CR-0-0-20	—	—	20
5	SF-22-0-8	22 (13.1)	—	8
6	SF-22-0-10	22 (13.1)	—	10
7	SF-44-0-3	44 (26.1)	—	3
8	SF-44-0-8	44 (26.1)	—	8
9	SF-44-0-10	44 (26.1)	—	10
10	SF-44-0-20	44 (26.1)	—	20
11	PF-0-8-8	—	8 (4.8)	8
12	PF-0-8-20	—	8 (4.8)	20
13	HY-22-5-3	22 (13.1)	5 (3.0)	3
14	HY-44-5-3	44 (26.1)	5 (3.0)	3
15	HY-44-8-3	44 (26.1)	8 (4.8)	3
16	HY-44-5-5	44 (26.1)	5 (3.0)	5
17	HY-44-5-10	44 (26.1)	5 (3.0)	10
18	HY-44-8-10	44 (26.1)	8 (4.8)	10

HY - 0 - 0 - 0

- Rubber content (%)
- Synthetic fiber content (lb/yd^3)
- Steel fiber content (lb/yd^3)
- CR: Rubber only; SF: Steel fiber reinforcement; PF: Polypropylene fiber reinforcement; HY: Hybrid (Both fibers reinforcement)

FIG. 2 Geometry of a flexural specimen and test setup.



displacement transducers (LVDTs) were centered and attached at the mid span on both sides of the beam with the aid of a steel frame. A deflection controlled test apparatus was used to apply a consistent loading rate of 0.0015 to 0.004 in./min (0.035 to 0.1 mm/min) up to a net deflection of $L/900$ and 0.002 to 0.012 in./min (0.05 to 0.3 mm/min) beyond a net deflection of $L/900$. The test was continued until the deflection reached $L/150$ or 0.12 in. (3 mm), which is described as the necessary deflection needed to calculate the toughness and residual strength in the specification of ASTM C1609 [13].

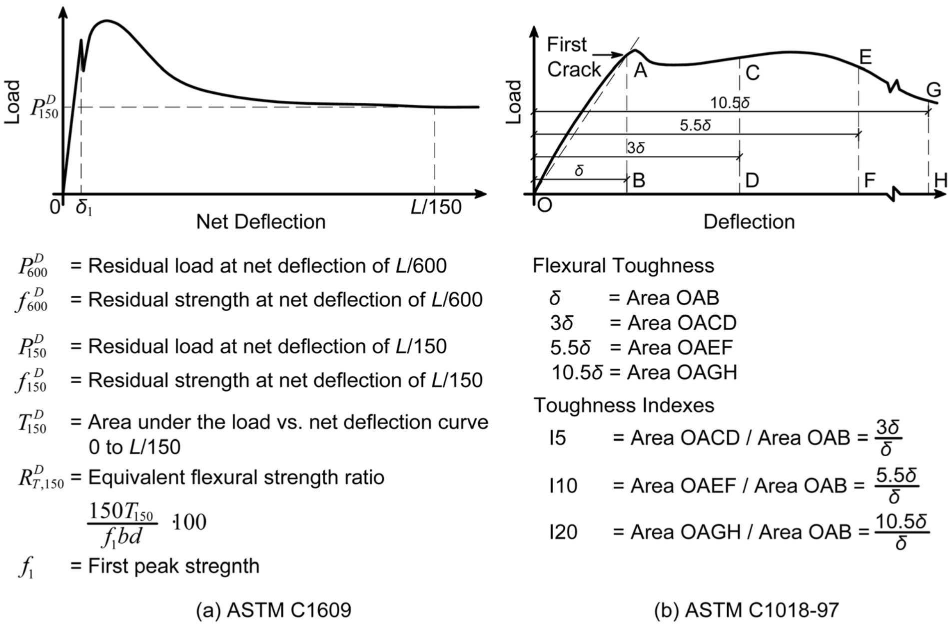
Based on ASTM C1609 [13] and ASTM C1018 [14], several indexes to describe the flexural performances of RC, SFRC, PFRC, and HYFRC were used in the results from the load-deflection curves. ASTM C1018 [14] was replaced by ASTM C1609 [13] because the determination of the first crack and measurement of the deflection corresponding to the first crack load were complicated in ASTM C1018 [14]. However, both ASTM C1609 [13] and ASTM C1018 [14] were used to evaluate the flexural performance (toughness) of the specimens in this study. As shown in **Fig. 3**, several parameters such as first-peak strength (f) at the deflection (δ) of first peak load, residual strength at the specific deflection of $L/600$ (f^D_{600}) and $L/150$ (f^D_{150}), toughness indexes (T^D_{150} and I5, I10, I20), and equivalent flexural strength ratio ($R^D_{T,150}$) are investigated according to ASTM C1609 [13] and C1018 [14]. The net deflections equal to $L/600$ and $L/150$ of the span are 0.03 in. (0.8 mm) and 0.12 in. (3.0 mm), respectively.

Test Results and Discussion

LOAD-DEFLECTION RESPONSE

Flexural responses of all designated concrete mixtures are presented in **Figs. 4(*a*)–4(*d*)**. As known, once the first crack was reached, a sudden decrease of the flexural load-carrying capacity was encountered in the rubberized concrete mix. The flexural strength decreased with an increase in the crumb rubber content as shown in **Fig. 4(*a*)**. The control mix (plain concrete specimen) without any rubber showed the highest flexural capacity (4300 lb = 18 kN) and the typical brittleness. CR-0-0-8 and CR-0-0-10 (rubber volume fraction of 8 % and 10 %) mixes exhibited a flexural capacity of 3 % and 2 % less than that of the control mix, respectively. The partial replacement of fine aggregates with the rubber showed insignificant reduction of the

FIG. 3 Methodology for calculating toughness: (*a*) ASTM C1609 [13], and (*b*) ASTM C1018-97 [14]. O: origin point in the load-deflection curve; A: first crack point in the load-deflection curve; and B: deflection at the first crack in the load-deflection curve.

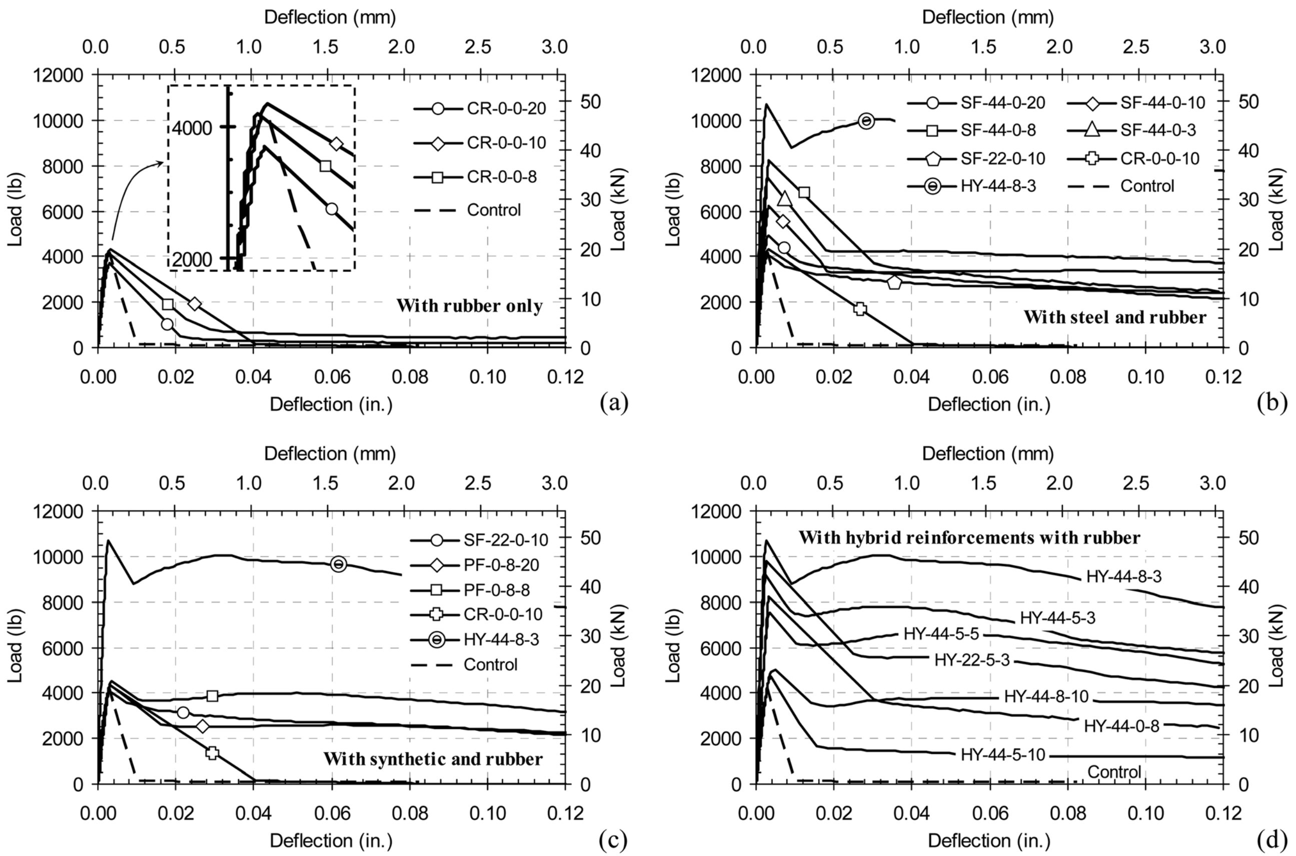


flexural capacity up to a rubber content of 10 %. However, the flexural capacity of CR-0-0-20 (rubber volume fraction of 20 %: rubber only) was 16 % less than that of the control mix. The slope of the load-deflection curve before cracking decreased as the rubber content was increased. RC beams (CR-0-0-8/CR-0-0-10/CR-0-0-20) experienced a less sharp drop of the load, indicating an improvement in ductility after the first crack occurred. At rubber contents of 20 % (CR-0-0-20), the reduction of peak load and an insignificant change of ductility were observed.

In **Figs. 4(*b*)** and **4(*c*)**, load-deflection curves of SFRC beams (0.17 % and 0.33 % by volume of steel fiber/8 %, 10 %, and 20 % by volume of rubber) and PFRC (0.52 % by volume of synthetic fiber/8 % and 20 % by volume of rubber) are presented. A high percentage of steel fiber volume led to an increase in the first crack load (first peak load) because of their high tensile strength and elastic modulus. However, this increase did not affect the increase in ductility significantly. Moreover, even though it is well known that the addition of crumb rubber exhibited a reduction in strength, incorporation of crumb rubber in conjunction with steel fibers enhanced both first crack load and ductility when 10 % rubber volume was used (SF-22-0-10/SF-44-0-3/SF-44-0-8/SF-44-0-10). Inclusion of steel fibers of 0.33 % of V_f (44 lb/yd^3) exhibited a significant increase in the flexural strength of the rubberized mixtures.

At the same volume fraction of steel fibers (0.33 % of V_f), the increase of crumb rubber to 10 % as the replacement of fine aggregates improved the first crack load and ductility. However, the further increase in crumb rubber volume fraction to 20 % (SF-44-0-20) decreased both the first crack load and ductility compared with those of SF-44-0-8 and SF-44-0-10. Moreover, unlike steel fiber–reinforced concrete mixtures without crumb rubber, which experienced a double peak response, in all

FIG. 4 Load-deflection curve of (*a*) CR specimens, (*b*) SF (steel + rubber) specimens, (*c*) PF (polypropylene + rubber) specimens, and (*d*) HY (steel + polypropylene + rubber) specimens.



cases of SFRC, a further strength improvement at the post-cracking stage was not observed. As far as the fiber pull-out performance, steel fiber in the rubberized concrete mix with zero slump showed poor bond performance between the cement paste and the steel fibers.

The results in **Figs. 4(*b*)** and **4(*c*)** showed that the substitution of the synthetic (polypropylene) fibers for steel fibers in rubberized concrete affected the post-peak response even though the addition of polypropylene fibers makes no contribution to an increase in the first peak load because of their low tensile strength. This is unlike the SFRC specimens. As the polypropylene fiber begins to bridge the crack, the load-carrying capacity of PFRC starts to increase the residual load because of the embossed surface of the polypropylene fibers. This was consistent with the results of Park et al. [15] and Sukontasukkul and Jamsawang [16]. Because the shape of the polypropylene fiber is fully embossed, a better friction bond is provided that leads to an increase in the crack-resistance capacity. Polypropylene fibers in rubberized concrete with zero slump perform better than steel fibers in terms of the increase in ductility.

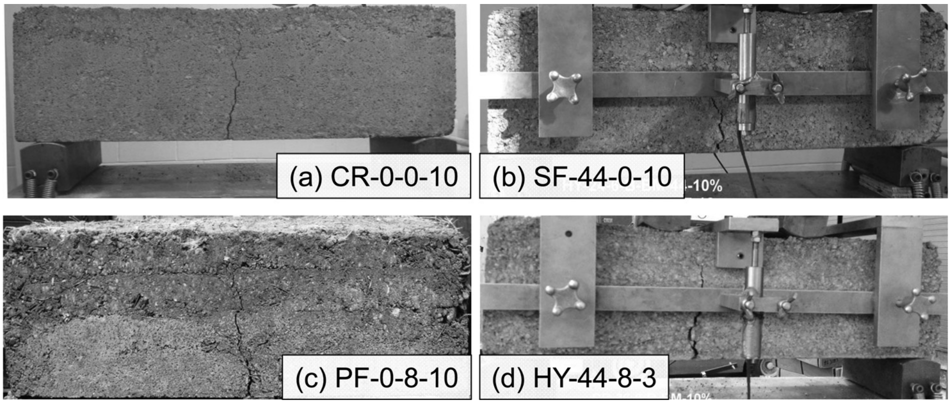
In **Fig. 4(*d*)**, the test results indicate a clear benefit from the incorporation of a hybrid fiber combination (both steel and polypropylene fiber) in the rubberized concrete mix. The combination of steel fibers and polypropylene fibers has a considerable effect on the increase in the first peak load and ductility of the rubberized concrete mixes. The flexural strength increased with an increase in the steel fiber content, and the highest post-peak behavior was provided by the higher percentages of polypropylene fibers because of the their crimped surface. The specimen of HY-44-8-3 showed the highest flexural strength and the greatest increase in the capacity of the energy absorption in all tested specimens. When the rubber content increased from 2 % to 10 % in the HYFRC mix, the first peak load and ductility were increased, and then decreased with any further increase in crumb rubber. In the rubberized concrete mix with the combination of steel and polypropylene fibers, an appropriate amount of rubber improves the flexural load-carrying capacity and ductility. However, too much content of crumb rubber over 8 % showed a negative effect on the flexural load-carrying capacity in HYFRC (HY-44-0-8/HY-44-5-10/HY-44-8-8). It was observed that crumb rubber can be replaced with an equal volume of fine aggregates up to 5 % in HYFRC without a reduction in the flexural strength.

In the case of the crack pattern, the most frequent failure type for the flexural beam test was a vertical crack in the center of the specimens as shown in **Fig. 5**. The crack pattern is independent of the type and content of fibers and crumb rubber.

TOUGHNESS

Toughness is measured by the energy absorption equivalent to the area under a load-deflection curve of the flexural test up to a specific deflection. Higher energy absorption implies higher ductility. Based on ASTM C1609 [13] and ASTM C1018-97 [14], first-peak strength (f) at the deflection (δ) of first peak load, residual strength at the specific deflections of $L/600$ (f^D_{600}) and $L/150$ (f^D_{150}), toughness indexes (T^D_{150} and I5, I10, I20), and equivalent flexural strength ratio ($R^D_{T,150}$) are shown in **Table 3** and **Fig. 6**. The values of residual strengths at $L/600$ and $L/150$ indicate the ability of fiber-reinforced specimens to sustain flexural load after the first crack at different levels of deflection. All fiber-reinforced specimens (SFRC, PFRC, and

FIG. 5 Failure types for flexural beam specimens.



HYFRC) appeared to have higher toughness than the control specimen and rubberized specimens (CR-0-0-8, CR-0-0-10, and CR-0-0-20) without any fiber reinforcement. This indicates that the fiber reinforcement is effective in controlling the rate of energy release by bridging cracks. In terms of toughness, the HYFRC was found to perform better than SFRC and PFRC. HY-44-8-3 showed the highest toughness performance between all types of reinforcement. However, it was observed that rubber contents in the HYFRC influenced the toughness. Compared with HY-44-5-3 ($T_{150} = 844.1$ lb · in.), the toughness at $L/150$ of HY-44-5-10 ($T_{150} = 388.8$ lb · in.) was decreased by 54.% with the addition of 7.% by volume of rubber. An excessive content of crumb rubber led to a negative effect on the toughness in HYFRC.

In the case of the equivalent flexural ratio ($R^D_{T,150}$), **Fig. 7** illustrates that the effect of polypropylene fiber reinforcement in rubberized concrete is considerable in terms of toughness. Although the addition of polypropylene fibers makes no contribution to an increase in the first peak load, the polypropylene fibers have a considerable effect on the increase of toughness in the rubberized concrete with zero slump. This might be attributed to the bond strength between the fiber and the matrix of the mixture. A stronger frictional bond, which mainly depends on the surface shape of fiber, might be formed because the surface of each polypropylene fiber is fully embossed.

Based on ASTM C1018 [14], the toughness indexes (I5, I10, and I20) of all specimens are shown in **Fig. 8**. Compared with the toughness in accordance with ASTM C1069 [13] (see **Fig. 6**), the differences in toughness indexes (I5, I10, and I20) between all mixtures are not considerable according to ASTM C1018 [14]. Moreover, although HY-44-8-3 showed the highest toughness performance between all types of reinforcement, it cannot be concluded that the effect of hybrid reinforcement using both steel and polypropylene fiber in rubberized concrete is considerable in terms of toughness based on ASTM C1018 [14]. Moreover, HY-44-5-3 can be considered to have higher toughness than that of HY-44-8-3 according to **Fig. 8** based on ASTM C1018. However, based on **Fig. 4(*d*)**, HY-44-8-3 showed the highest toughness (largest area under load versus deflection curve) definitely. Based on **Table 3** and **Fig. 6**, the value of T_{150} indicated that HY-44-8-3 exhibited larger

TABLE 3

Summary of flexural performances according to ASTM C1609 [13].

				L/600			L/150				
No.	Specimen ID	Peak Load lb (kN)	Deflection at Peak Load (δ) in. (mm)	P_{600} (lb) (kN)	f_{600} (psi) (MPa)	T_{600} (lb · in.) (kN · mm)	P_{150} (lb) (kN)	f_{150} (psi) (MPa)	T_{150} (lb · in.) (kN · mm)	f_r (psi) (MPa)	R_{150}
1	Control Beam	4178	0.0031	107.1	8.9	25.1	70.1	5.8	33.0	348.1	6.5
		(18.7)	(0.08)	(0.5)	(0.1)	(2.8)	(0.3)	(0.1)	(3.7)	(2.4)	
2	CR-0-0-8	4224	0.0027	369.4	30.7	51.1	219.7	18.3	74.8	352	14.7
		(18.9)	(0.07)	(1.6)	(0.2)	(5.8)	(1.0)	(0.1)	(8.5)	(2.4)	
3	CR-0-0-10	4355	0.0033	2158.1	179.6	100.6	9.1	0.7	125.4	362.9	24.0
		(19.5)	(0.08)	(9.6)	(1.2)	(11.4)	(0.1)	(0.1)	(14.2)	(2.5)	
4	CR-0-0-20	3723	0.0030	799.9	66.6	70.6	454.7	37.8	118.3	310.2	26.4
		(16.7)	(0.08)	(3.6)	(0.5)	(8.0)	(2.0)	(0.3)	(13.4)	(2.1)	
5	SF-22-0-8	6726	0.0042	4582.8	381.9	160.9	1651.2	137.6	365.5	560.5	45.2
		(30.1)	(0.11)	(20.4)	(2.6)	(18.2)	(7.3)	(0.9)	(41.3)	(3.9)	
6	SF-22-0-10	4129	0.0032	3042.9	253.5	98.4	2225.0	185.4	337.4	344.1	58.2
		(18.5)	(0.08)	(13.5)	(1.7)	(11.1)	(9.9)	(1.3)	(38.1)	(2.4)	
7	SF-44-0-3	7532	0.0030	4259.2	354.9	154.5	3769.3	314.1	520.9	627.7	57.6
		(33.7)	(0.08)	(18.9)	(2.4)	(17.5)	(16.8)	(2.2)	(58.9)	(4.3)	
8	SF-44-0-8	8295	0.0033	3767	313.9	182.2	2542.4	211.8	455.8	691.3	45.7
		(37.2)	(0.08)	(16.8)	(2.2)	(20.6)	(11.3)	(1.5)	(51.5)	(4.8)	
9	SF-44-0-10	6324	0.0034	3741.9	311.8	131.4	3741.9	311.8	473.0	527.0	62.3
		(28.3)	(0.09)	(16.6)	(2.1)	(14.8)	(16.6)	(2.1)	(53.4)	(3.6)	
10	SF-44-0-20	4971	0.0036	3372.6	281.0	108.9	2426.4	202.2	358.9	414.3	60.1
		(22.3)	(0.09)	(15.0)	(1.9)	(12.3)	(10.8)	(1.4)	(40.5)	(2.9)	
11	PF-0-8-8	4517	0.0035	3852.2	321.0	110.4	3171.2	264.2	443.7	376.4	81.8
		(20.2)	(0.09)	(17.1)	(2.2)	(12.5)	14.1)	(1.8)	(50.1)	(2.6)	
12	PF-0-8-20	4456	0.0035	2522.2	210.1	87.5	2276.8	189.7	313.1	371.3	58.5
		(20.0)	(0.09)	(11.2)	(1.4)	(9.9)	(10.1)	(1.3)	(35.4)	(2.6)	
13	HY-22-5-3	9891	0.0031	5582.3	465.1	224.1	4276.0	356.3	682.5	824.3	57.5
		(44.3)	(0.08)	(24.8)	(3.2)	(25.3)	(19.0)	(2.5)	(77.1)	(5.7)	
14	HY-44-5-3	9318	0.0022	7822.2	651.8	228.3	5783.7	481.9	844.1	776.5	75.4
		(41.7)	(0.06)	(34.8)	(4.5)	(25.8)	(25.7)	(3.3)	(95.4)	(5.4)	
15	HY-44-8-3	10688	0.0025	10044.5	837.0	280.2	7773.7	647.8	1101.9	890.7	85.9
		(47.9)	(0.06)	(44.7)	(5.8)	(31.7)	(34.6)	(4.5)	(124.5)	(6.1)	
16	HY-44-5-5	7578	0.0035	6469.0	539.0	185.2	5329.0	444.0	747.5	631.5	82.1
		(33.9)	(0.09)	(28.8)	(3.7)	(20.9)	(23.7)	(3.1)	(84.5)	(4.4)	
17	HY-44-5-10	2969	0.0037	937.0	78.0	44.0	727.0	60.5	388.8	247.4	42.6
		(13.3)	(0.09)	(4.2)	(0.5)	(5.0)	(3.2)	(0.4)	(44.3)	(1.7)	
18	HY-44-8-10	5097	0.0047	3735.8	311.3	112.8	3537.4	294.7	450.2	424.7	63.6
		(22.8)	(0.12)	(16.6)	(2.1)	(12.7)	(15.7)	(2.0)	(50.9)	(2.9)	

area under the load-deflection curve (HY-44-8-3: 1101 lb · in./HY-44-5-3: 844 lb · in.). It is attributed to the fact that 10.5δ is still less than $L/150$ (0.12 in.) because the deflection (δ) at first crack is very small in the elastic limit and the area under the

FIG. 6 Toughness (T_{150}) of concrete mixture according to ASTM C1609 [13].

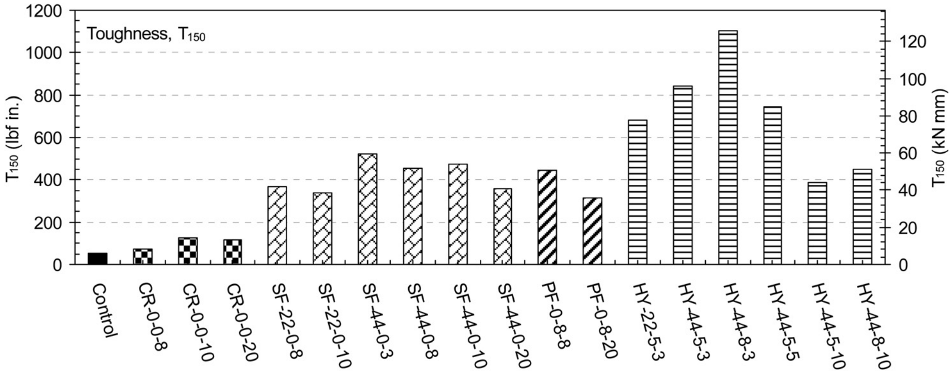


FIG. 7 Equivalent flexural strength ratio ($R^D_{T,150}$) of concrete mixture according to ASTM C1609 [13].

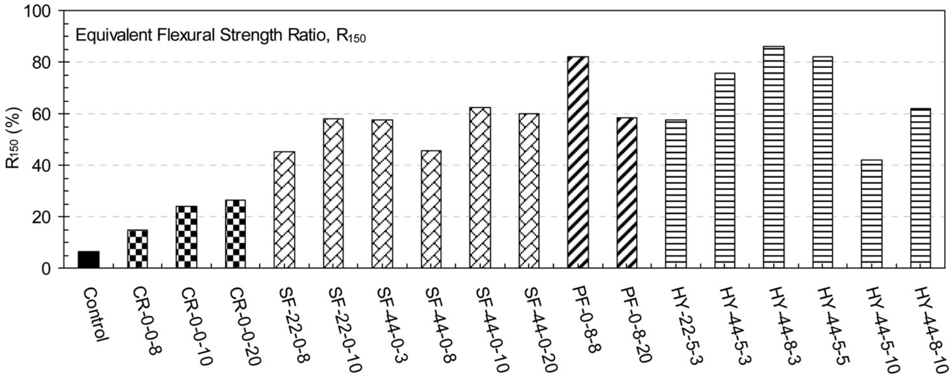
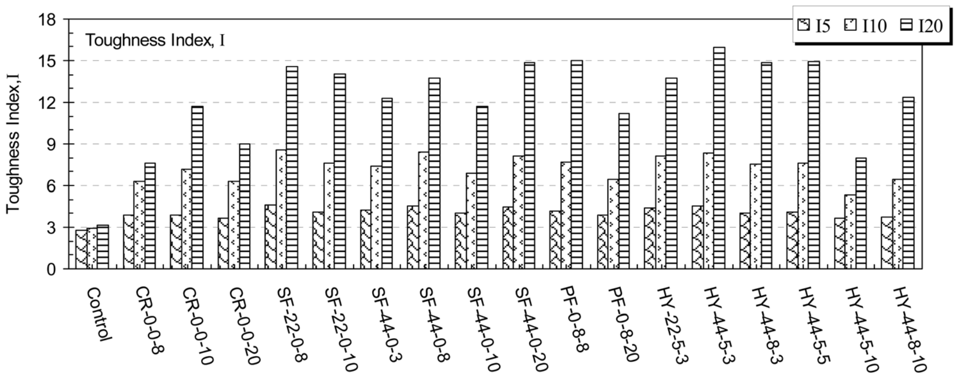


FIG. 8 Toughness indexes (I5, I10, ad I20) of concrete mixture according to ASTM C1018 [14].



load-deflection curve until the first crack [area OAB in **Fig. 3(*b*)**] affects the toughness. The lower area of load-deflection response until the first crack leads to an increase in the toughness, and this index cannot reflect the capacity of energy absorption between 10.5δ and $L/150$ of the deflection. However, this information is important to verify that hybrid fiber reinforcement is effective in increasing toughness in the rubberized concrete mixture. In the cases between PF-0-8-8 and HY-44-8-3, the toughness indexes based on ASTM C1018 [14] are 15.1 and 14.9, respectively. However, based on ASTM C1609 [13], the toughness values are 443.7 and 1101.9 lb · in. It can be concluded that the role of hybrid fiber reinforcement in the rubberized concrete mixture is significant in terms of the increase in toughness between 10.5δ and $L/150$.

Conclusion

This study focused on the experimental investigation of flexural performance of dry cast RC, SFRC, PFRC, and HYFRC, in which recycled crumb rubber was used to partially replace fine aggregates (sand) in zero-slump mixtures. The following conclusions can be drawn from this study:

1. A high percentage of steel fiber volume in the rubberized concrete led to an increase in the peak load. However, further improvement (post-cracking behavior) at the post-peak stage was not observed. That is, the effect of steel fiber reinforcement does not considerably improve the ductility of the rubberized concrete.
2. The substitution of synthetic (polypropylene) fibers for steel fibers in the rubberized concrete affected the post-peak response. The polypropylene fibers with an embossed surface have a considerable effect on the increase in toughness of rubberized concrete with zero slump. Therefore, the main contributor to the increase in ductility is the fiber surface shape.
3. The flexural properties (strength and toughness) for HYFRC with higher steel and polypropylene fiber contents are higher than those containing less steel and polypropylene fibers. HYFRC with 44 lb/yd^3 (0.33 % of V_f) of steel fibers, 8 lb/yd^3(0.33 % of V_f) of polypropylene fibers, and 3 % crumb rubber (replacement with the fine aggregates) showed higher peak loads and equivalent strength ratios and toughness than other mixtures.
4. Hybrid reinforcement (both steel and polypropylene fibers) in the rubberized concrete led to a significant improvement in the concrete ductility. However, the toughness and peak load decreased in HYFRC with rubber contents greater than 3 % (replacement with the fine aggregates).
5. An appropriate amount of rubber should be selected in HYFRC to effectively enhance its flexural load-carrying capacity and toughness. Excessive rubber content may cause a reduction in strength and ductility. It is suggested that, to enhance ductility, fine aggregates can be replaced with an equal volume of crumb rubber up to 5 % in HYFRC without a reduction in the flexural strength.

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