The Effect of Polypropylene Fibers on the Fracture Characteristics of Lightweight Aggregate Crumb Rubber Concrete Composites

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ABSTRACT

The increasing use of rubber tires and their low recycling ratio have made them a serious environmental problem. This work aims to develop and investigate enhanced lightweight aggregate crumb rubber concrete (PFLWACRC) composites regarding the fracture properties of concrete. Polypropylene (PP) fibers are commonly familiar with increased crack growth endurance of concrete. On the other hand, the reuse of waste rubber in concrete plays a major role in the mitigation of the effects of climate change. Various concrete mixtures were designed with conventional Portland cement and common lightweight coarse aggregates. The variables considered in this study are PP fibers in different percentages (0.2%, 0.4%, and 0.6% volume fraction), and crumb rubber with various substitution proportions (0%, 5%, 10%, 15%, 20%, and 25% of fine aggregates). Cement with 450kg/m^3 density with 10% silica fume was used. The fracture characteristics, which involve fracture toughness (KIC) and fracture energy generation (GF), of all concrete mixtures were evaluated by testing two types of samples, i.e. 54 notched concrete beams with dimensions of 10×10×52cm and 54 cylinders with diameter×height equal to 15×30cm. The results showed that the fracture toughness generation addresses the energy scattering limit of concrete mixtures. The findings showed that the existence of PP fibers increased the fracture energy and critical Crack Mouth Opening Displacement (CMOD$_c$). The PP fibers had a limited effect on the compressive strength and may even reduce it, but a remarkable enhancement of the energy absorption was observed.

Keywords-lightweight aggregates; silica fume; crack growth; polypropylene fibers; crumb rubber; fracture energy

I. INTRODUCTION

Fibers and waste rubber in Lightweight Aggregate Concrete (LWAC) are promising additive materials to control and improve its fracture behavior. The fracture properties of concrete altogether impact the underlying conduct of concrete constituents [1]. Authors in [2] examined the fresh properties of exact Low-Strength Rubber Concrete (LSRC) and Controlled Low-Strength Rubber Lightweight aggregate Cement (CLSRC) with unused-tire rubbers in different substitution percentages, namely 0%, 10%, 20%, 30%, and 40%. The percentage of substitution influences the unit weight and initial setting time. About 10% growth in the content of rubber fragments diminishes the unit weight by about 70kg/m^3. The compressive strength of CLSRC and CLSRLC declines even though the content of rubber substitution increments. Authors in [3] examined the mechanical properties and the penetrability of rubber treated plain pervious concrete. Three different sorts of rubber have been developed as a substitute for aggregates in the design of rubber-handled simple concrete combinations. In the analysis, four-detailed rubber substances by total aggregate volume were considered. The outcome showed that the utilization of rubber essentially exasperated the pervious concrete mechanical properties.

Generally, alternatives of common aggregates, including rubber grains, exhibit a critical increment in stiffness and ductility of concrete and a better damping limit. Authors in [4] examined the appropriateness of trash tire synthetic rubber in concrete as an alternative for river sand. Three water/cement ratios (0.40, 0.45, and 0.50) and 0–20% replacement of fine aggregates were used. In [5], tests were carried-out to evaluate characteristics such as compressive strength, flexural strength, abrasion resistance, microstructure, and water penetrability. It was found that a 50% replacement of aggregates with tire rubber might be used for regular fine aggregates without a significant decrease in strength. It was noticed that the replacement of mineral aggregates with tire-rubber particles showed a substantial decrease in ultimate compressive strength and modulus of elasticity. Due to this reduction in ultimate compressive strength, the maximum percentage of aggregate replacement with rubber should not be more than 25% [5]. In general, the crack generation in concrete containing waste rubber is smaller than that occurring in ordinary concrete. The mode of failure in tire-rubber concrete compared to that of plain concrete exhibits higher deformation. Future investigations are needed to address the energy retention of tire-rubber concrete under dynamic loads, and the toughness of tire-rubber cement under unfavorable enduring conditions. Authors in [6] proposed the replacement of aggregates with 20–40% crumb rubber. It was found that concrete mixtures with such substitutions showed beneficial and superior properties. Authors in [7] reported that the addition of crumb tire rubber in up to 5% volume fraction in a cement matrix does not yield a significant variation of concrete's maximum stress and elastic modulus. In terms of splitting tensile strength, Portland cement concrete specimens made with 25% of rubber fibers by total aggregate volume retained 20% of their splitting tensile strength after initial failure.

Cement and concrete were subjected to high-level warming in [8, 9]. It was discovered that the harm due to warming from 120 to 400^{o}C enlarges crack energy by half. Authors in [10] examined the residual fracture energy of cement paste, mortar, and concrete subjected to high temperature and found that the thermal damage due to heating from 120 to 400^{o}C increases the fracture energy by 50%. They reported that the post-cracking behavior of concrete specimens was unaffected by the partial substitution of fine aggregates with rubber particles having similar dimensions, whereas a good residual strength after cracking and significant energy absorption were observed for rubcrete mixes obtained by adding coarse rubber chips in place of coarse aggregates.

Among non-metal fibers, the impact of polypropylene (PP) compositions on the assets of LWAC has been examined thoroughly. The test consequences of [11-16] demonstrated that, if PP fibers are utilized in combination with a LWAC blend, they may have a moderate impact on the enhancement of the compressive strength and may even decrease it. The impact of 3 kinds of fibers on the properties of expanded clay LWAC was explored. PP composition did not influence the compressive strength, while carbon composition and steel fibers had impact up to 1.0% and up to 1.5%, respectively. The PP fibers can likewise be utilized in LWAC to avoid weak actions. Authors in [17] used small PP fibers (L = 1.3cm and D = 0.0015cm). They announced that PP fibers marginally improve the energy ingestion while steel fibers greatly affect the energy retention of concrete under pressure. The significance of the ductility of concrete constructions exposed to seismic loading is broadly recognized and configuration codes represent this limit. These perceptions accentuate the preferred position that PP fibers add to the pliability of pumice LWAC, which is viewed as weak. Subsequently, more productive and more efficient arrangements might be conceived by fusing pumice insubstantial aggregates with steel rods in mixtures [18-23]. The extent of this examination is unquestionably very restricted to give some exploratory information on the impact of PP fibers and scrap rubber on fracture properties (counting G_F and K_{IC}) of PP Fiber Lightweight Aggregate Crumb Rubber Concrete (PFLWACRC). An amount 10% silica rage has been utilized to upgrade the mechanical properties of this kind of concrete.

The impact of PP fibers on the properties of LWAC is examined in this paper. This investigation studied the crack generation of PFLWACRC. The impact of waste rubber on the crack growth of the PFLWACRC with different levels of PP fibers is presented. In PFLWACRC, PP fibers were utilized to improve the crack growth resistance of concrete, while the incorporation of waste rubber is eco-friendly and requires less energy.

II. EXPERIMENTAL PROGRAM

A. *Concrete Ingrendients*

- Cement: Ordinary Portland concrete (Type I) was used in the current study. The density of cement was kept constant as 450kg/m^3.
- Fine aggregates: Regular ordinary weight fine clean sand free from any contaminations was utilized. Specific gravity, water absorption, and fineness modulus of the soil were 2.3, 2.9%, and 2.2, respectively, according to ASTM C-33.
- Coarse aggregates: Normal lightweight aggregates (Pumic), obtained from southwestern Saudi Arabia, were utilized. Sieve analysis test for lightweight aggregates was conducted according to ASTM C 330. The properties of the Lightweight Aggregates (LWA) are given in Table I.
- PP fibers were added at 0.2%, 0.4 %, and 0.6%. The main properties of the fibers are shown in Table II.
- The crumb rubber utilized was obtained from used and worn-out vehicle tires. The particle diameter ranged

between 14 and 20 sieve size (0.85 - 1.40mm), as indicated by ASTM-E11-09, while the specific gravity was found to be 1.20, and the melting point was 200^{o}C. Scrap rubber with different quantities (0%, 5%, 10%, 15%, 20%, and 25%) was utilized.

- Admixture: super-plasticizer with a solid substance of 40% and water reduction of 25% with a density of 1,210kg/m^3 (ASTM C-494) was treated as intermixture to realize workable concrete mixtures (slump value of 120mm±25mm). Based on slump trails and tests, super plasticizer of 1.0% by weight of cement was used.
- Silica Fume (SF) was utilized in concrete mixes. It exhibited an explicit surface area of 19.7m^2/gm and specific gravity of 2.27. As a partial replacement, the amount of SF used was 10% by total weight of cement.
- Water: potable water was used in all concrete specimens. The 0.45 water-cement ratio (w/c) was kept constant for all mixes.

TABLE I. PROPERTIES OF LWA

Property	Specification/Value
Color	grayish/black
Bulk density (kg/m³) for coarse aggregates	780
Bulk specific gravity (SSD)	1.85
Oven dry specific gravity	1.66
L-A abrasion value	16.4
Water absorption	9.7%
Porosity	8.1%
N.M.S	14 mm

TABLE II. CHARACTERISTICS OF PP FIBERS

Property	Value
Tensile strength (Mpa)	450
Specific gravity	0.89
Elongation at peak (%)	18
young's modulus (GPA)	5
Length (mm)	60
Diameter (mm)	12

TABLE I. LWA DELIBERATE PROPERTIES

LWA type	Deliberate properties
LWA-FR0	LWA with 0% rubber at different levels of fiber content.
LWA-FR5	LWA with 5% rubber at different levels of fiber content.
LWA-FR10	LWA with 10% rubber at different levels of fiber content.
LWA-FR15	LWA with 15% rubber at different levels of fiber content.
LWA-FR20	LWA with 20% rubber at different levels of fiber content.
LWA-FR25	LWA with 25% rubber at different levels of fiber content.

The Lightweight Concrete (LWC) mixtures were divided into 6 groups based on the percentages of PP fiber replacement. Each group consisted of 9 150cm×30.0cm standard cylinders in conjunction, and 9 10cm×10cm×52cm notched beams. All tests were conducted after 28 days. Figure 1 shows the compressive strength vs the unit weight, and fiber percentage.

Fig. 1. Mix proportions by weight and compressive strength.

B. Flexural Tests

Three-point load setup was employed to address the rupture performance of PFLWACRC as per the proposal of RILEM Fracture System Commission (TC50-FMC) [18]. As demonstrated in Figure 2(a), the notched beams had effective length of 40.0cm and a notch at 30mm (a_0/h = 0.3) depth was located at the mid-span place. The test was conducted with a closed-loop electrohydraulic universal testing machine with a 1000kN capacity. Control specimens comprised of 3 cylinders with zero percentage of fibers and rubber. The properties (compressive strength and unit weight) of these specimens are almost the equivalent for LWAFR0. A load cell of 50kN capacity with accuracy of 1N plus a 5.0cm Linear Variable

Differential Transducer (LVDT) with 0.001cm precision were utilized to determine the weight combined with refraction at the middle of length, exclusively. Conversely, Crack Mouth Opening Displacement (CMOD) with a 1.0cm cut on measurements and 0.0001cm precision was used. Steady movement rate of 0.005cm/min was applied up to failure. The testing procedure of the 3-point twisting system (Figure 2(b)) intended to minimize the influence of compressive flexible deformity at the loading points (the platform and actuator head). Two LVDTs were mounted on the two inverse countenances for all specimens to evaluate the rebound at the halfway of length. Specimen, instrumentations, and test set-up are shown in Figure 2.

(a)
(b)
(c)

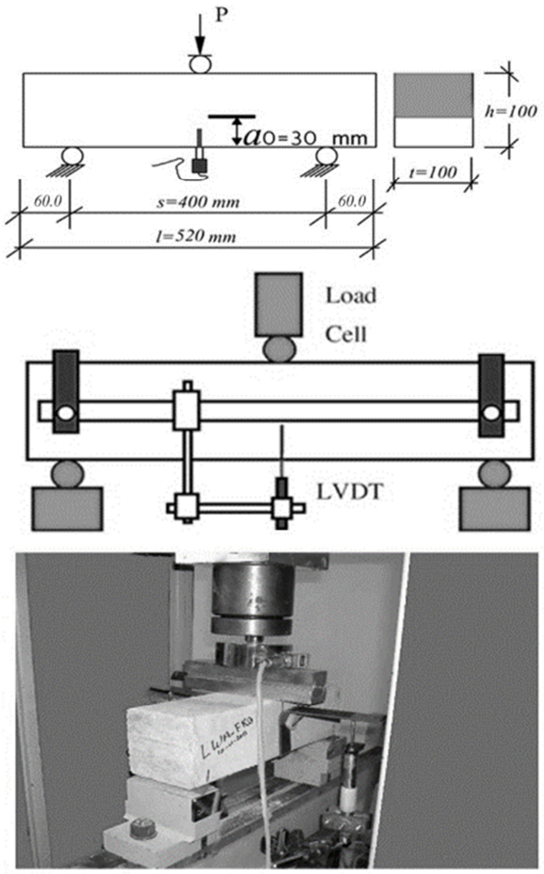

Fig. 2. Flexural three-point load-bending test: (a) Notched beam, (b) setup, (c) photo sample.

C. Evaluation of the Fracture Force

The fracture force is characterized as the all-out force disseminated across a unit section of a broken ligament. It is acquired as of the work carried out (the section below the P–δ arch). The fracture force of the jagged planks comprises 4 sections [1], and is mathematically expressed as:

$$W = W_0 + W_1 + W_2 + W_3 \quad (1)$$

where W_0 is the work done by the external force P, which is recorded by the data acquisition system, W_1 is the work performed by the ego-weight of the planks before the utilization of the outer force. It has a very small value, and can be neglected. W_2 and W_3 represent the extra work done for the duration of the packing cycle by the own substance of the planks. So, $W_2 = 0.5mg\delta_0$, and W_3 (the end part of the chart after δ_0), can't be estimated in the tests.

The computational derivation of the fracture energy is:

$$w_1 = \int_0^{\delta 0} p d\delta$$

In order to compute the extra work W_3 done by scaled weight, the plunging part of the deflection-load (δ–P) chart is misleadingly stretched out by curve fitting dependent upon the energy work technique [20, 21]:

$$p = \beta\delta^{-\lambda} \geq 0 \ (\beta,\ \lambda > 0)$$

$$lnp = \beta - \lambda \, \text{In}\delta \quad (2)$$

The dependability of the matching curves addressed by the consistency factor, R^2, and the particular fitting boundaries (for example β, λ, R^2) were calculated. W_3 is determined by (2)-(3):

$$w_3 = \int_{\delta_0}^{\infty} \frac{\beta}{\delta^{\lambda}} \, d\delta = \frac{\beta}{(\lambda-1)\delta_0{}^{(\lambda-1)}} \quad (3)$$

The physical fracture force of all concrete mixtures shows an agreement with (4), where A_{lig} is the zone of tendon, specifically $A_{lig} = t\ (h\text{-}a_0)$.

$$G_f = \frac{w_0+w_1+w_2+w_3}{A_{lig}} \quad (4)$$

The obtained outcome of the crack force of all concrete mixtures with different percentages of waste rubber and fibers is shown in Figure 3.

D. Evaluation of the Rupture Toughness

The rupture force (K_{IC}) of concrete reflects its capacity to avoid break down propagation and the capacity of resisting weak rupture in particular. The rupture durability of a concrete material is basically determined by (5) as per ASTM E399-74.

$$K_{IC} = \frac{P_{max}S}{th^{\frac{3}{2}}} f\left(\frac{a}{h}\right) \quad (5)$$

where P_{max} is the vertical upper limit load, h, t and S are the elevation, thickness, and length of the samples, respectively, and $f\left(\frac{a}{h}\right)$ is the numerical shape element, which is computed by:

$$f\left(\frac{a}{h}\right) = 2.9\left(\frac{a}{h}\right)^{\frac{1}{2}} - 4.6\left(\frac{a}{h}\right)^{\frac{3}{2}} + 21.8\left(\frac{a}{h}\right)^{\frac{5}{2}} - 37.6\left(\frac{a}{h}\right)^{\frac{7}{2}} + 38.7\left(\frac{a}{h}\right)^{\frac{9}{2}} \quad (6)$$

The contribution of PP fibers in concrete is that a bridging force is developed between the fibers and the cement paste, strengthening the material. The equation of ascertaining flexural rigidity suggested by ASTM refers to a simple material. The impact of flexural measure region on the fracture energy of PP fiber strengthened material is incorporated by the supplanting of the efficient fracture size (a_c), which is determined by $a_c = a_0 + \Delta a_c$. When the checking weight (P) arrives at its peak (P_{max}), the crack estuary hole movement goes its critical maximum value ($CMOD_c$), and the genuine length of pre-break is created from the first value (a_0) to the critical crack length (a_c). Thus, as indicated by the direct asymptotic behavior of superposition, a_c is determined by a LEFM equation (7) [19, 23]:

$$a_c = \frac{2}{\pi}(h + h_0)\arctan\sqrt{\frac{tE(\text{CMOD}_c)}{32.6p_{max}} - 0.1135} - h_0 \quad (7)$$

where h_0 is the width of the hardened layer employed to adjust fastening on instruments on the crack lip, (CMOD_c) is the significant amount of the crack lip hole movement, and E is the modulus of elasticity, calculated by:

$$E = \frac{1}{tc_i}\left[3.70 + 32.60\tan^2\left(\frac{\pi}{2}\frac{a_0+h_0}{h+h_0}\right)\right] \quad (8)$$

where $c_i = \frac{(\text{CMOD}_i)}{p_i}$ is an preliminary quantity defined at an capricious position, (P, CMOD) on the gradient phase of P-CMOD curves. The estimated calculations of the fracture force (K_{IC}) of all mixtures are reviewed in Figure 3.

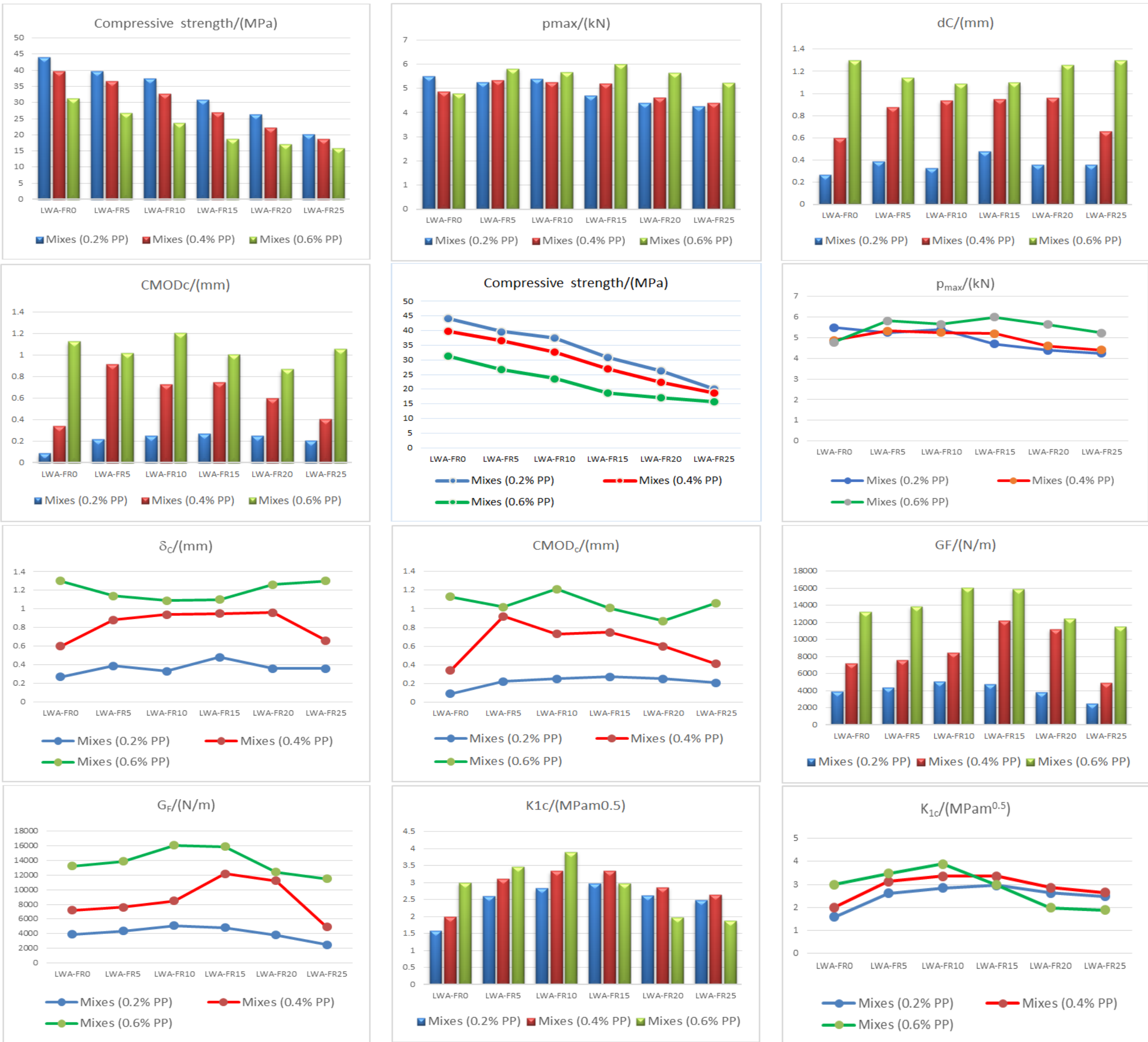

Fig. 3. Computed and experimental results.

III. RESULTS AND DISCUSSION

The densities of hardened concrete tested at 28 days are shown in Figure 1. It is observed that the PP fibers bring an unimportant impact on concrete samples. However, the solid thickness is predominantly influenced by the presence of morsel elastic. The solid thickness of the reference sample was 1870kg/m^3, the density of concrete comprised of 5%, 10%, 15%, 20%, and 25% waste rubber was 1815, 1785, 1743, 1711, and 1681kg/m^3, respectively. The specimens made up by 0.2%, 0.4%, and 0.6% PP fibers, almost had similar values. Considering the minimal specific gravity of rubber particles, the unit weight of the mixtures with rubber was reduced as the percentage of rubber increased [4, 17].

Based on the compressive strength results recorded in this study, a slight decrease in the compressive strength was observed as the PP fiber percentage increased. From Figure 1, it may be stated that the expansion of PP fibers up to 0.2% of concrete volume appears to have an insignificant impact on the compressive strength of concrete. Yet, adding more PP fibers, up to 0.6%, caused a reduction in compressive strength by about 10%.

The impact of the substitution of fine aggregates with scrap rubber at the compressive force is shown in Figure 1. It is obvious that there is degradation in compressive strength depending on the percentage of waste rubber used, around 15% for 10% of rubber used. The use of SF decreased the degradation in compressive strength [10]. The concrete samples containing rubber showed post failure pressure loads and experienced a large displacement before failure. The samples cracked and withstanded a portion of the ultimate load. The large noticed displacement and deformation are certainly related to the fact that the rubber aggregates can withstand huge distortions. It is well known that rubber materials exhibit a low elastic modulus which leads to a deferral in extending the crack and forestalling calamitous failure, which is generally experienced in plain concrete specimens.

The fracture properties of PFLWACRC beams with various replacement percentages of waste rubber and PP fibers were assessed by three-point loading tests. The obtained weight break cheek hole relocation (*P*-CMOD) relationship is shown in Figure 3. Furthermore, the impact of PP fibers and rubber in fracture force and toughness is shown in Figures 4 and 5. Established on the (δ–P) and P-CMOD behavior, the crack force (GF) and fracture stiffness durability (K_{IC}) of concrete for all mixtures was determined and is shown in Figure 3. It should be noted that each incentive in Figure 3 was the average of 3 samples in each group.

Obviously, the aim of inserting fibers and rubber to LWA is to enhance fracture behavior. The impacts of fibers and waste rubber on the deflection-weight (δ–P) and load crack mouth opening displacement (P-CMOD) behaviors are plotted in Figures 4 and 5, respectively. Generally speaking, PP fibers marginally improve the energy retention and durability of the material under flexible loads. Overall, PP fibers have a minimal impact on the ductility of LWC at 0.2% volume. For example, the presence of PP fibers expanded the absolute fracture energy and fracture energy of concrete as shown in Figure 5. On the other side, the addition of 0.2% PP increased somewhat the total energy. Figure 4 illustrates the correlation of load refraction behavior for 3 distinctive fiber sizes. Figure 4 demonstrates that the beams along with greater volumes of fiber content (specifically 0.6% by volume) demonstrate a superior resistance particularly beyond large deflections. Concrete mixtures containing 0.4% and 0.6% of PP fibers show more ductility than those with 0.2% PP fibers (Figure 4 (b)-(c)).

It appears that PP fiber volume fraction equal to 0.2% is inconsequential. In this manner, it is proposed that adding 0.4% PP fibers in mixtures improves the flexural properties of LWC. It is seen that the refraction associated to extreme weight increases with the increase of fiber size. This is recognized as the impact of fibers bridging and catching cracking. Figure 4 additionally displays the liner flexible segment of the curvature prior to the propagation of micro cracks in the matrix when using PP fibers. Due to lacking stiffness, it was difficult to gauge the dropping part of LWC. Figure 5 depicts the CMOD relations for 3 distinctive fiber volume substances. It should be noted that, at similar loads after cracking, the beam with larger volume of fibers exhibits substantially more CMOD values.

(a)

(b)

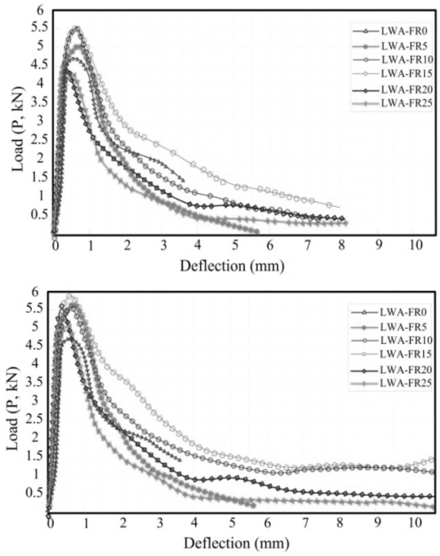

Fig. 4. Load-deflection curves of all mixes containing (a) 0.2% and (b) 0.4% PP.

(a)

(b)

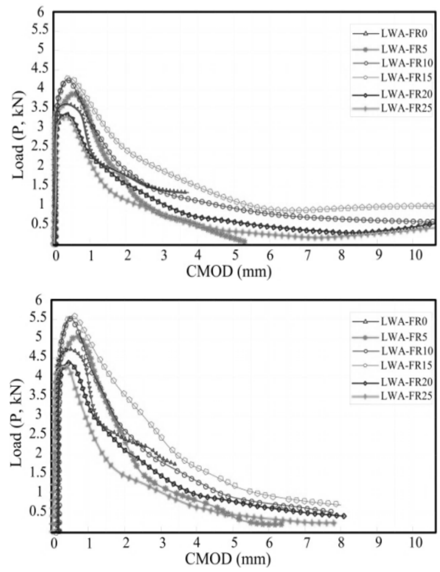

Fig. 5. Load – CMOD Curves of all mixes containing (a) 0.2% and (b) 0.4% PP.

A. Fracture Energy

The values of the fracture force of the concrete mixtures are displayed in Figure 3. The impacts of fibers and rubber on the rupture vitality and fracture energy of material mixtures are shown in Figures 4 and 5, respectively. It is obvious that the addition of rubber effectively affects the rupture vitality of material mixtures up to 10%. This outcome demonstrates that fitting rubber waste improves the energy ingestion limit of the concrete. However, too much rubber may negatively affect the energy retention limit. Accordingly, to viably improve the energy assimilation limit of concrete mixes, a fitting measure of rubber ought to be chosen. This result is in accordance with [17, 24]. On the other hand, the fracture properties can be improved with the addition of PP fibers, particularly fracture energy (Figures 3-4). The fracture energy of the concrete mixtures increases by more than 3.0 by expanding the fiber content from 0.2% to 0.6%. The fibers delay the crack spread and do not go to rapid failure, which causes an expansion in the weight carrying capability of beams [25].

B. Rupture Durability

The impact of adding rubber fibers on the durability of the mixtures is shown in Figure 5. It can be noticed from Figure 5 that the rupture force of the mixtures clearly changes with increasing fiber content. With the addition of rubber, the impact of fiber content on the rupture force of the material mixtures is predictable. The rupture force originally increased when up to 15% rubber substance was used and it decreased with further increment of elastic substance until 25%, with the fracture energy being the smallest at 0.2% fiber content. At 0.2% PP fiber, the fracture energy increased by about 80% and 88% when rubber was added by 10% and 15%, respectively. This increase diminished to 56% at 25% rubber substitution. A similar pattern was noticed to the 0.4% and 0.6% PP fiber concrete mixes.

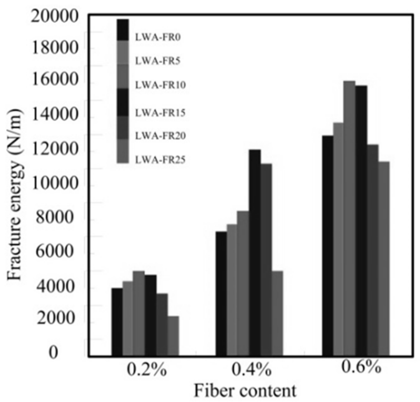

Fig. 6. Effects on fracture energy combined with elastic substance on the fiber.

As shown in Figures 6 and 7, the elevated addition of fibers and rubber may prompt a large increase of the rupture stiffness, maybe because the material power relies on the intensity of the substance and the aggregates are improved by the presence of fibers [18]. For concrete mixtures arranged with various replacement percentages of fiber and rubber, the distinction in the highest pressure and rupture force may be identified with the force of the interfacial connection. Through vibrations, the water within the material is allowed to go to the LWA due to their extreme-water retention limit, making a moderately superior w/c incentive. Accordingly, a more grounded bond may be framed between the cement paste and LWA, particularly when SF is added to the concrete blend. The above outcome showed that adding rubber improves the protection of concrete mixtures from brittle fracture. However, adding too much rubber may negatively affect that protection. It very well may be inferred that the ideal estimations of rubber to upgrade the fracture properties lie between 10% and 15%, while the PP fibers should not be under 0.4% volume fraction.

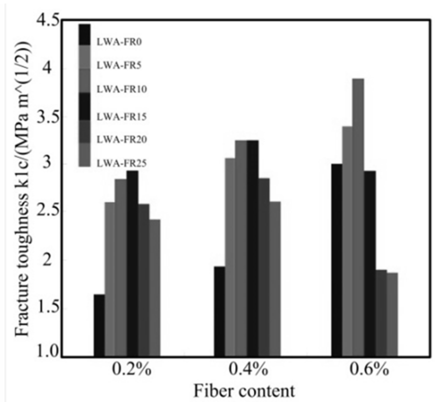

Fig. 7. Effect of fiber and rubber on rupture stiffness.

IV. CONCLUSIONS

In the current study, the impact of the addition of PP fibers and rubber waste in concrete mixtures on the fracture toughness and fracture energy of LWC were addressed. The progression of 3-point load on 10cm×10cm×52cm beams was examined. Based on the experimental results and the derived calculations, the following conclusions were drawn:

- The addition of PP fibers has irrelevant impact on the density of concrete samples. The concrete density is predominantly influenced by the use of scrap rubber. A serious dilapidation of compressive strength was observed for all concrete mixtures by expanding the rubber substance addition to more than 15%.
- PP fiber addition prompts a critical expansion in the fracture toughness. For addition of the rubber substance from 5% to 10%, the fracture toughness originally increased, whereas the addition up to 25% diminished the increment of fracture toughness.
- PP fibers have no recognizable impact on the hardened properties of concrete at replacement level below 0.2%. The addition of 0.4% PP fibers in concrete affects the compressive behavior. Nonetheless, 0.4% PP fibers increased slightly both fracture toughness and fracture energy. The impact of PP is undeniable in the concrete mixtures. The proposed dose of PP fibers to be utilized in lightweight concrete in order to avoid brittle failure is up to 0.4%.

- Suitable waste rubber level improves the concrete brittlness behavior, however, an excessive amount of rubber may negatively affect this protection. The ideal addition of rubber content to improve the crack behavior varies between 10% and 15%, while PP fiber addition up to 0.4% volume fraction was acknowledged.

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