FRACTURE BEHAVIORS OF POLYPROPLENE FIBER LIGHT WEIGHT AGGREGATE CONCRETE WITH CRUMB RUBBER

سلوك الكسر لخرسانة الياف البولي بروبلين الخفيفه المحتوية على المطاط المفتت

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سلوك الكسر لخرسانة الياف البولي بروبلين الخفيفه المحتوية على المطاط المفتت

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الملخص:

يهدف هذا البحث الى دراسة سلوك الكسر للخرسانة ذات الركام الخفيف المحتوية على نسب مختلفة من الياف البولي بروبلين وكذلك المطاط المفتت، حيث تم اضافة الياف البولي بروبلين لتحسين مقاومة التشرخ لهذا النوع من الخرسانة بينما كان الهدف من اضافة المطاط المفتت التخلص من نفايات الاطارات وحماية البيئة من التلوث. وقد تم اضافة ١٠% سيليكافيوم لتعويض بعض النقص في مقاومة الضغط نتيجة اضافة فتات المطاط . وقد تم تصميم عدة خلطات من الخرسانة الخفيفة الوزن باستخدام ركام محلي الانتاج لمحتوى اسمنت ثابت مقداره ٤٥٠ كجم/ م٣ لجميع الخلطات لنسب مختلفة من الياف البولي بروبلين (٠,٢ ، ٠,٤ ، ٠,٦ %من حجم الخرسانه) وكذلك استبدال الرمل بنسب مختلفة من المطاط المفتت (٥، ١٠ ، ١٥ ، ٢٠ ، ٢٥ % من وزن الرمل). وقد تم دراسة سلوك الكسر للخرسانه من خلال تحديد متانة الكسر (K ic) و طاقة الكسر(Gf) لمختلف الخلطات وذلك باجراء اختبار الانحناء الذي تم لعدد ٥٤ كمرة بأبعاد ١٠٠ ×١٠٠ × ٥٢٠مم وكذلك عدد من الاسطوانات ١٥٠ × ٣٠٠ مم. وقد اوضحت النتائج ان كلا من طاقة الكسر ومتانة الكسر تزداد بوجود ١٠ % من محتوى المطاط ثم تقل بعد زيادة المحتوى. كما اوضحت النتائج ان طاقة الكسر تزداد بتواجد الياف البولي بروبلين وأن ألياف البولى بروبلين ذات تأثير محدود على مقاومة الضغط للخرسانه الخفيفه.

FRACTURE BEHAVIORS OF POLYPROPLENE FIBER LIGHT WEIGHT AGGREGATE CONCRETE WITH CRUMB RUBBER

Majid Matouq Assas

ABSTRACT:

This paper studied the fracture behaviors of a polypropylene fiber reinforced light weight aggregate rubber concrete (FLWARC). The effects of rubber content on the fracture behaviors of the FLWARC With different levels of polypropylene fiber contents were analyzed. In FLWARC, the polypropylene fiber was used to improve the crack resistance of concrete, while the inclusion of crumb rubber is mainly for environment protection and energy dissipation. Just 10% of silica fume was used to reduce the loss of strength due to the increase of rubber contents. A series of concrete mixes were prepared with ordinary Portland cement, locally produced natural light weight coarse aggregates (Pumic), polypropylene fiber with volume-fraction of 0.2% 0.4 % &0.6%, while the crumb rubber with different replacement ratios of 0%, 5%, 10%, 15%, 20% and25% of fine aggregate (sand). All mixes were prepared at constant level of binder content equal to 450Kg/m3. The fracture properties, including fracture toughness (KIC) and fracture energy (GF), of the different concrete mixes, were obtained through three-point bending tests on 54 notched beams with sizes of 100 mm x 100 mm x 520 mm and 54 cylinders of 150mm diameter and 300mm length. The results indicated that both the fracture toughness and fracture energy first increase up to 10% rubber content and then decrease with increase of the rubber content; at certain rubber content, the mixes had the highest toughness. It demonstrated that the existing of polypropylene fiber increased the fracture energy and critical crack mouth opening displacement (CMODcri). The PP fibers have a relatively low effect on the improvement of the compressive strength and may even reduce it but remarkable enhance the energy absorption was observed.

Keywords: polypropylene fiber, light weight aggregate, Crumb rubber, Silica fume, Fracture properties.

1. INTRODUCTION

Studies on the fracture properties of concrete have recently attracted more attentions. The fracture energy is defined as the energy absorbed to create a unit area of fracture surface, representing the energy dissipation capacity of overall loading process. The higher brittleness and lower mechanical properties of lightweight aggregate concrete (LWAC) compared to normal weight concrete (NWC) at the same compressive strength has prevented it from being widely used in the construction industry despite its many advantages. Studies have shown that the use of fibers and rubber in LWAC is an appropriate solution to resolve such problems. The fracture properties of concrete significantly influence the structural behavior of concrete components, Zhang B.(2011)[1]. Her-Yung Wang et al (2013)[2] investigated the fresh properties and 1 day-aged compressive strength of controlled low-strength rubber concrete (CLSRC) and controlled low-strength rubber lightweight aggregate concrete (CLSRLC) with five waste-tire rubber replacement of 0%, 10%, 20%, 30% and 40% are studied, respectively. The unit weight and initial setting time are affected by the amount of rubber particles that have been substituted for natural aggregate. An average 10% increase in the amount of rubber particles decreased the unit weight by approximately 69 kg/m^3. The compressive strength of CLSRC and CLSRLC decrease while the amount of rubber replacement increases. Mehmet Gesogiu, et al. (2014) [3] studied the properties of rubberized plain pervious concrete in terms of the mechanical properties and the permeability. Three types of rubber were used in the production of rubberized plain pervious concrete mixtures which obtained by partially replacing the aggregate with rubber. One water-cement (w/c) ratio, one moist curing period, and four designated rubber contents by total aggregate volume were considered as experimental parameters. The results compared with non-rubberized pervious concrete (control) mixture. The use of rubber significantly aggravated the pervious concrete mechanical properties and its permeability but in different degrees according to the rate and type of rubber used. However, replacement of natural aggregate with rubber particles resulted in a significant increase of toughness and ductility of concrete as well as better damping capacity. Blessen Skariah Thomas, et al, (2014) [4] investigated the suitability of waste tire rubber in cement concrete as a partial replacement for natural river sand. The water/cement was ratios of 0.4, 0.45 and 0.5 were also studied. 0–20% substitution of fine aggregates, in multiples of 2.5% was done with discarded tire rubber (crumb rubber). The specimens with 0% discarded tire rubber were taken as control mix. Tests were done to determine the compressive strength, flexural strength, abrasion resistance, micro-structure, water permeability, and Sorptivity in concrete specimens. It was observed that discarded tire rubber may be utilized for the partial replacement for natural fine aggregates up to 7.5% without enough reduction in its desired strength. Ali R. Khaloo (2008) [5] noted that the substitution of mineral aggregates with tire–rubber particles in concrete results in large reductions in ultimate strength and the tangential modulus of elasticity. Due to the considerable decrease in ultimate strength, rubber concentrations exceeding 25% are not recommended. Crack width in rubberized concrete is smaller than that of plain concrete, and the propagation of failure symptoms is more gradual and uniform. The failure state in tire–rubber concrete compared to plain concrete is characterized by more deformation. He mention that there is a need for future studies to investigate energy absorption of tire–rubber concrete under dynamic loading, and also the durability of tire–rubber concrete under adverse weathering conditions. Alio. Atahan, et al(2012) [6] design an experimental program of six different concrete mix containing various amounts of coarse and fine crumb rubber were tested for properties important to concrete safety barriers. Eighteen samples – three of each mix design – were tested under static compression to determine the compressive strength and elastic modulus values. Another eighteen samples were subjected to dynamic drop tests to assess the effect of rubber on energy dissipation. Test results show that increasing the amount of rubber decreases the compressive strength and elastic modulus of the concrete, while significantly increasing impact time and energy dissipation capacity. It was determined that replacing 20–40% of aggregates with crumb rubber creates concrete mixes that would be useful for concrete safety barriers in locations where strength, fracture resistance and energy dissipation are required. Finally, concrete mixes with greater than 60% of aggregates replaced by crumb rubber would be useful for concrete impact attenuators in locations where low impact severity is of ultimate importance, and fracture or fragmentation upon impact is acceptable. Hernandez-Olivares et al. (2002) [7] have reported that addition of crumb tire rubber volume fractions up to 5% in a cement matrix does not yield a significant variation of the concrete mechanical features, either maximum stress or elastic modulus. In terms of splitting tensile strength, Portland cement concrete specimens made with 25% of rubber by total aggregate volume retained 20% of their splitting tensile strength after initial failure. Rafat Siddique, Tarun R. Naik (2004)[8].and Menou et al.(2006) [9] 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 ^{0}C increases the fracture energy by 50% compared with the reference tests at room temperature. M.A. Aiello and F. Leuzzi(2010)[10] reported that the post-cracking behavior of concrete specimens was unaffected by the partial substitution of fine aggregate with rubber particles having similar dimensions; whereas a good residual strength after cracking and a significant energy absorption were observed for rubcrete mixes obtained by adding coarse rubber chips in place of coarse aggregate.

Among the several types of non-metallic fibers, the effects of PP fiber on the properties of LWAC have been investigated. The test results of some researchers [11, 12, 13, 14, 15, and 16] have shown that, generally, if the PP fibers are used in single form in the mixture of a LWAC mixture, they have a relatively low effect on the improvement of the compressive strength and may even reduce it. The effect of three types of fibers on the properties of expanded clay LWAC was investigated. Among these fibers, the PP fiber does not affect the compressive strength, while carbon fiber has the highest effect, up to 1.0 %, and steel fiber up to 1. 5%. The PP fibers can also be used in LWAC to prevent brittle behavior. Libre et al. (2011) [17] reported that low strength pumice LWAC is brittle. They concluded that the minimum amount of PP fibers (L = 12 mm and D = 0.016 mm) to prevent brittle behavior of such LWAC is about 0.4% by volume of concrete. In addition, they reported that PP fibers slightly enhance the energy absorption while steel fibers have a great effect on the energy absorption of concrete under compression.

The importance of ductile behavior of concrete structures subjected to seismic loading has been widely acknowledged by engineers and researchers and design codes account for this capacity. These observations emphasize the advantage that polypropylene fibers contribute to ductility of pumice lightweight aggregate concrete which is considered to be brittle. Thus, more efficient and also economical solutions may be possible by incorporating both pumice lightweight aggregate and reinforcing fibers in concrete mixes. These will results in a reduced dead load and also ductile behavior in all mode of loading [18-25]. However, the scope of this study is certainly far too limited to provide some experimental data on the effect of polypropylene fiber and crumb rubber on fracture properties (including the fracture energy G_F and fracture toughness K_{IC}) of (FLWARC). 10% silica fume is used to enhance the mechanical properties of this type of concrete.

2. Experimental work

2.1Materials

A locally produced ordinary Portland cement (Type I, Locally produced in Saudi Arabia.) was used in this investigation; the cement content was kept at constant level 450 kg/m^3. Natural normal weight fine clean sand free from any impurities was used. The sand properties namely the specific gravity, water absorption and fineness modulus were 2.3, 2.9% and 2.2 respectively. The fine aggregate was confirming with (ASTM C-33) requirements.

Natural lightweight aggregate (Pumic) material was used, come from south western of Saudi Arabia. The lightweight aggregates were separated by particle size using sieve analysis as per ASTM C 330, thereby reducing the influence of water absorption. The main properties of light weighjt aggregate were reported in Table 1.

Polypropylene fiber was added to all mixes with different volume fraction of 0.2% 0.4 % &0.6%. The main properties of fiber were reported in Table 2. Crumb rubber, obtained from waste tires, has an average particle diameter of 14 - 20 sieve size (i.e. 0.85 - 1.40 mm according to ASTM-E11-09), a specific gravity of 1.20, and a melting temperature of 200^{0}C. Crumb Rubber with varied content (0%, 5%, 10%, 15%, 20% and 25%) was used.

Table 1. Properties of light weight aggregate (LWA).

Color	grayish/black
Bulk density (kg/m^3) for coarse aggregate	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	14mm

Table 2. properties of polypropylene fibers

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

In addition, a commercially available naphthalene-based super-plasticizer with a solid content of 40% and a water reducing rate of 25% with a density of 1,210 kg/m^3 was used as admixture to achieve slump of the concrete mixes around 120 mm±25mm. The chemical admixture was confirming with ASTM C-494. The amount of super plasticizer was 1.0% by weight of cement based on slump tests. Silica fume used in concrete mixes have specific surface of 19.7 m^2/gm and specific gravity of 2.27, the contents of silica fume (SF) are 10% by weight as a partial replacement of cement. Water used for mixing and for curing all concrete mixes and specimens clean fresh water, free from any impurities, while the water-binder ratio was kept constant for all mixes and equal to 0.45.

A total of six groups of mixes, were prepared using light weight concrete aggregate (LWC), Each group of concrete mixes includes 9 cylinders with dimensions of 150 mm x 300 mm (diameter and height) and 9 notched beams with dimensions of 100 mm x 100 mm x 520 mm,. All tests were carried out 28 days after the casting. The mix proportions unite weight and compressive strengths are presented in Table 3.

2.2 Bending tests

A three-point load was used in the study to determine the fracture performance of the new concrete material FLWARC in accordance with the recommendation of RILEM Fracture Mechanics Committee (TC50-FMC) [18]. As shown in Fig. 1(a), the notched beams used for the three-point load test had dimensions of 100 mm x 100 mm x 520 mm and a span of 400 mm; a notch with a depth of 30 mm (a_0/h = 0.3) was located at the mid-span place. The test was conducted on a closed-loop

Electro Hydraulic universal testing machine with a 1000-kN capacity and three control modes: load, displacement control and strain control.

Table 3. Mix proportions and compressive strengths.

Mix	**compressive strength (MPa)**			**Unite weight (kg/m^3)**	**Mix proportions (unit weight: kg/m^3)**									
	PP fiber				**W/C**	**W**	**OPC**	**SF**	**LWA**	**Sand**	**Rubber**	**Fiber**		
	0.2%	**0.4%**	**0.6%**									**0.2%**	**0.4%**	**0.6%**
LWA-FR0	**44.08**	**42.75**	**39.23**	**1870**	**0.45**	**202**	**405**	**45**	**567**	**954**	**-**	**1 .82**	**3.64**	**5.46**
LWA-FR5	**39.67**	**37.66**	**35.03**	**1815**	**0.45**	**202**	**405**	**45**	**567**	**906**	**8.01**	**1 .82**	**3.64**	**5.46**
LWA-FR10	**37.56**	**35.68**	**33.18**	**1785**	**0.45**	**202**	**405**	**45**	**567**	**858**	**16.02**	**1 .82**	**3.64**	**5.46**
LWA-FR15	**30.83**	**28.98**	**27.24**	**1743**	**0.45**	**202**	**405**	**45**	**567**	**810**	**24.03**	**1 .82**	**3.64**	**5.46**
LWA-FR20	**26.36**	**25.30**	**23.78**	**1711**	**0.45**	**202**	**405**	**45**	**567**	**763**	**32.o4**	**1 .82**	**3.64**	**5.46**
LWA-FR25	**20.12**	**18.71**	**16.84**	**1681**	**0.45**	**202**	**405**	**45**	**567**	**715**	**40.05**	**1 .82**	**3.64**	**5.46**

LWA-FRO: light weight aggregate concrete specimen with o% rubber at different levels of fiber content.

LWA-FR5: light weight aggregate concrete specimen with 5% rubber at different levels of fiber content.

LWA-FR10: light weight aggregate concrete specimen with 10% rubber at different levels of fiber content.

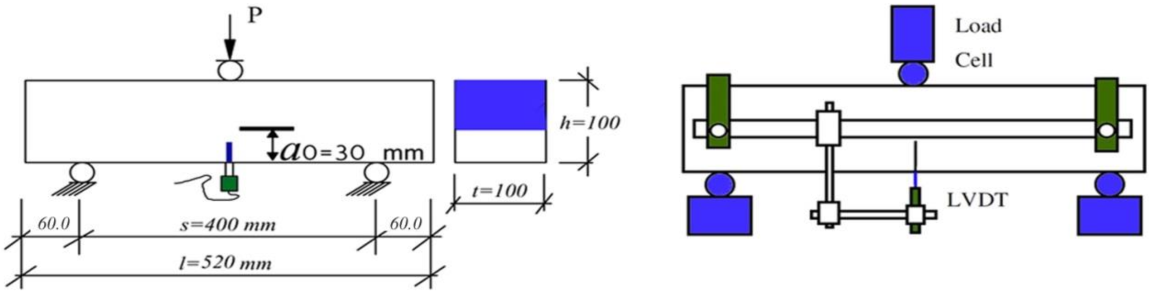
LWA-FR15: light weight aggregate concrete specimen with 15% rubber at different levels of fiber content.

LWA-FR20: light weight aggregate concrete specimen with 20% rubber at different levels of fiber content.

LWA-FR25: light weight aggregate concrete specimen with 25% rubber at different levels of fiber content.

The measured unit weight for 0.4% PP fiber only.

Control specimens consist of three cylinders of zero percent fiber and rubber content, were cast. The measured properties (compressive strength and unit weight) of these specimens are nearly the same for LWAFR0.



(a) Notched beam of three-point load -bending test

(b) Set-up of three-point load-bending test

(c)Test set-up in 1000 kN testing machine

Fig. 1 Test set up of three point load

A 50-kN load cell with the precision of 1 N and a 50-mm displacement transducer (LVDT) with the accuracy of 0.01 mm were applied to obtain the load and deflection at the mid-span respectively, while the crack mouth opening displacement (CMOD) was measured with a 10-mm clip-on gages with the accuracy of 0.001 mm. During the loading process, a constant displacement rate of 0.05 mm/min with the central deflection as the control parameter was applied until the final failure of the specimen. In addition, a testing strategy used in the three-point bending method [Fig. 1(b)] was designed to eliminate the negative effect of compressive plastic deformation on the compressed parts of specimens (e.g. the pedestal and actuator head) on the measurement. Both the specially designed testing system and the precision of measurement ensure the accuracy of the load–deflection (P–δ) curves and load-CMOD (P-CMOD) curves [19]. Two displacement transducers were fixed on the two opposite faces of each specimen in order to evaluate the mid span deflection. The specimen and set-up of three-point-load test are shown in Fig. 1(c).

2.3 Determination of the fracture energy

The fracture energy, defined as the total energy dissipated over a unit area of the cracked ligament, it obtained from the work done by the force (the area under the load–deflection curve). The fracture energy of the notched beams includes four parts as shown in Fig. 2 [1], which can be 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 done by the self-weight of the beams before application of the external force P, it is very small and can be neglected; W_2 andW_3 are the additional work done during the loading process by the self-weight of the beams, in which there exists a equation of $W_2 = 0.5mg\delta_0$; W3, the end part of the curves after δ_0, cannot be measured in the tests. The computational steps of the fracture energy are as follow:

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

$W_2 = 0.5mg\delta_0$, in which mg ($g = 9.81\ m/s^2$) is the self-weight of the beams.

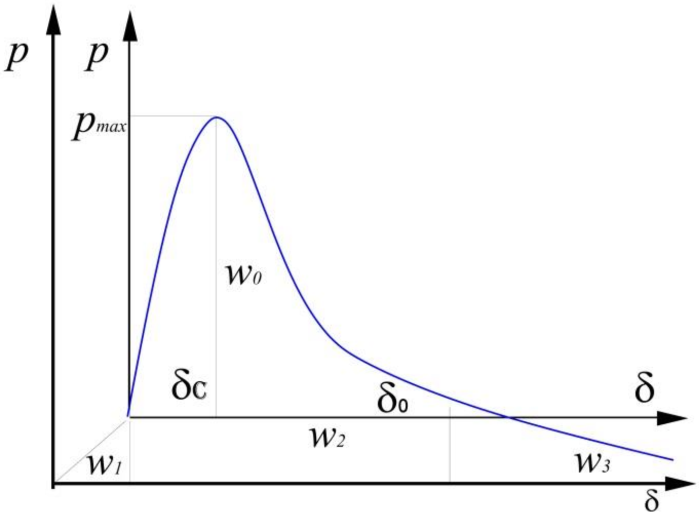


Fig.2. Estimation of fracture energy of concrete using three-point loads [1].

Calculating the additional work W_3 done by scaled weight. First, the descending branch of the load–deflection ($P–\delta$) curve is artificially extended by curve-fitting based on the power function method [20, 21]:

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

$$Inp = \beta - \lambda \,\mathrm{In}\delta \tag{2}$$

The reliability of the fitting curves is represented by the reliability coefficient, R^2, and the specific fitting parameters (i.e. β, ƛ, R^2) are computed. Thus, W_3 can be calculated by the following formula (2-3).

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

The real fracture energy of all mixes is obtained in accordance to the formula after W_0, W_2 and W_3 are obtained. Where, A_{lig} is the area of ligament, namely A_{lig} = t (h-a_0).

$$G_f = \frac{w_0+w_1+w_2+w_3}{A_{lig}} \tag{4}$$

The calculated results of the fracture energy of all mixes with various contents of crumb rubber and fibers are summarized in Table 4.

2.4. Determination of the fracture toughness

The fracture toughness (K_{IC}) of concrete reflects the ability of concrete material to resist crack extension, namely the ability of resisting brittle fracture. The fracture toughness K_{IC} of a concrete material is calculated by formula (5) according to ASTM E399-74.

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

Where P_{max} is the vertical peak load; h, t and S are respectively the height, width and Span, of the specimens; a_0 is the notch depth; $f\left(\frac{a}{h}\right)$ is the geometric shape factor, calculated by formula (2-6).

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

The inclusion of polypropylene fiber introduces the anchoring force between polypropylene fiber and concrete matrix, which causes the fracture process zone of polypropylene fiber reinforced concrete larger than that of plain concrete. The formula of calculating fracture toughness recommended by ASTM, however, is based on the plain concrete material. The influence of fracture process zone on adhesive fracture toughness of polypropylene fiber reinforced concrete is included by the replacement of a with the effective crack length a_c in formula (6) [19, 22].The effective crack length (a_c) was calculated by $a_c = a_0 + \Delta a_c$. When the testing load (P) reaches its maximum (P_{max}), the crack mouth opening displacement gets its critical value $(CMOD)_c$, and the real length of pre-crack also develops from the initial value (a_0) to the critical effective crack length (a_c). Hence according to the linear asymptotic superposition principle, ac can be calculated by a LEFM formula (7) [19, 23]:

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

Where h_0 is the thickness of steel sheet used to set up the clip-on gages on the crack Mouth (i.e. additional thickness); (CMOD)c is the critical value of the crack mouth Opening displacement; E is the modulus of rupture, expressed by formula (8):

(Case in the table) is an initial value determined at a arbitrary point (P, CMOD) on the ascent stage of P-CMOD curves.

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

Where $c_i = \frac{(cmod)_i}{p_i}$ is an initial value determined at an arbitrary point, (P, CMOD) on the ascent stage of P-CMOD curves? The calculated results of the fracture toughness (K_{IC}) of all mixes are summarized in Table 4.

3. Results and discussion

The bulk densities of hardened concretes which were measured at 28 days are listed in Table 3. It is noted from the bulk density results that the PP fibers have insignificant effect on the density of concrete specimens. But, the concrete density is mainly affected by incorporation of crumb rubber. While the density of samples that contain no crumb rubber were 1870, the density of concretes of those made up of 5%, 10%,15%,20%,25%crumb rubber were 1815,1785,1743,1711,1681kg/m^3 respectively and those made up 0.2%, 0.4% and 0.6% PP fibers volume ratios, were nearly the same values. Because of low specific gravity of rubber particles, unit weight of mixtures containing rubber decreases with the increase in the percentage of rubber content. Moreover, increase in rubber content increases the air content, which in turn reduces the unit weight of the mixtures [4, 17].

From the compressive test results obtained in this research, slightly strength reduction was observed and it may be concluded that PP fibers have slightly decrease the compressive strength of concrete. From Table 3 it may also be said that the addition of PP fibers up to 0.2% of concrete volume seems insignificant effect on the compressive strength of concrete. But adding more pp fibers up to 0.6% of concrete volume was decrease the compressive strength by about 10% only.

On the other hand, the effect of the replacement of the fine aggregate by crumb rubber on the compressive strength was recorded in Table 3. Losses in compressive strength were more than 50% was observed depending on the volume percentage of rubber content. The losses in compressive was acceptable (around 15%) at rubber content 10%. The existence of silica reduced the losses in compressive strength compared with previous studies [10]. The specimens containing rubber exhibited post failure compression loads and underwent significant displacement before failure. Although, the specimens are highly cracked, they were able to withstand some of the ultimate load. The large displacement and deformation which were observed were due to the fact that rubber aggregate has the ability to withstand large deformations. Rubber aggregate particles seem to act as springs and cause a delay in widening the cracks and preventing the catastrophic failure which is usually experienced in plain concrete specimens.

The fracture properties of fiber light weight aggregate rubber concrete(FLWARC) beams including different levels of crumb rubber and various contents of polypropylene fiber were determined by the three-point loading tests on centrally notched beams. The measured load–deflection (P–δ) curves and load-crack mouth opening displacement (P-CMOD) curves are presented in Figs. 3 and 4 respectively. Also the effect of polypropylene fiber and rubber contents on the Fracture energy and Fracture toughness are graphed in Figs.5 and 6 respectively. The fracture energy (G_F) and fracture toughness (K_{IC}) of concrete for all mixes were calculated and reported in Table 4 and analyzed based on P–δ and P-CMOD curves. It should be noted that each value in Table 4 was the average value of three specimens in each group.

Of course the main objective of adding fibers and crumb rubber to the lightweight aggregate concrete, in this research, was to improve the fracture behavior. Accordingly, the effects of fibers and crumb rubber on the measured load–deflection (P–δ) curves and load-crack mouth opening displacement (P-CMOD) curves are presented in Figs. 3 and 4 respectively. These curves are discussed in more details. As is well established, PP fibers slightly enhance the energy absorption and toughness characteristic of concrete under bending. The effect of PP fibers on improving ductility of concrete in compression is more pronounced when no fibers incorporated in concrete mixes.

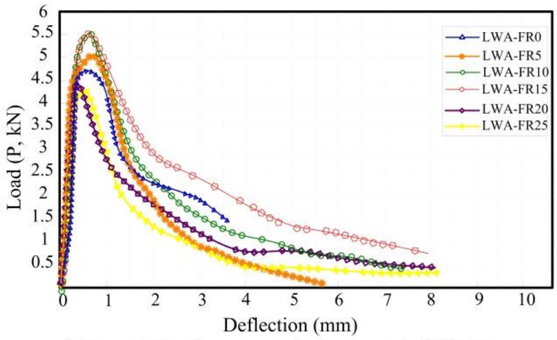
In general, PP fibers have slightly effect on ductility of lightweight concrete at 0.2% volume fraction. For instance, the addition of PP fibers increased the total fracture energy and fracture toughness of concrete as reported in Table 4. On the other side, the addition of 0.2% PP increases slightly the total energy. Fig. 3 shows the comparison of load–deflection behavior for three different fiber volume contents. Fig. 3 indicates that the beam with larger volume of fiber content (namely, 0.6% by volume) exhibits higher resistance especially after larger deflection. Concrete mixes incorporating 0.4% and 0.6% of PP fibers shows better ductility behavior than those with 0.2% PP fiber Fig.3 (b ,c). It seems that, for PP fiber volume fraction less than or equal to 0.2%, fiber effects on flexural behavior are insignificant and rather inconsistent. Therefore, it is suggested that at least 0.4% PP fiber should be used in concrete mixes to improve the flexural properties of lightweight concrete. It is observed that the deflection corresponded to ultimate load increases with the increase

of fiber volume fraction, and the descending branch of the flexural load–deflection curves tends towards gently after maximum load for high polypropylene fiber volume fraction. This may be attributed to the influence of fiber arresting cracking. Fig.3 also shows that the initial liner elastic part of the curve before matrix micro cracking increased with the addition of steel fibers. Due to inadequate machine stiffness, it was impossible to measure the descending branch of LWC.

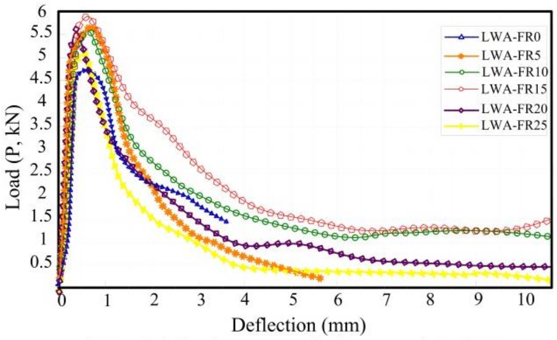
Fig. 4 describes the load–CMOD relations for three different fiber volume contents. It is noted here that, at the same loads after cracking, the beam with larger volume of fibers exhibits much more CMOD values.

Table 4. Fracture toughness and fracture energy results.

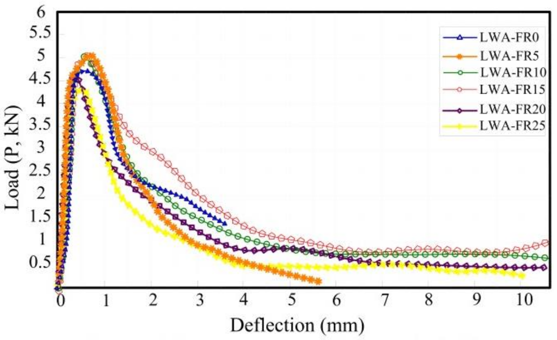
Results	LWA-FR0	LWA-FR5	LWA-FR10	LWA-FR15	LWA-FR20	LWA-FR25
(a) The experimental and calculated results of mixes (0.2% PP) Compressive strength/(MPa)	**44.08**	**39.67**	**37.58**	**30.83**	**26.36**	**20.12**
p_{max}/(kN)	**5.5**	**5.25**	**5.4**	**4.70**	**4.4**	**4.25**
δ_C/(mm)	**0.27**	**0.39**	**0.33**	**0.48**	**0.36**	**0.36**
$\mathbf{CMOD}_c$/(mm)	**0.09**	**0.22**	**0.25**	**0.27**	**0.25**	**0.21**
G_F/(N/m)	**3900.**	**4371.**	**5085.**	**4811.**	**3809.**	**2502.**
k_{1c}/(MPa $m^{\frac{1}{2}}$)	**1.58**	**2.61**	**2.84**	**2.97**	**2.62**	**2.48**
Results	**LWA-FR0**	**LWA-FR5**	**LWA-FR10**	**LWA-FR15**	**LWA-FR20**	**LWA-FR25**
(b) The experimental and calculated results of mixes (0.4%PP) Compressive strength/(MPa)	**39.75**	**36.66**	**32.68**	**26.98**	**22.30**	**18.71**
p_{max}/(kN)	**4.87**	**5.33**	**5.25**	**5.20**	**4.61**	**4.41**
δ_C/(mm)	**0.60**	**0.88**	**0.94**	**0.95**	**0.96**	**0.66**
$\mathbf{CMOD}_c$/(mm)	**0.34**	**0.92**	**0.73**	**0.75**	**0.60**	**0.41**
G_F/(N/m)	**7211.00**	**7610.00**	**8493.00**	**12213.00**	**11226.00**	**4912.00**
k_{1c}/(MPa $m^{\frac{1}{2}}$)	**1.99**	**3.12**	**3.35**	**3.35**	**2.87**	**2.65**
Results	**LWA-FR0**	**LWA-FR5**	**LWA-FR10**	**LWA-FR15**	**LWA-FR20**	**LWA-FR25**
(c) The experimental and calculated results of mixes (0.6% PP) Compressive strength/(MPa)	**31.29**	**26.75**	**23.66**	**18.8**	**17.1**	**15.8**
p_{max}/(kN)	**4.78**	**5.82**	**5.66**	**6.00**	**5.64**	**5.23**
δ_C/(mm)	**1.30**	**1.14**	**1.09**	**1.10**	**1.26**	**1.30**
$\mathbf{CMOD}_c$/(mm)	**1.13**	**1.02**	**1.21**	**1.01**	**0.87**	**1.06**
G_F/(N/m)	**13236**	**13900**	**16100**	**15913**	**12430**	**11500**
k_{1c}/(MPa $m^{\frac{1}{2}}$)	**3.00**	**3.47**	**3.90**	**2.98**	**1.98**	**1.88**



(a) Load-deflection curves of mixes contain 0.2% PP

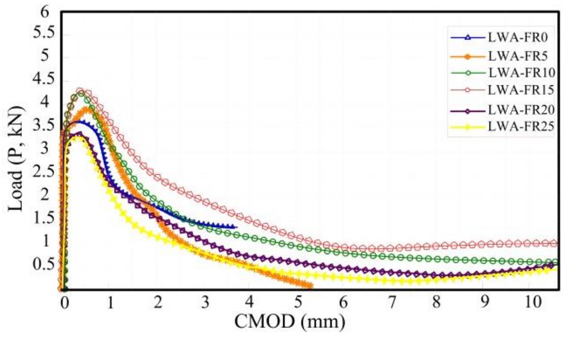


(b) Load-deflection curves of mixes contain 0.4% PP

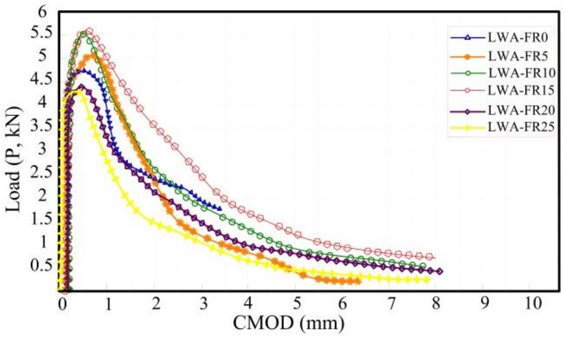


(c) Load-deflection curves of mixes contain 0.6% PP

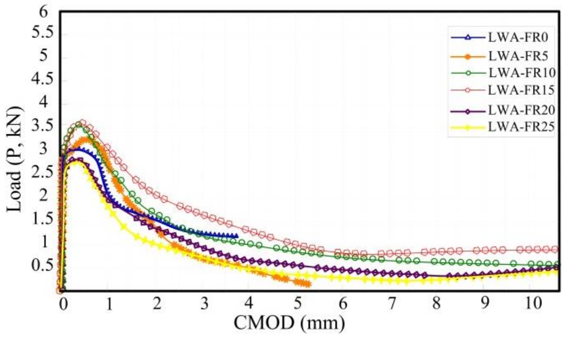
Fig. 3 load – deflection curves of all mixes



(a) Load-CMOD curves of mixes contain 0.2%PP fiber



(b) Load-CMOD curves of mixes contain 0.4% pp fiber



(c) Load-CMOD curves of mixes contain 0.6% pp fiber

Fig.4 load – CMOD curves of all mixes

3.1. Fracture energy

The Values of the fracture energy of all types of concrete mixes were reported in Table 4. The effects of fiber and rubber contents on the fracture energy and fracture toughness of concrete mixes were also represented in Fig. 5&6, respectively. It can be seen from Table 4 and Fig. 5 that, the rubber contents has remarkable effects on the fracture energy of concrete mixes up to 10%. For example at 0.2% fiber content, The fracture energy of the concrete mixes increases by about 12%, 30%,23% at 5,10% and 15% rubber content respectively, and then decreased by about 36% by increasing the rubber content up to 25% due to the loss occurred in the compressive strength of concrete mixes at higher levels of rubber content (see Table 4, Fig.5). These results indicating that appropriate rubber content enhances the energy absorption capacity of the concrete but too much rubber may have a negative effect on the energy absorption capacity. Thus, to effectively improve of the energy absorption capacity of concrete mixes, an appropriate amount of rubber should be selected for light weight concrete. This was consistent with the results of Kayali O et al. [24], and Libre NA et al. [17]. On the other hand, it can improve the fracture properties by addition polypropylene fiber, especially the fracture energy [see Fig. 4, Fig.5]. The fracture energy of the concrete mixes increase by more than 3.0 times by increasing the fiber content from 0.2% to 0.6%. This may be due to the inclusion of fiber in LWAC increases its fracture energy. This may be due to that, after matrix cracking, the fibers will carry the load that the concrete sustained until cracking by the interfacial bond between the fibers and the matrix and also, the fibers resist the propagation of cracks and do not fail suddenly, which causes an increase in the load carrying capacity of beams. [25]

3.2. Fracture toughness

The effects of fiber and rubber content on the fracture toughness of concrete mixes were shown in Fig. 6 respectively. It can be seen from Table 4 and Fig.6 that the fracture toughness of the concretes mixes changes obviously by increasing fiber content. However, with the different replacement ratios of crumb rubber, the influences of fiber content on the fracture toughness of the concretes mixes are consistent. The fracture toughness first increased up to 15% rubber content like fracture energy and then decreased with increase of rubber content until 25% , with the fracture toughness being smallest at 0.2 fiber content [see Fig. 6]. At 0.2 PP fiber the fracture toughness increased by about 80% and 88% when the rubber content increased by 10% and 15% respectively. This increasing reduced to 56% at 25% rubber content. The same trend was observed for 0.4% and 0.6% pp fiber concrete mixes. This may be caused by the non-uniform distribution of the Polypropylene fiber in the crack surface and worth of a separate investigation.

Also it can be seen from Table 4 and Fig. 6 that increase the fiber and rubber content to higher levels may leads to a significant increase in the fracture toughness, and that the concrete mixes has high resistance to brittle fracture. This may be due to is well known that the concrete strength depends on the strength of the cement paste, the aggregates and the interfacial bond between the cement paste and the aggregates enhanced by fiber existence [18]. For concrete mixes prepared with different levels of fiber and rubber contents, the difference in the peak stress and fracture toughness might be related to the strength of the interfacial bond. During vibration, the water inside the cement paste may move to the light weight aggregates due to their high water absorption capacity, creating a relatively high w/c value in the vicinity of light weight aggregates. As a result, a stronger bond might be formed between the cement paste and LWA especially when silica fume added to concrete mix. The above results indicated that appropriate rubber content improves the resistance to brittle fracture of the concrete mixes but too much rubber content, may have a negative effect on the resistance to brittle fracture. It can be concluded that the optimum values of rubber content to enhance the fracture properties ranged between 10% to 15% rubber contents, while the pp fiber contents must be no less than 0.4% volume fraction.

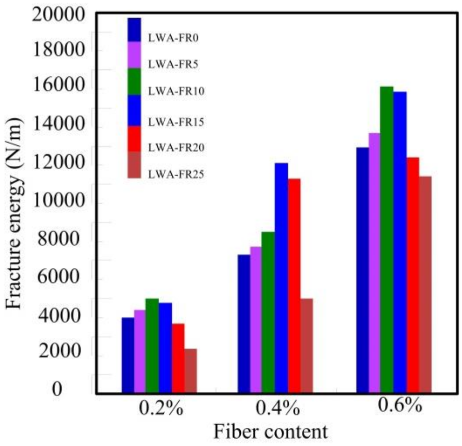


Fig. 5 Effect of fiber and rubber content on the fracture energy

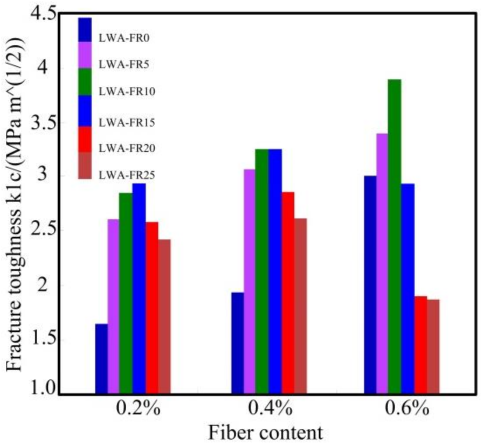


Fig. 6 Effect of fiber and rubber Content on the fracture toughness

4. Conclusions

In this paper, a series of three-point bending tests on notched beams of 100 mm x 100 mm x 520 mm were conducted. The fracture energy and fracture toughness were calculated and the effects of fiber and Rubber contents on them were analyzed. The following conclusions can be drawn from this research:

(1) The bulk density results that the PP fibers have insignificant effect on the density of concrete specimens. But, the concrete density is mainly affected by incorporation of crumb rubber.

(2) A severe degradation of compressive strength has been found for all concrete mixes by increasing the rubber content more than 15%.This indicates that the energy dissipation capacity of concrete mixes increases as rubber content rise, which is opposite to the trend of the compressive strength.

(3) The fracture energy represents the energy dissipation capacity of concrete mixes, while the fracture toughness reflects resistance to brittle fracture of concrete mixes. An addition the polypropylene fiber leads to a significant increase in the fracture toughness. While the rubber content increased from 5% to 10%, the fracture toughness first increased and then decreased with increase of rubber content up to 25%

(4) The main mechanism responsible for the increase in the fracture energy is that, the of polypropylene fibers resist the propagation of cracks and do not fail suddenly, which causes an increase in the load carrying capacity of beams.

(5) Polypropylene fibers have no detectable effect on mechanical properties of hardened concrete at volume below 0.2% volume ratios. Besides, addition of 0.4% PP fibers in concrete mixes has a slightly influence on compressive characteristics. However, 0.4% PP fibers increased both fracture energy and fracture toughness to some extent. The improving effect of PP fibers is more recognizable in the mixes. So, the minimum amount of polypropylene fibers to be used in lightweight concrete to prevent brittle behavior is about 0.4% by volume of concrete.

(6) The appropriate rubber content improves the resistance to brittle fracture of the concrete mixes but too much rubber content, may have a negative effect on the resistance to brittle fracture. It can be concluded that the optimum values of rubber content to enhance the fracture properties ranged between 10% to 15% rubber contents, while the pp fiber contents up 0.4% volume fraction was accepted.

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