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Investigation on the Effect of Polyethylene Terephthalate (PET) Fiber and Crumb Rubber on Energy Absorption Capacity of Concrete

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ABSTRACT

The accumulation of waste, especially plastic and car tires, has become a major problem facing society today. Therefore, through this research, these wastes were recycled and used to improve some properties of concrete. Recycled crumb rubber from car tires was used instead of sand as a 10% partial replacement. The substitution was done by two methods: random and equivalent-size substitution. As well, 1% polyethylene terephthalate (PET) fiber was added to the volume of concrete to improve some properties of rubberized concrete. Compressive strength and ultrasonic pulse velocity tests (UPV) were conducted in this study to investigate the efficiency of PET rubberized concrete. An impact resistance test was also conducted to investigate the ability of PET rubberized concrete in terms of energy absorption. Slabs of size 50 cm×50 cm×5 cm were utilized for low-velocity impact tests. The results indicated there was a reduction in compressive strength, and UPV results were observed in PET fiber rubberized concrete. The reduction was 37.47% and 5.4%, respectively, as compared with the PETC mixture, and the result of the dynamic modulus of elasticity showed the same pattern as that of the UPV test. In contrast, there was an improvement in the impact resistance when PET fiber and crumb rubber were used; it increased by 117.63% and 52.9% for random and equivalent replacement, respectively, as compared with PETC.

1. Introduction

Due to the fast increase in modern life, waste accumulation and natural resource depletion are increasing, and this causes pollution to have a greater effect on our lives (Tempa et al., 2022). The increasing use of automobiles in our lives has made waste tires a critical issue. Every year, about 1000 million tires reach the end of their service life, and 5000 million more are expected to be disposed of regularly by 2030 (Sofi, 2018). One of the major threats of discarded tires is slow decomposition and durability because of their combination. It contains approximately 50% rubber (natural rubber, butadiene rubber, and styrene-butadiene rubber), with the remaining components

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being carbon black, metal, textile, zinc oxide, sulphur, and additives (Záleská et al., 2019). Recycled rubber aggregate can be used in construction or in different applications. Rubberized concrete is attracting attention for lightweight non-structural applications such as vibration damping of structures and geotechnical works. Accordingly, it can be used in earthquake shockwave absorbers and airport runways; this represents one form of energy absorption (Bala & Gupta, 2021). Many researchers have investigated the use of crumb rubber as a partial replacement for aggregate in different sizes, shapes, and percentages. Aiello and Leuzzi (2010) used tire shreds to partially replace coarse and fine aggregates. The results showed that the size of the rubber particle has an important effect on the compressive strength. They observed that the loss in compressive strength when coarse aggregates were replaced was greater than the loss of compressive strength when fine aggregate was replaced by tire particles. Furthermore, Youssf et al. (2017) used five different percentages of rubber aggregate (10%, 20%, 30%, 40%, and 50%) to investigate the impact resistance. They also found that at 10% and 50% rubber content, the impact resistance of concrete improved by 1.55 and 3.52 times, respectively, compared to traditional concrete. On the other hand, waste plastic causes similar environmental problems. One of the solutions used to get rid of plastic waste is by burning it, but this affects the environment because of the release of toxic gases and also the absorption of waste through the soil, which has effects on humans, animals, and plants (Jankauskaite et al., 2008). It is necessary to find a suitable and environmentally friendly alternative method to solve these problems, such as using this waste plastic in the production of concrete or mortar (Jassim, 2017), to reduce the harmful effect on the environment. Plastic waste may be considered a typical material for the production of lightweight green concrete that can be used as a non-structural component in building construction (Almohana et al., 2022). PET can be used in concrete in different volume fractions, shapes, and lengths. Asha and Resmi (2015) used PET fiber with two different straight shapes and crimped in three different percentages (0.5%, 1%, and 1.5%) with (8, 15, and 23) aspect ratios that were used in this study. An improvement was observed in compressive strength by 18% and 16%, respectively. The splitting tensile strength also increased by 42% and 37% for crimped and straight fiber, respectively, when using a 15-aspect ratio of 1%. Another study conducted by Al-Hadithi et al. (2013) used PET as fiber with three volume fractions (0.5%, 1%, and 1.5) to investigate the impact resistance of concrete. They found an improvement in concrete impact resistance of 340% when the percentage of PET fiber was 1.5%. Rubberized concrete, as previously mentioned, has fewer mechanical properties compared to ordinary concrete, and this is because rubber is soft and has a low specific gravity compared to normal aggregates. Also, more air gaps in the composition of rubberized concrete were found. As a result, to improve the properties of rubberized concrete, recycled plastic (PET) that was collected from beverage waste was added to improve some of the properties of rubberized concrete, such as tensile strength and bending, in addition to increasing its ability to absorb more energy. The combination of PET fiber with rubberized concrete was investigated by Sakulneya and Wattanachai (2018). Different percentages of crumb rubber aggregate with 0.5% and 1% of PET fiber were carried out. The results showed that when 1% PET fiber with 8% crumb rubber was used, an enhancement in some mechanical properties of concrete was noticed.

The purpose of this study is to investigate the effect of crumb rubber aggregate and PET fiber on some properties of concrete. Based on previous studies, the properties of rubberized concrete showed a variation depending on the replacement ratio and the size of the rubber particles. Therefore, the equivalent size replacement was taken into account in this study. Two types of replacement of fine aggregate by crumb rubber were utilized: random and the equivalent size of rubber aggregate replacement. For both types of replacement, a constant rubber content of 10% was kept. The rubberized concrete that was produced was combined with 1% of PET fibers to evaluate the improvement of this type of concrete in terms of energy absorption capacity under impact loading.

2. Experimental work

2.1. Materials used

Ordinary Portland cement (OPC) Type I was used as a binder in this experiment, which confirms the Iraqi specification IQS 5/2019 (I.Q.S., 2019). The chemical and physical properties of cement are shown in Table 1. Natural river sand was used in this study as fine aggregate with a maximum size of 4.75 mm. Crushed gravel of 10 mm maximum size and 2.65 specific gravity was used in this experiment. The sieve analysis of sand and crushed gravel is illustrated in Table 2, which meets the Iraqi specification No. 45/1984 (I.Q.S., 1984).

Tap water was used in this experiment for mixing and curing. In this research, the waste tires from vehicles were used as crumb rubber aggregate, as shown in Fig. 1(a). It is used as a partial replacement by 10% of the fine aggregate by volume. The properties of rubber aggregate are illustrated in Table 3. The particle size distribution of aggregates is shown in Fig. 2. Recycled waste plastic is used as a PET fiber in concrete, as shown in Fig. 1(b), with properties as shown in Table 4. A superplasticizer, Sika viscocrete-5930 of type F, was used as a high water reduction admixture to maintain the desired workability for mixtures that have PET fiber. It flows the specification of ASTM 494 (2013). The properties of SP are shown in Table 5.

This research involved the preparation of six different mixes by using the volume method: the first mix is the OPC, which is normal concrete; the second mix is the PETC, which includes added PET fiber to the OPC; and the third mix is Ru10C, which means replacing 10% of the fine aggregate with crumb rubber. Ru10P is the fourth mix that involves adding PET fiber to Ru10C. Finally, Ru10C-E and Ru10P-E represent the mixes that contain crumb rubber with an equivalent replacement of an equivalent size of sand. The equivalent replacement process is carried out by sifting the weight of the sand according to the weight of the mixture on a series of sieves. Then the sand that accumulated on the sieve number 1.18 mm and passed from sieve number 4.75 mm is taken and replaced by 10% with crumb rubber, which is also sifted and accumulated on the sieve number 1.18 mm. That means replacing the sand with the same size of rubber with and without PET fiber. The concrete mix proportions are shown in Table 6.

Table 1 – Physical properties and chemical compositions of cement.

Physical properties		
Type of Test	**Results**	**limits of specification according to IQS 5/2019**
Initial setting time (min)	160	≥ 45 min
Final setting time (min)	245	Not more than600 min
Fineness (cm^2/gm) by Blaine method	2530	≥ 2500
Compressive strength at 2 days (MPa)	12.5	≥ 10 MPa
Compressive strength at 28 days (MPa)	42.5	≥ 32.5 MPa
Chemical composition		
Chemical composition	**Content % by cement weight**	**limits of specification according to IQS 5/2019 [56]**
SiO_2	21.10	-
CaO	64.10	-
Fe_2O_3	3.40	-
Al_2O_3	3.81	-
MgO	2.20	A maximum of 5%
SO_3	2.33	2.8% maximum

(a) Rubber aggregate

(b) PET fiber

Fig. 1 Rubber aggregate and PET fiber

Table 2 – Sieve analysis for fine and coarse aggregate.

Fine aggregate		
Sieve size (mm)	**Cumulative passing %**	**Limits of specifications according to I.Q.S 45/ 1984(I.Q.S., 1984) (zone2)**
10mm	100	100
4.75mm	97.48	90-100
2.36mm	83.89	75-100
1.18mm	70.44	55-90
0.6µ	53.54	35-59
0.3µ	15.84	8-30
0.15µ	2.25	0-10

Coarse aggregate			
No.	**Sieve size (mm)**	**Cumulative passing %**	**Limit of Iraqi specification No.45 /1984(I.Q.S., 1984).**
1	20	100	100
2	14	100	90-100
3	10	80.7	50-85
4	5	9	0-10

Table 3 – Properties of rubber aggregate.

Specific gravity	Maximum size	Fineness modulus
1.10	2.36 mm	2.24

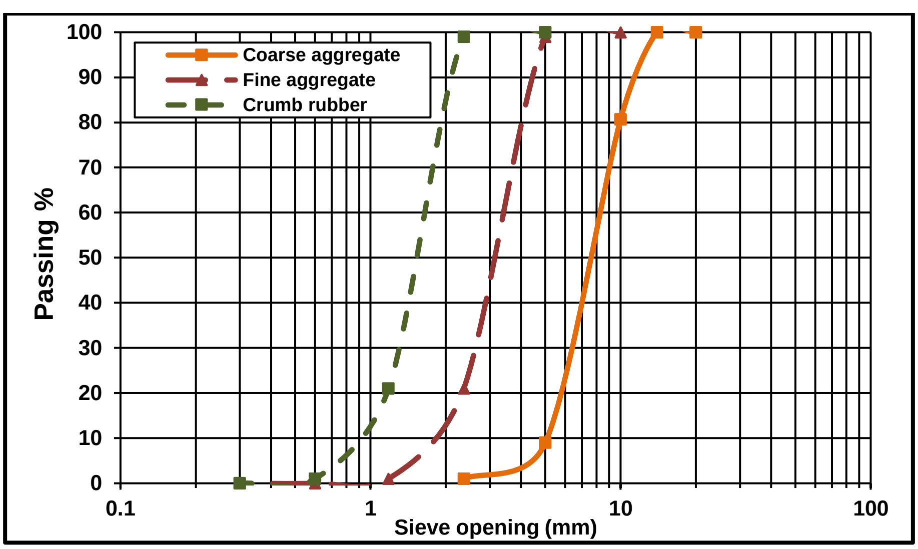


Fig. 2 Particle size distributions of aggregates

Table 4 – Properties of PET fiber.

Density	Length	Width	Thickness	Aspect ratio (l/d)
1.3 gm/cm^3	50 mm	4 mm	0.3 mm	40.5

Table 5 – Properties of SP type F.

Appearance	Viscous liquid/ Turbid liquid (ASTMC494-04, 2013)
Color	Light brown
Transport	Non-hazardous
pH	4-4.8
Storage	Should be stored at 5-35o C in original containers
Density	1.084 ± 0.01

Table 6 – Mix-proportion of concrete (kg/m^3).

Mix	Cement	Gravel	Sand	Rubber	PET	Water	SP
OPC	400	1075	760	-	-	192	-
Ru10C	400	1075	682	37.3	-	192	-
PET C	400	1075	760	-	13	192	1.2
Ru10P	400	1075	682	37.3	13	192	1.2
Ru10C -E	400	1075	682	37.3	-	192	-
Ru10P -E	400	1075	682	37.3	13	192	1.2

where: OPC represents the plain concrete without any addition, whereas PETC refers to adding 1% PET fiber by volume of concrete to OPC.
Ru10C refers to rubber replacement with 10%.
Ru10P indicates Ru10C, with an addition of 1% PET fiber by volume of concrete.
Ru10C-E and Ru10P-E refer to the mixtures with an equivalent size replacement. This means replacing the rubber with the same sand size to get rid of the problem of discontinuous gradation.

2.2. Mixing and Casting

A pan mixer was used for mixing concrete ingredients. First, the dry materials (cement, sand, gravel, and rubber) were mixed for two minutes, as shown in Fig. 3(a), then water was added gradually during the mixing process and continued for another two minutes. If the mixture contains PET fibers, the SP was solved by mixing with water, adding gradually to the concrete mix, and mixing for three minutes. During the wet mix, PET fiber was added by spreading it to ensure good distribution, as represented in Fig. 3(b), and mixing for another two minutes. Then a cube with dimensions of 100mm×100mm×100mm and slabs with size 50cm×50cm×50mm were the specimens that were conducted in this experiment. According to ASTM C192 (2014), the molds were cleaned to remove any unwanted parts and then painted with a layer of oil. Then the concrete was poured into the molds and compacted with a vibrator.

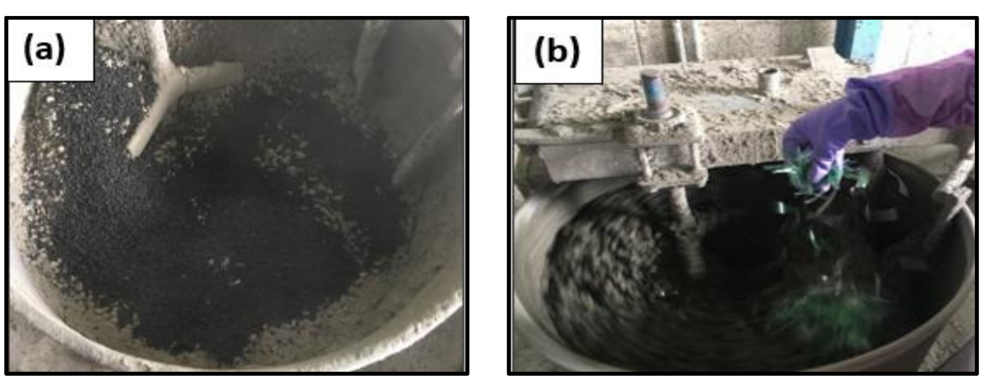


Fig. 3 Process of (mixing) a) dry ingredients (b) addition of fibers

3. Results and discussions

3.1. Compressive strength

The compressive strength was calculated according to BS EN 2009 as the average of three cubes. The results are presented in Table 7 for all mixes. It can be concluded that the PETC mix has the highest value of 53 MPa. However, the increase in strength was slightly by 3.3% compared to OPC. The increase in strength was attributed to the presence of PET fibers, which affected the microstructure of the concrete by increasing its homogeneity, leading to cohesive concrete (Al-Hadithi et al., 2019; Enad et al., 2021). It was also reported that the optimum content of PET fiber is 1% (Gu & Ozbakkaloglu, 2016). Beyond this amount, degradation in strength was observed. Including crumb rubber aggregate in the concrete mixture at 10% led to a decline in compressive strength of 13.8% as compared with OPC.

This reduction in adhesion to the rubber particles is much softer than that of fine aggregate; in addition, the low adhesion between these particles and cement paste (Jankauskaite et al., 2008).

Table 7 – Result the compressive strength of different concrete mixes.

Mix	Compressive strength (MPa)	red% to OPC	red% to PETC
OPC	51.3	-	-
PETC	53	-3.3	-
Ru10C	44.2	13.8	-
Ru10P	33.14		37.47
Ru10C-E	42.3	17.5	
Ru10P-E	32.6		38.5

A sharp drop in compressive strength was observed when rubber aggregate was added to PET fiber concrete, as shown in Fig. 4. The reduction was 37.47% at 10% rubber content compared to PETC. As well, this mixture has a lower compressive strength than OPC. The explanation for this significant reduction could be attributed to the weak adhesion between the PET fiber and concrete mixture due to the smooth texture of its surface (Marthong, 2015). As well, the addition of rubber aggregate and PET fiber to the concrete mix led to a weaker concrete microstructure due to the formation of voids in it. On the other hand, using an equivalent replacement of rubber aggregate didn't improve the compressive strength, but it decreased it. Also, Ru10P-E was reduced by 38.5% as compared with PETC.

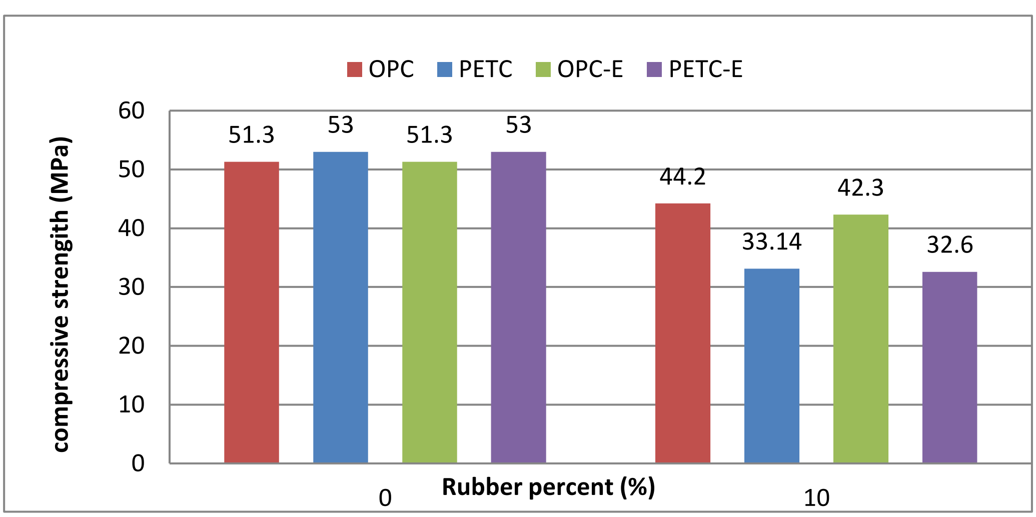


Fig. 4 Results of compressive strength

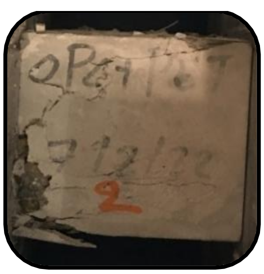
Mixed Ru10C-E was observed to decrease by 17.5% as compared with OPC. It is worth mentioning that the mixture with an equivalent replacement size and 1% PET fiber has a greater reduction in compressive strength than that without PET fiber. This reduction refers to an increase in voids between rubber and PET fiber. However, the equivalent replacement has a greater reduction in compressive strength than a random-size replacement.

Despite the loss in strength, the combination of PET fiber and rubber aggregate led to enhanced ductility. This can be explained by the tendency of rubberized concrete to withstand additional loads beyond or after peak loading. The role of PET fibers is to prevent the sudden breakdown of the concrete specimen. Figure 5 shows the mode failure of concrete cubes after the compression test**.**

(a) OPC

(b) Ru10C

(c) Ru10C-E



(d) PETC

(e) Ru10P

(f) Ru10P-E

Fig. 5 Failure modes of concrete cubes

3.2. Ultra sonic pulse velocity (UPV)

Ultrasonic pulse velocity (UPV) is a non-destructive test used to evaluate the quality of concrete and is widely used in many countries (Mohana, 2020). This test was conducted using a 100-mm cube, as shown in Fig. 6. According to ASTM C597(2009), all concrete mixtures can be classified as good, as shown in Fig. 7. The inclusion of crumb rubber led to a decrease in UPV by 3.45% for 10% content. This reduction was attributed to the increase in the air void when crumb rubber aggregate was added (Mohammed et al., 2011). The reduction in UPV is by 2.75% for PETC as compared with OPC. The reduction of RU10P is by 5.4%, as compared with PETC. On the other hand, using crumb rubber as an equivalent replacement gives approximately the same result as other mixtures. From the result, it can be observed that the decline in UPV of rubberized concrete with PET fiber is greater than that without PET fiber. This property is useful for sound absorption in buildings in which the combination of rubber and PET fiber is expected to enhance the capacity to absorb the transmitted velocity.

Fig. 6 Ultrasonic pulse velocity test

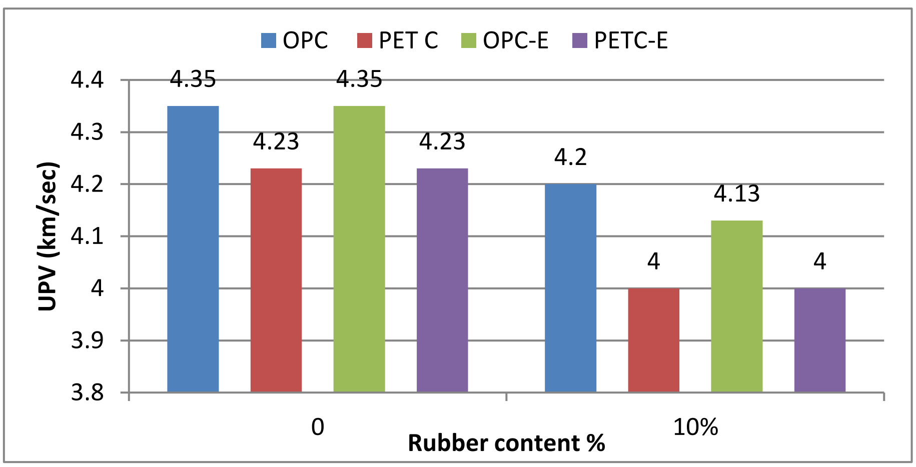


Fig. 7 Results of UPV test

3.3. Dynamic modulus of elasticity

The dynamic modulus of elasticity was calculated in this experimental work according to Uygunoğlu and Topçu (2010) by using the following equation:

$$E_D = \left[\rho \frac{V^2}{g}\right] \times 10^{-2} \quad \textbf{(1)}$$

where:
V – UPV (km/sec);
ρ – Bulk density (kg/m^3);
g – Gravity acceleration (9.81 m/sec^2)
The results of bulk density were illsurated in Table (8)

Table 8 – Results of bulk density.

Mix	Bulk density (Kg)
OPC	2416
PETC	2326
Ru10C	2336
Ru10P	2223
Ru10C-E	2360
Ru10P-E	2218

The result of the dynamic modulus is represented in Fig. 8.

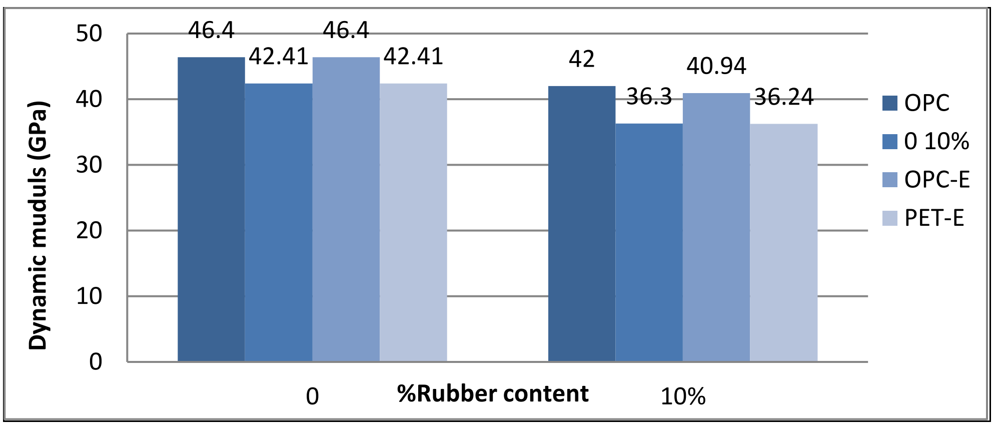


Fig. 8 Results of dynamic moduluse of elasticity

For Ru10C mix, the dynamic modulus of elasticity was reduced by 9.9% as compared to OPC, and it was 9.1% for PETC as compared with OPC. Further decrease in dynamic modulus of elasticity was obserevd in the resullts of Ru10P mix, the reduction was 14.4% as compared to PETC. The reason behind this reduction is the increased porosity with the inclusion of crumb rubber aggregate, which affects the compaction of the mixture, as well as that Young's' modulus of crumb rubber aggregates was lower than normal aggregate. The equivalent replacement results also show the same trend as in the random replacement.

3.4. Impact Resistance

In general, using crumb rubber as a partial replacement of aggregate can improve impact resistance, and this increase is proportional to rubber content (AbdelAleem et al., 2018). This is because crumb rubber is more elastic, deforms more easily, and has a lower stiffness than fine aggregates (Mohammed et al., 2017). In addition, when the PET fiber was added to rubberized concrete, the impact strength increased. This increase is attributed to the ability of PET fiber to absorb more energy before failure and the ability of PET fiber to bridge cracks. Slabs with dimensions of 50 cm×50 cm×5 cm (length, width, and depth) were carried out in this test. All slabs were tested after 28 days of curing. A steel frame was manufactured and used in this examination. An iron ball with an 80 mm diameter and 4.380 kg weight (including a hook at the top of the ball) was dropped through a tube with a height of 1 m and a diameter of 100 mm. The tube contributed to the free fall of the ball in the center of the slab. This ball connected with an elastic rope that slipped along a roller to assist in the process of raising and lowering the ball. as shown in Fig. 9. In this test, the number of blows was recorded when the first crack occurred as well as when the slab failed. The width of the first and ultimate cracks was also recorded by using the microscope for tiny cracks and strips for visible cracks. The impact energy was calculated using the following equation:

$$EI = N \times m \times g \times h \quad (2)$$

when : EI: Energy of impact; Jule (J) ,
N: numbers of blows
m: weight of the iron ball, kg
g: gravity acceleration, m/s^2
h: height of drop iron ball,m.

Table 9 shows the number of blows at the first crack and failure. Also, the crack width and energy at the first and final cracks are recorded.

Table 9 – Results of impact test.

Mix	No. blows		Crack width (mm)		Average impact energy(J)	
	first crack	failure	first crack	failure	first crack	failure
OPC	2	4	0.45	1.1	85.94	171.78
	2	4	0.4	1.3		
PETC	1	7	0.05	1.5	42.97	365.255
	1	10	0.05	1.9		
Ru10C	2	5	0.3	2.15	64.45	236.325
	1	6	0.15	2.5		
Ru10P	1	19	0.1	1.9	42.97	794.91
	1	18	0.15	1.95		
Ru10C-E	1	4	0.1	2.25	42.97	257.81
	1	8	0.1	1.85		
Ru10P-E	1	13	0.05	2.35	42.97	558.58
	1	13	0.05	2.6		

Fig. 9 Impact test apparatus.

The results in Fig. 10 indicate that when crumb rubber was partially replaced by aggregate and PET fiber was added to the concrete mixture, the impact strength increased, so that the energy needed to cause failure was also increased as compared with OPC. However, the increase in impact energy was 37.57% and 112.63% for Ru10C and PETC as compared to OPC. An increase of 117.63% for Ru10P as compared with PETC means there is a positive effect of PET rubberized concrete on impact energy because of the inclusion of rubber particles, which absorb more energy and behave as elastic springs in the concrete sample, in addition to PET fiber, which absorbs more energy.

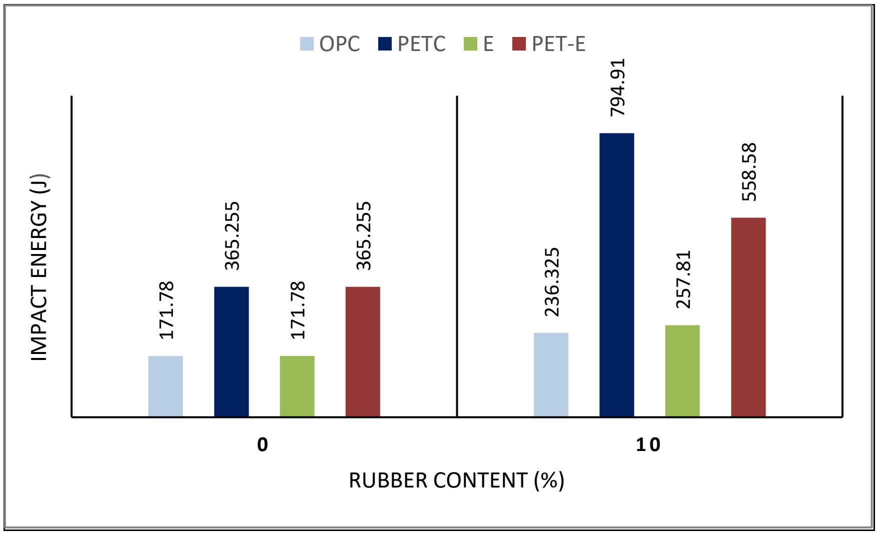
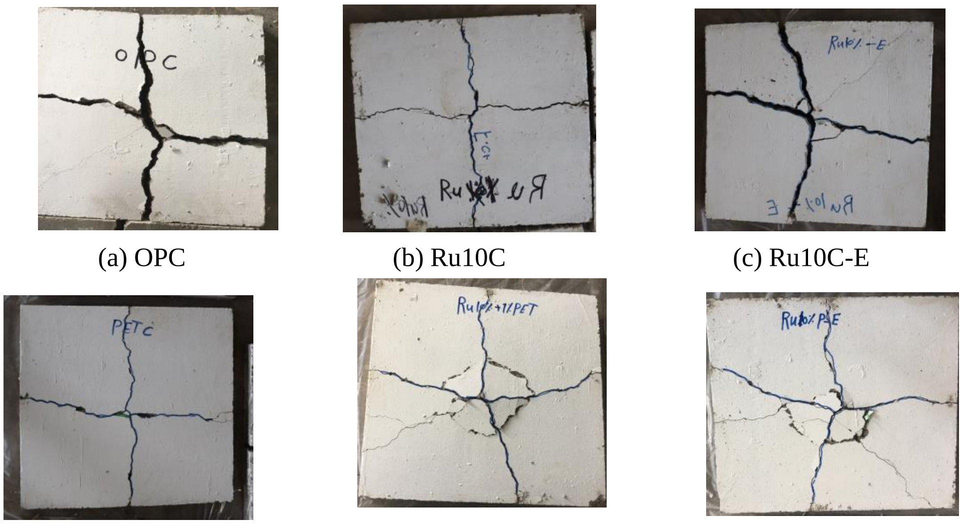


Fig. 10 Result of impact energy.

The equivalent size replacement also shows an increase in impact resistance of 50% for Ru10C-E as compared with OPC. When PET fiber was added to these mixtures, the impact energy increased by 52.9% as compared with PETC. The equivalent replacement result of the impact energy was less than the random replacement when PET fiber was added. This decrease in impact energy was attributed to the low strength of these mixtures.

Another parameter can be obtained from the results, which is the width of the crack measured using a microscope or strips, depending on the size of the crack width. This explains the effect of crumb rubber and PET fiber on concrete to prevent sudden collapse, as shown in the result of the OPC having a 0.45 mm width for the first crack at the second blow, then failing at the fourth blow with a 1.1 mm width, which means there is no long time between the first crack appearance and when the failure occurred. In contrast, the presence of crumb rubber and PET fiber decreases the width of the first crack and makes it between 0.05 and 0.15 mm because of the ability of rubber particles to prevent the cracks from growing and stopping early full separation of the concrete (Muhammad & Abdul-Kadir, 2020). In addition, the property of PET fiber to bridging cracks, as well as its longest time between the first crack and failure as RU20P, Fig. 11 clarifies the failure mode of slabs.



(a) OPC (b) Ru10C (c) Ru10C-E

(d) PETC (e) Ru10P (f) Ru10P-E

Fig. 11 Mode failure after impact test

4. Conclusions

According to the experimental results that were obtained in this study, the major findings can be summarized as follows:

1. Incorporating crumb rubber in a concrete mixture as a random or equivalent size replacement reduced the compressive strength.
2. Adding 1% PET fiber to the concrete mixture showed a slight increase in compressive strength, but it was reduced when added to rubberized concrete.
3. UPV results for all mixtures were decreased as compared to OPC. However, it exhibited further reduction when 1% PET fiber was added. The reduction was 5.4% for Ru10P, as compared with PETC.
4. The results of the dynamic modulus of elasticity showed the same pattern as the UPV result, which was reduced by 14.4% for Ru10P as compared with PETC. The equivalent replacement showed approximately the same result as a random replacement.
5. Impact resistance is considered one of the most important tests in which rubber and PET fibers play an important role in improving it, as it improved by 117.63% for the mixture Ru10P as compared with PETC. PETC was increased by 112.36% as compared with OPC.

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