[Mansoura Engineering Journal](https://mej.researchcommons.org/home)

Volume 48 | Issue 4 Article 5

2023

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Metwally Abd Allah Abd-Elaty
Professor, Structural Engineering Department, Faculty of Engineering, Tanta University, Tanta, Egypt

Mariam Farouk Ghazy
Professor, Structural Engineering Department, Faculty of Engineering, Tanta University, Tanta, Egypt

Omar Hussein Khalifa
Assistant Lecturer, Structural engineering department, Faculty of Engineering, Tanta University, Tanta, Egypt, omar.hussien@f-eng.tanta.edu.eg

ORIGINAL STUDY

Mechanical and Impact Properties of Fibrous Rubberized Geopolymer Concrete

Metwally A.A. Abd-Elaty, Mariam F. Ghazy, Omar H. Khalifa*

Structural Engineering Department, Faculty of Engineering, Tanta University, Tanta, Egypt

Abstract

Geopolymer concrete significantly contributes to reducing harmful emissions by reducing the cement industry and replacing it with by-product materials produced by different industries. Geopolymers have enhanced mechanical properties compared with cementitious products, however, their ductility and impact resistance tend to be relatively low. Additionally, the used rubber tires provide a significant environmental risk. Consequently, this research's primary objective is to develop and investigate improved rubberized geopolymer concrete concerning ductility and impact resistance. Reusing Crumb Rubber (CR) as an alternative to natural sand was investigated to meet these goals using volume replacement ratios of (3%, 6%, and 9%). Additionally, different volume fractions of polypropylene fibres (0.25%, 0.5%, and 0.75%) were used. Investigations have been done on how CR content affects the material's physical, mechanical and impact characteristics. Research has also been done on the impact of adding polypropylene fibres to Rubberized Geopolymer Concrete (RGC). The findings revealed that, even though the mechanical properties of RGC are lower, the mode of failure, toughness, flexural performance, and impact resistance have been significantly enhanced due to the synergistic influence of CR and fibres. Furthermore, incorporating CR with polypropylene fibers is better than using CR only. For instance, the toughness indices reached the best enhancement using 6% CR with 0.5% polypropylene fibers. Moreover, the impact resistance results indicated that incorporating CR with polypropylene fibers significantly affects the absorbed energy to failure hitting a 240% increment. Moreover, the results of the microstructure exploration confirmed the achieved mechanical properties.

Keywords: Crumb rubber, Ductility, Impact resistance, Mechanical properties, Toughness index

1. Introduction

Cementitious products are the most widespread building material all over the world, which are used in various applications starting from building blocks to infrastructures applications, despite the well-known environmental problems caused by the Portland cement industry (Kupaei et al., 2013; Patil et al., 2014). To produce more sustainable materials replacing Portland cement in concrete, geopolymer technology has been presented as an innovative technology that gives an economic and environmentally friendly alternative to Portland cement (Davidovits, 1991). Geopolymer composites, also known as alkali-activated binder composites manufactured by a polymeric process between an alkaline solution and a material rich in silicon and aluminium such as fly ash, ground granulated blast furnace slag, metakaolinite, and rice husk ash which are either by-product materials or having a geological origin (Davidovits, 1999; Topark-Ngarm et al., 2015). Many research works concluded that geopolymers have superior early strength, improved mechanical properties, lower creep and volume change, high thermal stability, and long-lasting durability, in addition to high resistance to acids (Azmi et al., 2016; Hager et al., 2021; John et al., 2021).

On the other hand, one of the widespread problems that threaten our environment nowadays is the tons of used tires which left annually in landfills

Received 23 February 2023; revised 12 May 2023; accepted 14 May 2023.
Available online 10 July 2023

* Corresponding author at: Structural Engineering Department, Faculty of Engineering, Tanta University, Seberbay Campus, Tanta, 31511, Egypt.
Fax: +2040-3453860.
E-mail address: omar.hussien@f-eng.tanta.edu.eg (O.H. Khalifa).

https://doi.org/10.58491/2735-4202.3054

everywhere around the world without adequate recycling (Abdullah et al., 2015; Kotresh and Belachew, 2014; Roychand et al., 2020). These landfills are accountable for a major environmental problem as it contains toxic and soluble components, provide breeding areas for rodents, and provide a fire danger whose extremely poisonous fumes contaminate the environment and natural resources (Al-Nasra and Torbica, 2013; Arif Khan et al., 2013; Guelmine et al., 2016; Siddique and Naik, 2004). Currently, Crumb Rubber (CR) can be exploited as an alternative to part of natural aggregates in mortar and concrete, contributing to reducing environmental risks, conserving natural resources and improving some important concrete properties such as impact, thermal, and sound properties (Pongsopha et al., 2022; Sukontasukkul, 2009).

Incorporating a variety of useless materials, such as Fly Ash (FA), slag, and CR from used tires, as well as dispensing Portland cement and conserving energy, results in more sustainable products, such as Rubberized Geopolymer Concrete (RGC). The usage of this form of concrete is strongly promoted in particular applications to protect the environment and improve concrete properties in a specific direction that serves various construction applications (Luhar et al., 2019; Tahwia et al., 2022a; Tahwia et al., 2022b). Additionally, the durability and the performance of cement and geopolymer-based composites under impact and dynamic loads, are negatively impacted by their low tensile strength and brittleness (Gomes et al., 2020; Lazorenko et al., 2020). Such materials have a low cracking resistance; therefore, it is crucial that these properties be improved.

The most significant physical and mechanical characteristics of rubberized mortar and concrete have been investigated by previous studies (Roychand et al., 2020; Tahwia et al., 2022a; Abd-Elaty et al., 2022; Elzeadani et al., 2021). All of these studies demonstrated that increasing CR content in mortar or concrete decreases compressive strength and some other mechanical properties. There are several plausible explanations for the negative impact of CR on composite strength. For instance, the CR particles were categorized as big holes in the composite by Goulias and Ali (1998). This explanation, however, might be a bit perplexing because CR particles, as opposed to pores, help to transfer the stresses of the applied forces (Turatsinze et al., 2006). According to Turatsinze et al. (2006), the bond flaws between CR particles and the matrix, which result in a poor interfacial transition zone, are the major cause of the composite strength drop. Tahwia et al. (Tahwia et al., 2022a) attributed the weak bonding between geopolymer gel and CR particles to the hydrophobicity and high friction coefficient of the rubber, in addition to the increase in the porosity, leading to decreasing the microstructure's density slightly.

The use of rubberized concrete as a structural material in traditional structural members is limited because of the lower mechanical properties of rubberized concrete if compared with traditional concrete. The reduction in the mechanical properties increases with the increase in rubber content, however, the ductile performance, high energy absorption, high damping coefficient and high toughness are positive characteristics of rubberized concrete which makes it very suitable for structural elements under impact, dynamic, and collision loads and other application that need reduced compressive strength, lightweight, high toughness and high impact resistance (Turatsinze et al., 2006; Eltayeb et al., 2021). Recently, studies have been conducted to highlight the dynamic properties of rubberized concrete as a substitution for its weaknesses in static properties such as damping (Xue and Shinozuka, 2013), energy dissipation, stiffness degradation (Eltayeb et al., 2020), impact and collision resistance (Pham et al., 2018), seismic and earthquake resistance (Moustafa et al., 2017), and mechanical characteristics under high strain rates like dynamic compressive strength (Liu et al., 2012), dynamic splitting tensile strength (Feng et al., 2018), and dynamic flexural strength (Feng et al., 2019).

All aforementioned investigations are about traditional cement concrete and there are very limited publications about the impact and dynamic properties of RGC. Aly et al. (2019) concluded that RGC is a sustainable alternative solution for cement concrete, especially for concrete applications in roads, and airports paving slabs. Aly et al. (2019) also concluded that in the impact resistance test by increasing the crumb rubber replacement ratio the gap between the number of blows till the initial crack and the number of blows till the total failure significantly increased, which indicates the increase in ductility of RGC. In another investigation on geopolymer concrete uses CR in its natural condition and after surface treatment with 1 Molarity NaOH for 24 h, Bhavani et al. (2021) concluded that by increasing rubber content the flexural impact resistances of geopolymer concrete increased significantly using both treated and untreated rubber.

Additionally, rubberized concrete has a low unit weight because CR has a significantly lower relative density compared to ordinary aggregates, which lowers the density of concrete when particles are replaced with it (Shu and Huang, 2014). Depending

Table 1. XRF analysis results of FA (Abd-Elaty et al., 2022).

Element	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	P_2O_5	Na_2O	K_2O	TiO_2	Cl	SO_3	MnO_2
Weight %	58.68	5.41	27.70	1.84	0.72	0.58	0.23	1.20	2.22	0.04	0.23	0.03

on the size and content of the CR, utilizing 10% and 30% CR as a partial alternative to sand by mass can decrease the density of cement concrete by 14% and 28%, respectively producing lightweight concrete having a density of 1800 kg/m^3 with 30% CR replacement ratio (Sukontasukkul, 2009).

In the current work, continuing research in the direction of sustainability and environmental preservation, the effect of incorporating CR on the mechanical, toughness and impact properties of RGC have been studied. Moreover, the effect of merging both CR and PP fibers on the properties of geopolymer concrete has been studied. The major goals of this research work were to use CR from used rubber tires and PP fibres to enhance important characteristics of geopolymer concrete, including ductility and impact resistance.

2. Experimental work

2.1. Materials

This study employed fly ash (FA) class F complies with ASTM-C618 (ASTM-C618, 2019) and has a relative density of 2.31 as the basic alumino-silicate material to create geopolymer mixtures. The FA was analyzed by XRF test to identify its chemical composition, which is depicted in Table 1. A mixture of sodium hydroxide (NH) (16 Molar) and sodium silicate solution (NS) with a fixed NS to NH ratio of 2.5 was utilized as the alkaline liquid. The fine aggregate utilized was medium well-graded siliceous sand that met ASTM-C33 (ASTM-C33, 2018) requirements and had a relative density of 2.5 and a fineness modulus of 2.47. The coarse aggregate used was basalt has a nominal maximum particle size of 14 mm, a finesse modulus of 6.09 and a relative density of 2.87. The utilized Crumb Rubber (CR) is obtained from a nearby recycling facility that creates CR from discarded tires using the cracker mill method and granular method, which was explained by Azmi et al. (2016). The used CR is a mix of three sizes (0–1 mm, 1–3 mm and 4 mm) by a ratio of 1: 1: 1 by mass without any surface treatment as shown in Fig. 1. Table 2 lists the characteristics of the rubber, basalt, and sand that were used, and Fig. 2 displays the used sand and rubber's grain size distribution curves. Polypropylene (PP) fiber mesh (12 mm length) meets the terms of BS.EN-14889-2 (BS.EN-14889-2, 2006) as reported by the manufacturer was utilized in this study. To control concrete workability, a superplasticizer (SP) type (F) with a Naphthalene sulfonate basis that complies with ASTM-C494 (ASTM-C494, 2017), was utilized.

2.2. Mix proportions and samples preparation

To study the impact of CR content, PP fiber volume fraction, and both CR and PP fibers on the properties of Rubberized Geopolymer Concrete (RGC), a total of 12 mixtures were prepared. Three mixtures were designed by replacing 3%, 6%, and 9% of the sand by volume with CR. Furthermore, three mixes were designed to study the effect of PP fibres on the characteristics of geopolymer concrete at 0.25%, 0.5%, and 0.75% volume fractions. Additionally, the PP fiber volume fraction was kept at 0.5% and the CR content was changed to 3%, 6%, and 9% in three other mixes. Ultimately, the CR content was kept at 6% and the PP fibers volume fraction was changed to 0.25%, and 0.75% in two other mixes, all these mixes were compared by the control mix. Table 3 lists the constituents of the concrete mixtures. All mixes had an alkaline solution to FA ratio of 0.475, an NS to NH ratio of 2.5, and an NH molarity of M16, and a superplasticizer was added to control the mixtures' workability. To assure the homogeneity of the mixture, the FA, sand, and basalt were first dry-mixed together in a rotary mixer for 2 min The alkaline solution was then added, and everything was blended again for 4 min The SP was then gently

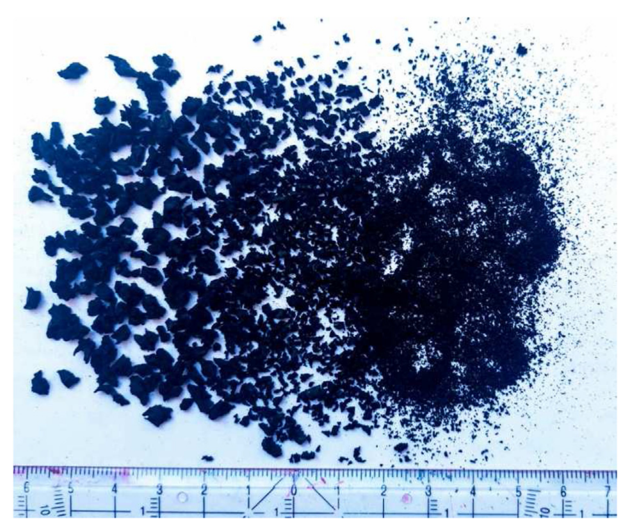


Fig. 1. The used CR particle sizes.

Table 2. Characteristics of basalt, sand, and CR.

Material	Basalt	Sand	CR
Unit Weight (kg/m^3)	1650	1500	615
Specific Gravity	2.87	2.50	0.94
Fineness Modulus	6.09	2.47	3.66

added to the mixture. After that, the CR and/or fibres were progressively added to the mixture and mixed continuously for at least 3 min, until the mixture became glossy and well-combined. This mixing procedure aligned well with the mixing procedure of Tahwia et al. (Tahwia et al., 2022a).

The samples were cast and compacted for 60 s on a vibrating table. Following this, the moulds were covered and stored at ambient temperature (25 ± 3 °C and 60 ± 5% relative humidity) for 1 day as a rest period, after that the samples were heat cured for 72 h at 60 °C. The heat-curing process improves the geopolymerization process by getting longer polymer chains, which improve the dissolving rate of alumino-silicate minerals by increasing the composite temperature (Abdellatief et al., 2022). Before stripping, the specimens were stored for another day at an ambient temperature. Finally, the samples were demolded and stored at room temperature until the testing time.

2.3. Test methods

2.3.1. Fresh and physical tests

After mixing, the slump test was carried out in accordance with ASTM-C143 (ASTM-C143, 2012) to assess the impact of CR and PP fibres on the consistency of RGC. Slump tests were carried out in the laboratory at 25 ± 3 °C and 60 ± 5% RH. After the curing period, concrete unit weight was determined in the dry condition according to BS.EN-12390-7 (BS.EN-12390-7, 2009) to assess the impact of using CR on the density of hardened concrete.

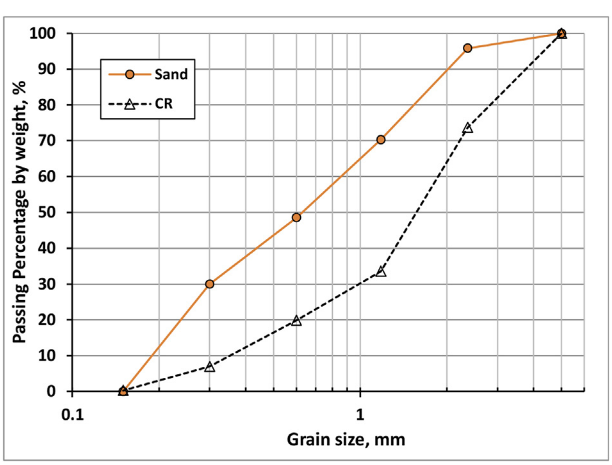


Fig. 2. Particle size distribution of sand and CR.

2.3.2. Mechanical properties

To measure the concrete compressive strength, the concrete was poured into cubic moulds in dimensions 150 × 150 × 150 mm into three layers. Each one was compacted by a vibration table. The compressive strength test was conducted at 7, and 28-days age according to BS.EN-12390-3 (BS.EN-12390-3, 2019).

To study the effect of CR and PP fibers on the flexural strengths of different concrete mixes, three beams with dimensions of 100 × 100 × 500 mm were prepared -for each concrete mix-by the same proportions mentioned in Table 3. The beams were poured into two layers. Each one was compacted mechanically using a vibration table. The beams were tested under a three-point loading test according to ASTM-C78-02 (ASTM-C78-02, 2017) with a span of 40 cm to obtain flexural strength at 7, and 28-days age. Moreover, the toughness indexes I_{10} and I_{20} were measured according to ASTM-C1018 (ASTM-C1018, 1997) from load−deflection relationship in flexural test results. Three samples were utilized for each test, and the average value was reported.

Additionally, 100 mm diameter and 200 mm height cylindrical samples were made to assess the impact of CR on the splitting tensile strength at seven and 28 day as well as the modulus of elasticity at twenty-eight days according to ASTM-C496 (ASTM-C496, 2017), ASTM-C469 (ASTM-C469, 2017), respectively. The cylinders were poured into three layers. Each layer was compacted mechanically using a vibration table.

All mechanical tests were performed in the laboratory at a temperature of 25 ± 3 °C and relative humidity of 60 ± 5%. Three samples were tested in each property and the average reading was recorded. The compressive strength test and splitting tensile strength test were performed using a hydraulic compressive testing machine of 2000 kN capacity and the flexural strength test and modulus of elasticity test were performed using a data collection system-equipped universal testing machine with a 300 kN capacity as shown in Fig. 3.

2.4. Impact test

The impact resistance under flexural load test was performed according to Aly et al. (2019) and Al-Tayeb et al. (2022) using the drop weight test as shown in Fig. 4 to determine the potential energy of RGC and fibrous RGC. The test was conducted by

Table 3. Concrete mixtures proportions of RGC, kg/m^3.

Mix No.	Mix ID	FA	Basalt	Sand	CR	Polyprop-ylene Fibers	Solution (Solution/ FA = 0.475)		Super Plasticizers	Slump, mm
							NH (M16)	NS		
1	CCO	400	1365.8	509.9	–	–	54.29	135.71	4	150
2	C3R	400	1365.8	494.6	5.77	–	54.29	135.71	4	150
3	C6R	400	1365.8	479.3	11.54	–	54.29	135.71	4	140
4	C9R	400	1365.8	464.0	17.31	–	54.29	135.71	4	120
5	C0.25F	400	1360.8	508.0	–	2.25	54.29	135.71	4	120
6	C0.50F	400	1355.8	506.1	–	4.5	54.29	135.71	4	110
7	C0.75F	400	1350.7	504.3	–	6.75	54.29	135.71	4	90
8	C0.50F3R	400	1355.8	490.9	5.73	4.5	54.29	135.71	4	120
9	C0.50F6R	400	1355.8	475.7	11.45	4.5	54.29	135.71	4	110
10	C0.50F9R	400	1355.8	460.6	17.18	4.5	54.29	135.71	4	100
11	C0.25F6R	400	1360.8	477.5	11.50	2.25	54.29	135.71	4	100
12	C0.75F6R	400	1350.7	474.0	11.41	6.75	54.29	135.71	4	80

C#F#R: concrete mix containing #% PP fibers and #% CR; C#F, Concrete mix containing #% PP fibers; C#R, Concrete mix containing #% CR; CCO, Concrete control geopolymer Mix.

dropping a steel ball with a mass of 2 kg (19.62 N) on the mid-span of 100 × 100 × 500 mm concrete beam specimens from a height of 100 cm through a guiding plastic pipe. The loading frame is attached to this guiding pipe, which directs the ball so that it falls precisely where it is supposed to (mid-span of the beam specimens) for all blows. The beam was simply supported under the impact load with a span of 450 mm; however, clamps were used to prevent the beam from rising after the impact. The steel ball was pulled up to the specified height and left to drop freely by an automatically controlled motor at a rate of 10 blows per minute. The number of impact blows required for the first visible crack and the total failure of the beam were recorded.

2.4.1. Microstructure analysis

Scanning Electron Microscope SEM analysis was conducted to explore the microstructure of the investigated geopolymer concrete mixtures. SEM analysis was conducted using a (JSM-6510LV) electronic microscope on parts of concrete samples.

3. Test results and discussion

3.1. Fresh and physical results

3.1.1. Workability

The results of the slump test of different concrete mixtures depict the effect of incorporating CR and/or PP fibers on the consistency of geopolymer concrete. As shown in Fig. 5 and Table 4, the incorporation of PP fibers decreases the slump of geopolymer concrete, and the reduction increased with the increase of PP fibers volume fraction reaching 40% reduction by using 0.75% PP fibers. Incorporating PP fibers in concrete reduces the flowability by creating higher interlocking, cohesion and bond among concrete constituents in freshly mixed concrete (Fallah and Nematzadeh, 2017; Hossain et al., 2019). This reduction was more than the reduction of incorporating CR in the geopolymer concrete, which may be due to the relatively smaller replacement ratio of sand by CR. Moreover, using both CR and PP fibers leads to more reduction in the flow hitting a 45% reduction in the mixture containing 75% PP fibers with 6% CR. The reduction of the slump of RGC is related to the jagged edges of the CR surface nature due to the cutting process of tiers as described also by Taha et al. (2003) and Hesami et al. (2016).

3.1.2. Unit weight

Incorporating CR decreases the unit weight of the hardened geopolymer concrete, and the reduction is directly proportional to CR content. The specific gravity of the CR particles is approximately 2.6 times lower than that of natural sand, often resulting in a decrease in the hardened concrete's unit weight. Using 9% CR decrease the unit weight of the geopolymer concrete by about 2.3%.

3.2. Compressive strength

The impact of utilizing CR and PP fibers in the compressive strength of geopolymer concrete is presented in Fig. 6 and Table 4. The results revealed that using CR in geopolymer concrete decreases the compressive strength by an acceptable ratio if compared with the benefits gained in toughness. The CR content has a significant impact on this reduction. For instance, incorporating 3%, 6%, and 9% CR decreases the compressive strength of geopolymer concrete by an average of 1%, 9.2%, and 12.3% at 28 days, respectively.

(a) (b) (c)

Fig. 3. Mechanical properties tests of concrete samples (a) Compressive strength test, (b) Flexural strength test, and (c) Splitting strength test.

These outcomes are consistent with those of Luhar et al. (2018), who found that the compressive strength of RGC decreased by 12% by using 10% CR as a partial replacement of fine aggregates. Accordingly, incorporating 15% CR as a partial replacement of sand by volume considers an acceptable ratio and this percentage can be increased to 20% and 30% by using higher binder content, lower solution-to-binder ratio and metakaolin as reported also by Ismail and Hassan (2016). Additionally, Keleştemur et al. (2012) achieved rubberized self-compact concrete with 40 MPa compressive strength by using 30% CR as a partial replacement of coarse aggregate. Even if the compressive strength is lower, incorporating CR into geopolymer concrete has a remarkable effect on the failure pattern of the geopolymer concrete particularly by increasing the CR content. The failure pattern of geopolymer concrete including CR shifts from brittle to more ductile when compared to geopolymer concrete without CR, and this finding supports the toughness increment brought on by the addition of CR.

Fig. 4. The impact resistance under flexural load test.

Additionally, incorporating PP fibers with different volume fractures (0.25%, 0.5%, and 0.75%) decreases the compressive strength of geopolymer concrete mixtures (mixes 5 to 7) by around 2.3%, 10.7% and 13.8%, respectively compared to the control mix. It might be because the PP fibre and binder (regardless of the type of binder) have a weak bond, which leads to decreasing the compressive strength of the mix (Aulia, 2002; Ranjbar et al., 2016).

On the other hand, incorporating 0.5% PP fibers with 3%, 6%, and 9% CR decreases the compressive strength by 3.6%, 8.2%, and 13.3%, respectively if compared with the mixture containing 0.5% PP fibers only. Whilst, adding 0.25% and 0.75% PP fibers with 6% CR decrease the compressive strength by approximately 16% and 30%, respectively compared to the control mixture.

3.3. Splitting tensile strength

Fig. 7 shows the splitting tensile strength results of all geopolymer concrete mixtures at different ages. The results revealed that using CR in geopolymer concrete decreases the splitting tensile strength and the decrease proportioned with the CR replacement ratio, reaching about 24.5% reduction by using 9% CR. That reduction can be ascribed to the same causes of decreasing compressive strength. However, by using PP fibers, the splitting tensile strength increased by a tiny fraction (i.e., 4.1% by using 0.5% PP fibers). Moreover, incorporating both materials in geopolymer concrete is better than using CR only according to the test results.

3.4. Flexural strength

The flexural strength test results of RGC at 28 days age is shown in Fig. 8 and Table 4. Using 3% CR increased the 28 days flexural strength by 5.6%, However, by increasing the replacement ratio, the flexural strength decreased by a tiny fraction. By

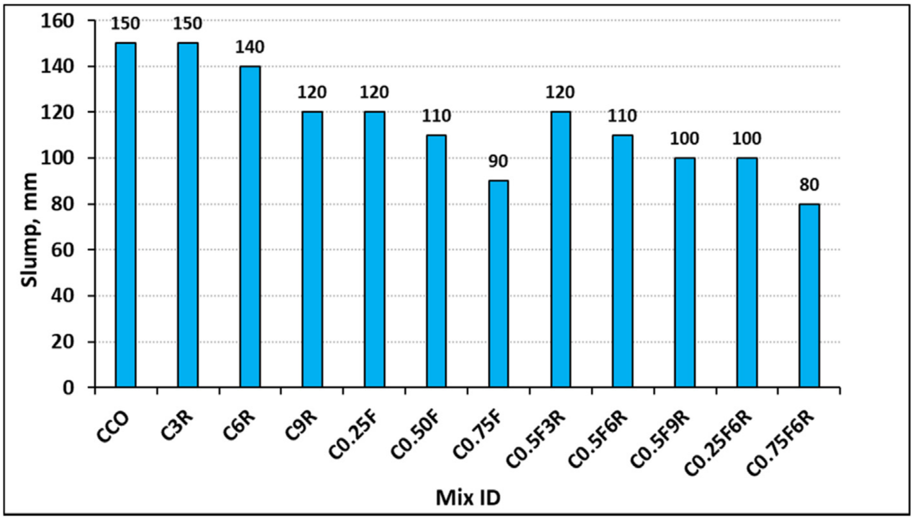


Fig. 5. Slump test results of the investigated geopolymer concrete mixes.

increasing the PP fiber's volume fractions the flexural strength increased reaching about 34% by using 0.75% PP fibers. However, using both CR and PP fibers decrease the flexural strength of geopolymer concrete. For example, by using 0.5% PP fibers the flexural strength decreased by 6.3%, 15.2%, and 21.3% by adding 3%, 6%, and 9% CR, respectively. Additionally, using 6% CR with 0.75% PP fibers increases the flexural strength by only 17.2% compared with 34% in the case of 0.75% PP fibers only. This may be due to the large amount of material with a lower stiffness (i.e. CR and PP fibers) in the composite.

3.5. Relation between flexural and compressive strength

The relation between flexural strength and compressive strength of the investigated geopolymer concrete mixtures at 28 days is presented in Fig. 9 as a percentage. As it shown, incorporating CR into geopolymer concrete mixtures increases the flexural strength to compressive strength ratio reaching a 12.6% increment by using 9% CR for that grade of concrete. A similar trend has been recorded by Zheng et al. (2011) in rubberized cement concrete. Additionally, adding PP fibers increases the flexural strength to compressive strength ratio remarkably hitting around 56% enhancement with using 0.75% PP fibers. However, incorporating both CR with PP fibers increases the ratio by a low percentage, except for the mixture C0.75F6R, which gave the best enhancement in the ratio of flexural strength to compressive strength (66.5% increment). It may be attributed to the high-volume fraction of PP fibers which enhances the flexural strength significantly.

3.6. Load-deflection behaviour

The relations between the load and the maximum deflection at 28 days are shown in Fig. 10. Using CR

Table 4. Mechanical test results of the investigated geopolymer concrete mixes.

Mix No.	Mix ID	Slump	Compressive Strength, MPa		Flexural Strength, MPa		Splitting Tensile Strength, MPa		Elastic Modulus (28 days), GPa
			7 days	28 days	7 days	28 days	7 days	28 days	
1	CCO	150	57.9	58.7	5.40	5.53	4.95	5.10	29.3
2	C3R	150	57.0	58.1	5.30	5.84	4.85	4.90	28.3
3	C6R	140	51.2	53.3	4.50	5.52	4.22	4.28	27.4
4	C9R	120	48.8	51.5	4.45	5.44	3.78	3.85	26.4
5	C0.25 F	120	56.5	57.3	5.55	5.77	4.95	5.15	28.6
6	C0.50 F	110	51.3	52.4	5.92	6.12	5.22	5.31	28.8
7	C0.75 F	90	48.3	50.6	6.39	7.43	4.97	5.05	27.3
8	C0.50F3R	120	46.3	50.5	5.10	5.18	4.91	4.96	27.2
9	C0.50F6R	110	45.0	48.1	4.47	4.69	4.51	4.62	26.6
10	C0.50F9R	100	42.9	45.4	4.01	4.35	4.21	4.33	25.8
11	C0.25F6R	100	48.5	49.1	4.39	4.50	4.44	4.51	26.9
12	C0.75F6R	80	40.2	41.3	5.68	6.48	4.30	4.43	24.6

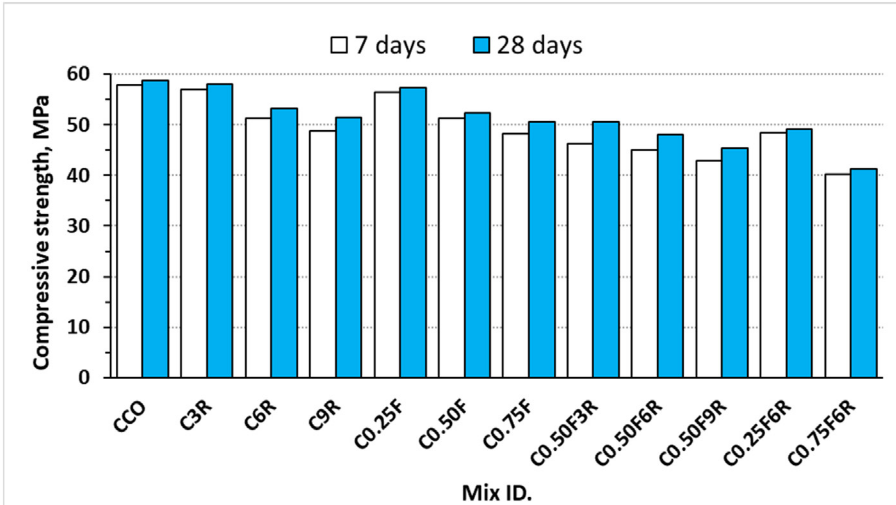


Fig. 6. Compressive strength of the geopolymer concrete mixes.

and PP fibres simultaneously improves the load-deflection curves and noticeably raises the toughness of the geopolymer concrete, as can be seen from the figure. Additionally, the toughness indexes I_{10} and I_{20} have been calculated for the 28 days test results according to ASTM-C1018 (ASTM-C1018, 1997) and the results are shown in Fig. 11. The results indicate that using 3%, 6% and 9% CR as a part of the fine aggregate's volume in geopolymer concrete increases the toughness index I_{20} by an average of 12%, 18% and 26%, respectively. Moreover, regarding toughness and force absorption, utilizing CR with PP fibres is preferable to using PP fibres only. For instance, adding 6% CR increases the toughness index I_{20} by 34.8%, 51.5%, and 14.6% when compared to mixes with only 0.25%, 0.50%, and 0.75% PP fibres, respectively.

3.7. Static modulus of elasticity

Fig. 12 and Table 4 present the elastic modulus results of all geopolymer concrete mixes, the results showed that utilizing CR in geopolymer concrete reduces the elastic modulus and the reduction is directly proportional to the CR content. For instance, using 9% CR as a part of the fine aggregate's volume decreases the elastic modulus (i.e., 29.3 GPa for the control mix) by about 10%, whereas using up to 0.5% volume fraction of PP fibers has a lower effect on the modulus of elasticity

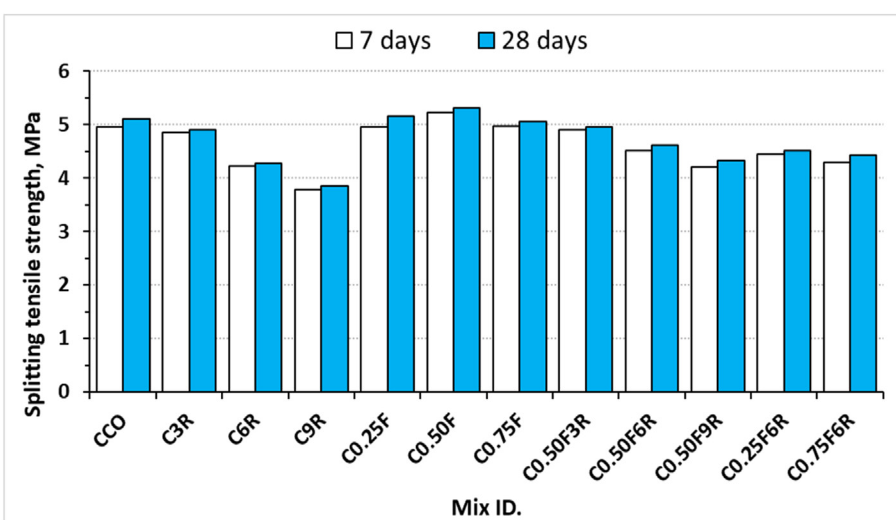


Fig. 7. Splitting tensile strength of the geopolymer concrete mixes.

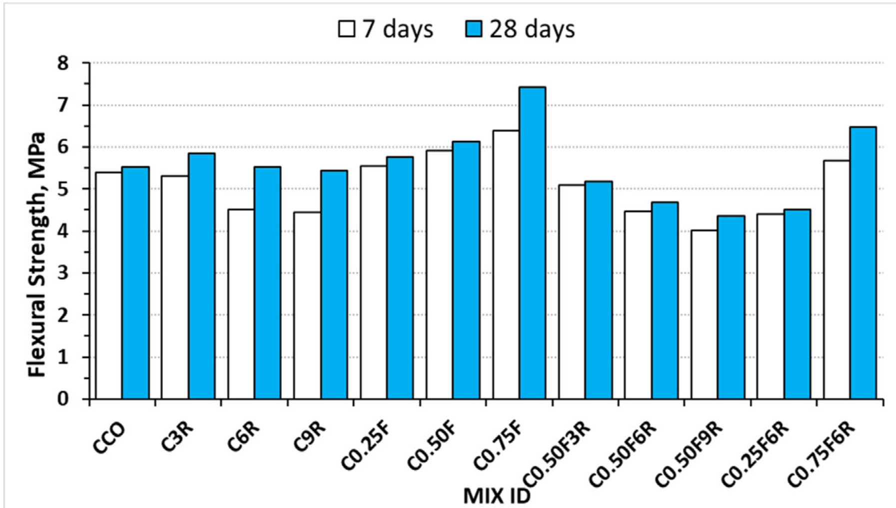


Fig. 8. Flexural strength of the geopolymer concrete mixes.

of geopolymer concrete. However, using 6% CR with 0.25%, 0.5% and 0.75% PP fibers reduces the elastic modulus by 8.2%, 9.2% and 16%, respectively. The high proportion of low-stiffness materials (CR and PP fibers) is what causes C0.75 F6R mix to have the lowest elastic modulus. Furthermore, it is the same cause which affects the workability, increases the particles that have a low bond with the matrix at the interfacial transition zone, especially between the CR particles and the matrix as explained by Turatsinze et al. (2006) and finally leads to decreasing the compressive strength and the elastic modulus.

3.8. Impact resistance test results

Impact resistance under flexural load for various geopolymer concrete mixtures is presented in Fig. 13 as the number of blows until the first visible crack (Ni) and the number of blows until the total failure (Nf). As it is shown, using CR particles increases the initial and final absorbed energy. This increment proportioned with the CR replacement ratio gaining up to 22% and 45% at initial crack and failure, respectively by using 9% CR compared with the control mix. Additionally, incorporating PP fibers in geopolymer concrete raises the absorbed energy, remarkably, hitting 106% and 160% at initial crack and failure, respectively by using 0.75% PP fibers. Moreover, merging both materials in the same mixture has a neglectable effect on the absorbed energy at the initial crack if compared with the mix containing PP fibers only which may be attributed to the lower compressive strength in the mixtures containing both materials, however, it has a significant effect on the absorbed energy at failure. For instance, by

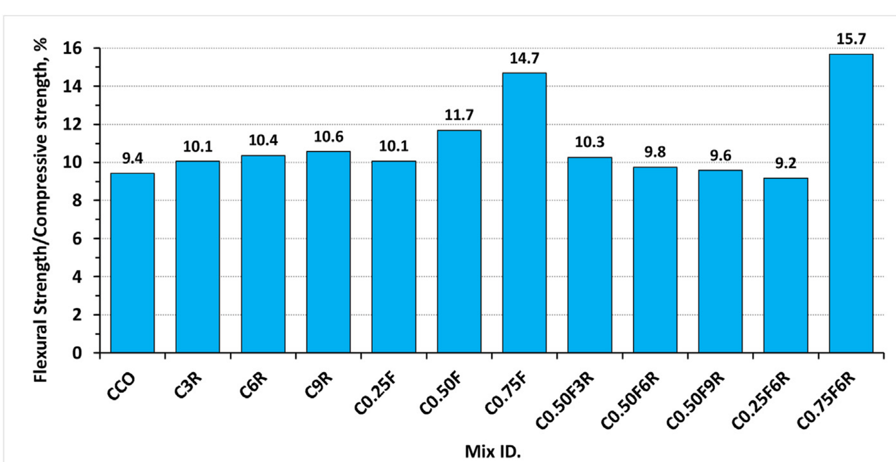


Fig. 9. Relationship between flexural and compressive strength at 28 days.

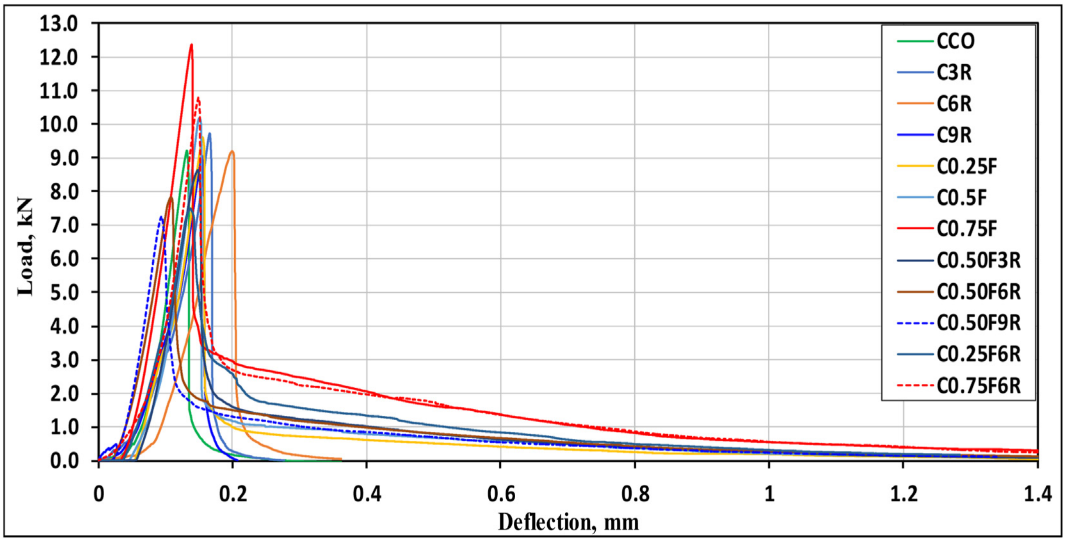


Fig. 10. Load-deflection curves of rubberized geopolymer concrete at 28 days.

comparing the results of C0.75F and C0.75F6R, the absorbed energy until the initial crack increased from 106% to 117%, respectively, however, the total absorbed energy until failure raised dramatically from 160% to 240%, respectively. The gaining in the impact energy and the higher toughness of RGC may be ascribed to the low stiffness of the CR particles.

3.9. Microstructure results

Figs. 14 and 15 show the SEM images for CCO, C0.5F6R and C0.75F6R geopolymer concrete mixtures. Fig. 14 shows the Interfacial Transition Zone ITZ between CR particles and the geopolymer matrix. A small degree of magnification was used to examine the ITZ which appears as a void gab along the surrounding edges of the CR particles reflecting the weak bond between the CR particles and the geopolymer matrix. This weak ITZ explains the strength loss of the mixtures containing CR particles. Fig. 15 shows the microstructure of the geopolymer concrete matrix in different mixtures. In all images in the figure the regular spherical particles are unreacted FA particles may be due to the large quantity of FA in the geopolymer concrete mixtures or it may require a curing temperature higher than 65 °C for the polymerization process to take place with all FA particles. Additionally, all the half-spherical shape voids are places of FA particles, whilst the irregular and dark voids are air voids

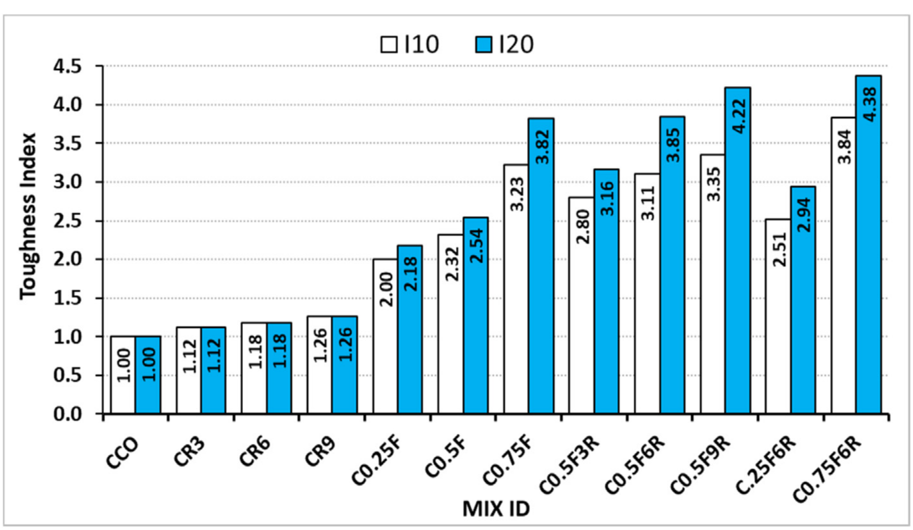


Fig. 11. Toughness indexes of rubberized geopolymer concrete at 28 days.

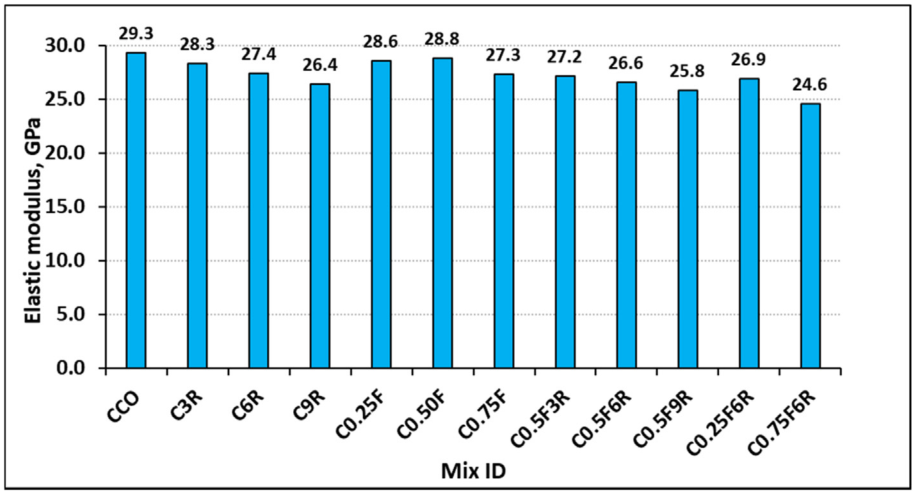


Fig. 12. Elastic modulus of rubberized geopolymer concrete mixes at 28 days.

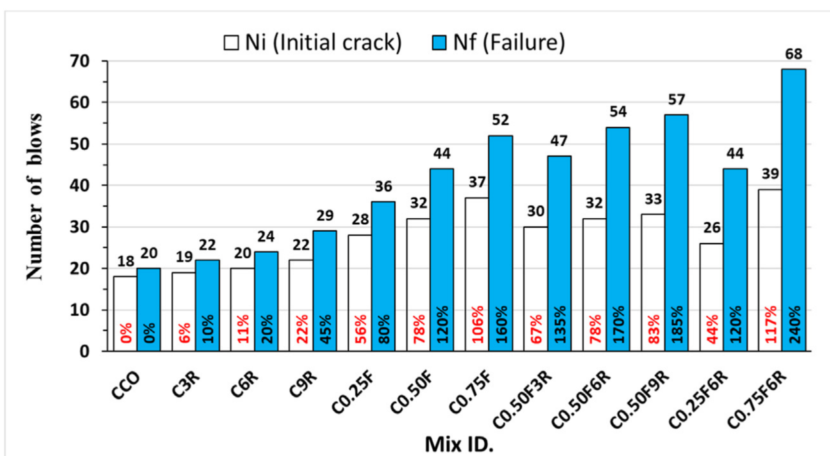


Fig. 13. Number of blows and the percentage of gain in impact-resistant test.

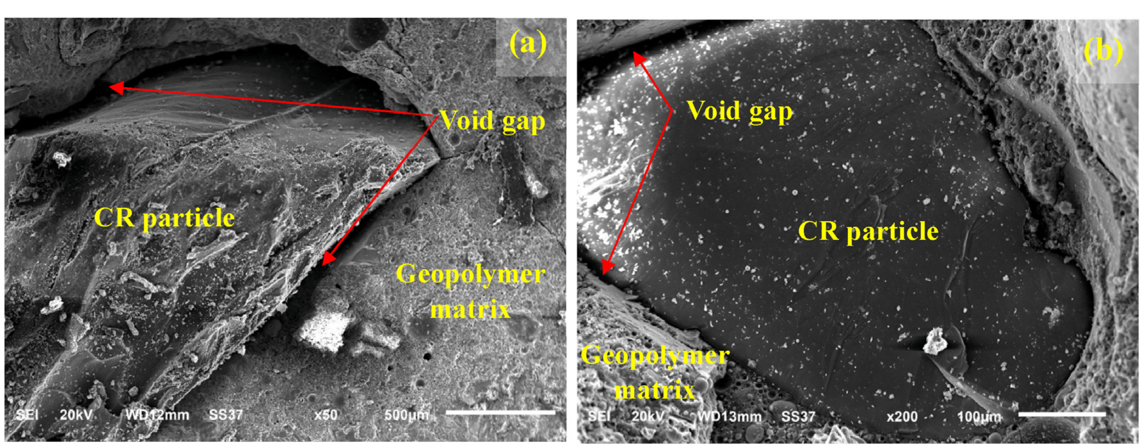
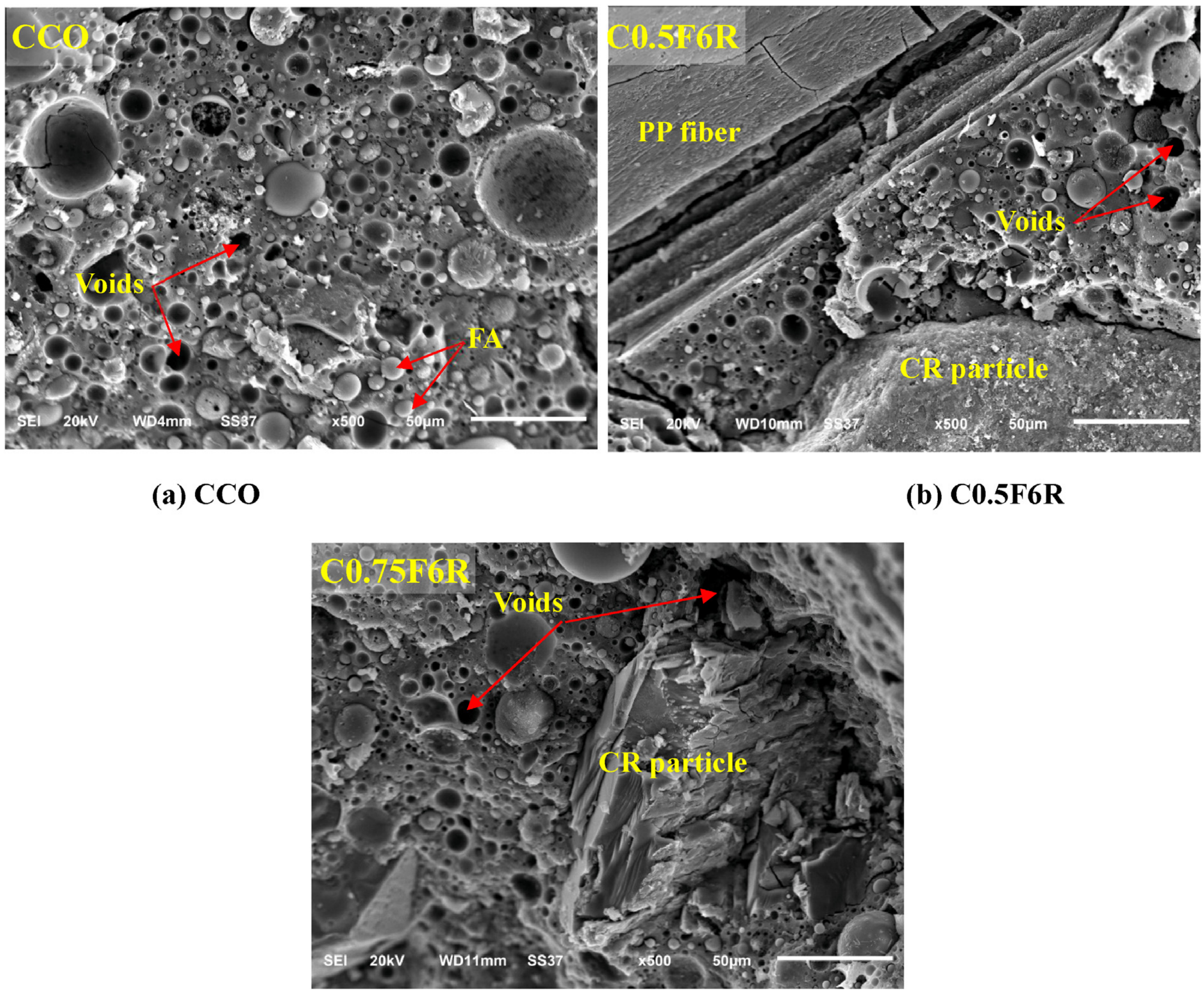


Fig. 14. SEM micrographs show the CR-matrix interface, (a) 50X and (b) 200X.



(a) CCO **(b) C0.5F6R**

(C) C0.75F6R

Fig. 15. SEM micrographs show the microstructure of the geopolymer concrete, (a) CCO, (b) C0.5F6R, and (c) 0.75F6R.

which relatively large in C0.5F6R and C0.75F6R compared to CCO mix due to the relative hydrophobic characteristics of the CR particles which take in large amounts of air in concrete. The relatively large quantities of puros in mixtures containing CR particles are considered another reason for the strength loss of the rubberized geopolymer concrete.

4. Conclusions

In this study, the effects of substituting some of the natural sand by volume with crumb rubber (CR) in FA-based geopolymer concrete have been experimented. Furthermore, the influence of utilizing CR with polypropylene (PP) fibers on the fresh properties, mechanical properties, and impact resistance of geopolymer concrete has been investigated. The key findings from this study can be summed up as follows.

(1) The slump of geopolymer concrete is inversely proportional to the CR content, reaching a 20% reduction by using 9% CR.
(2) Incorporating CR in geopolymer concrete up to 9% replacement of sand has little effect on compressive, and flexural strength reaching 12% and 1.6% reduction, respectively, however, they are predicted to decrease more by increasing the CR replacement ratio.
(3) Incorporating 6% CR with 0.75% PP fiber increased the flexural strength of geopolymer concrete by about 17%, however, the compressive strength and the splitting tensile strength decreased by about 29% and 13%, respectively.
(4) Using CR in geopolymer concrete remarkably increases the toughness indices. Moreover, the best results for I_{20} have been reached for 9% CR as a 26% increment. Additionally, it is preferable

to combine CR with PP fibres rather than CR only. For instance, using 6% CR with 0.50% PP fibers gives the best enhancement as I_{20} enhanced by 51.5% over the mixture containing 0.5% PP fibers only.

(5) In the impact resistance under flexural load test, the absorbed energy up to the first crack and failure increased remarkably by using CR gaining up to 22% and 45% at the initial crack and failure, respectively by using 9% CR compared with the control mix. Moreover, incorporating CR with PP fibers has a substantial effect on the absorbed energy at failure hitting a 240% increment by using 6% CR with 0.75% PP fibers.
(6) SEM analysis proves that the interfacial transition zone between CR particles and the concrete matrix is very weak due to the relatively hydrophobic characteristics of the CR particles which also take in large amounts of air in concrete which explains the decreased mechanical properties.
(7) Based on the experimental results and discussion, it is recommended to use 6% CR with 0.5% PP fibers which is considered the optimum mixture to get the best impact and toughness properties with moderate compressive strength and other mechanical and physical properties. Additionally, the mix containing 6% CR with 0.75% PP fibers is considered the optimum mixture to get higher impact and toughness properties with low compressive strength requirements.
(8) The properties of the developed mixtures draw attention to its proposed applications in situations where impact resistance and high toughness are required such as industrial floors, railway sleepers, and structural elements exposed to collision loads and explosions.

Author credit statement

Metwally Abd Allah Abd-Elaty: Conceptualization, Methodology, Validation, Writing – review & editing.

Mariam Farouk Ghazy: Validation, Writing – review & editing, Data curation, Formal analysis.

Omar Hussein Khalifa: Investigation, Resources, Visualization, Writing – original draft.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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