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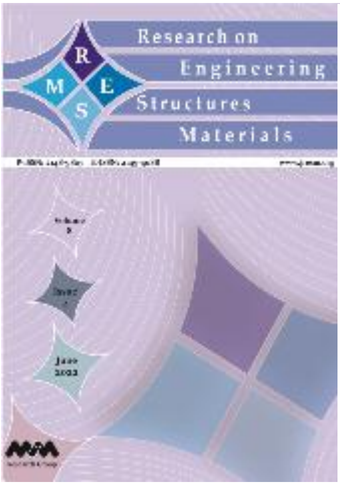

Properties of modified metakaolin-based geopolymer concrete with crumbed rubber waste from damaged car tires

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Research Article

Properties of modified metakaolin-based geopolymer concrete with crumbed rubber waste from damaged car tires

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Abstract

Waste rubber tires are materials that have a negative impact on the environment. Therefore, it is essential to use waste rubber recycled from damaged tires (CRWA) in geopolymer concrete (GPC) by different partial volumetric replacements to natural coarse aggregate (0, 10, 20, 25%) after preparation to a gradation similar to that for natural coarse aggregate. Calcium oxide and silica fume were substituted in metakaolin (MK) at 5 wt%. The GPC mix consisted of MK after modification, coarse aggregate, fine aggregate sodium hydroxide solution, sodium silicate solution, superplasticizer, and extra water, with quantities of 372, 911, 83, 192, 4, and 52 kg/m^3, respectively. It is clear from the experimental results that the mechanical properties of geopolymer concrete decreased with the increase in the content of the crumbed rubber waste aggregate. The compressive, splitting tensile, and flexural strengths decreased by approximately 38.6, 44.6, and 52.6%; 10.6, 15.2 and 21.2%; and 6.25, 12.75, and 16.5% when the crumbed rubber aggregate was 10, 20 and 25%, respectively. In addition to recycling the rubber waste from damaged tires, desirable properties can be obtained, starting from not using water in curing GPC and rapid strength development at early ages. There is a clear improvement in the thermal properties and weight of GPC containing CRWA by reducing the thermal conductivity and dry density by including 10, 20, and 25% CRWA compared with the reference GPC without this waste material.

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1. Introduction

According to the World Commission on Environment and Development, sustainability is ensuring that the current demand of humanity can be achieved without affecting the needs of future generations. At the Earth Summit in 1992, seven principles were defined for achieving environmental efficiency, including reducing the amount of materials used in products, reducing the energy consumption of products, reducing the emissions of toxic gases, increasing the recyclability of materials, exploiting the use of renewable materials as much as possible, increasing the durability of products, and increasing the service life of products [1,2]. In 1978, Davidovits [3] developed concrete in a different way than at that time using some byproducts from the construction industry, and named it geopolymer concrete.

GPC is an inorganic composite material created by interacting strongly alkaline substances with an aluminosilicate source and aggregate. It is possible to use aluminosilicate from waste materials such as ground granulated blast furnace slag, fly ash, and natural pozzolans, such as metakaolin. Geopolymer concrete can provide many environmental advantages. Using recycled materials instead of cement, geopolymer concrete can reduce

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carbon dioxide emissions by up to 80%, as well as save energy and natural resources and avoid environmental problems caused by conventional concrete. [4,5].

Tire rubber disposal has become one of the most significant environmental issues in the world today. Throughout the world, tires are routinely discarded, buried, or thrown away, posing a very serious threat to the environment[6].

The effect of the inclusion of different percentages of CRWA from damaged car and truck tires that can be used as partial replacements for fine and coarse natural aggregates (0, 10, 20, and 30%) on the properties of geopolymer concrete based on slag as a binder was studied by Aly et al. [7]. Waste rubber was divided into particle sizes passing through sieve No. 40 as fine aggregate and particle sizes from 1-4 mm as coarse aggregate. The most important of the researcher's conclusions is that the compressive strength was slightly enhanced with increasing rubber percentage up to 10%; however, an increase in rubber content higher than 10% leads to a decrease in the compressive strength by 24% and 34% for rubber percentages of 20 and 30% at 28 days and 21% and 28% at 60 days, respectively. The flexural and splitting strengths suffer reduction with the increase in the replacement of rubber content by 20, 30, and 30% for splitting strength and 34.6, 23, and 35.5% for flexural strength. The impact resistance of geopolymer concrete is greatly enhanced due to the presence of rubber, which leads to an increase in the ductility and energy absorption of approximately 50, 150, and 200% for 10, 20, and 30% rubber waste content compared with geopolymer concrete without rubber waste [7].

The use of recycled rubber in GPC was carried out by Kurek [8], fly ash was utilized as a binder activated by NaOH with a concentration of 14 M and sodium silicate with a modulus of 2.5. Rubber granules from recycling waste tires were used with a small size in the 0-0.8 mm range and a large size in the 1-4 mm range. Then, 25-50% of the sand was replaced by fly ash, and 12.5-25% of the sand was replaced in the first case with granules of waste tire rubber, once in a small size and again in a large size. The GPC specimens were cured at a temperature of 75°C for 24 hours, then left at room temperature until the test time at 7 and 28 days. The results explained that the density increases by increasing the proportion of sand from 25-50%, while it decreases when replacing sand with rubber. The highest decrease in density was obtained when using rubber of small sizes. The compressive strength of GPC increases when sand is replaced with fly ash, but decreases when rubber inclusions are added. However, a 12.5% substitution of sand with waste rubber of 1-4 mm particle size resulted in a significant increase in the compressive strength.

Yeluri and Yadav [9] reviewed the mechanical properties of using rubber tire waste as aggregate in GPC. The results demonstrated that the inclusion of rubber in geopolymer concrete enhances its workability but reduces its flow value. As the rubber content increased, the compressive strength decreased by 60% for specimens with 15% rubber in concrete and 10% in mortar. However, the rubber content had a positive effect on the splitting and flexural strengths. The highest flexural strength was achieved at 30% waste rubber, replacing the fine aggregate.

Previous local studies using local metakaolin as a base material produced GPC with a compressive strength ranging from 3 to 41 MPa. To increase the compressive strength of metakaolin-based GPC, further research is needed to improve or modify Iraqi metakaolin. One possible factor is the R-value Si/Al or molar ratio, which is the ratio of silicates to aluminates in the binder. This ratio affects the polymerization process and the mechanical properties of GPC[10–13]. Davidovits recommended that the optimal Si/Al ratio for achieving maximum strength and durability is 1:4 [3,14,15].

It was noted that few investigations are studying all the properties of concrete that use this type of geopolymer concrete with crumbed rubber aggregate wastes, and there is little research conducted for geopolymer concrete produced from other materials with rubber wastes. This research aims to improve the strength of metakaolin-based GPC by using silica-rich materials such as silica fume or calcium-rich materials such as calcium oxide as a weight replacement for local metakaolin by changing the R-value and selecting the optimum mixture. Then, a comprehensive study was carried out to investigate the effect of the inclusion of different contents of CRWA on some properties of this GPC, so this research is considered an important addition in the field of construction.

2. Experimental Work

2.1. Materials

The kaolin clay found in Iraq's western desert was subjected to several processes, including grinding and burning at 700 degrees Celsius for two hours, to be converted into metakaolin, which conforms to the American standard ASTM C618 [16] as natural pozzolanic material class N, as a source of silica and alumina for the production of geopolymer concrete. The physical and chemical characteristics of the metakaolin utilized are shown in Tables (1) and (2), respectively.

Table 1. Physical properties of metakaolin

Physical Properties	MK	Requirements of ASTM C 618 [16]
Strength activity index at 7 days (%)	113	≥75%
Retained on 45 µm (%)	18.5	≤34%
Specific surface area (m2/kg)	14300	--
Specific gravity	2.64	--
Color	White –pinky powder	--

Table 2. Chemical properties of metakaolin

Oxide Composition	Weight (%)	Requirements of ASTM C 618 [16]
SiO_2	62.410	SiO2+ Al2O3+ Fe2O3= 98.327 ≥ 70
Al_2O_3	35.026	
Fe_2O_3	0.891	
K_2O	0.908	
TiO_2	0.531	
CaO	0.143	
SO_3	0.027	≤4%
MnO	0.002	
LO I	0.71	≤10%

LOI: Loss of ignition.

The alkaline solution used as an activator for the production of geopolymer concrete consisted of sodium hydroxide (NaOH) with a purity of 99.5% and sodium silicate (Na_2SiO_3). The natural fine aggregate used had a maximum size of 5 mm. The sieve analysis and the properties of fine aggregate are shown in Table (3), which conforms to Iraqi Standard No. 45/2016, gradation zone No. 2 [17]. The natural coarse aggregate used in this research was crushed gravel with a maximum size of 10 mm. The sieve analysis and the properties of the coarse aggregate are shown in Table (4), which is in accordance with Iraqi Standard No. 45/2016 [17].

Potable water was used for two purposes in the geopolymer concrete mixtures: to dissolve the 13 molar sodium hydroxide granules (with a molecular weight of 0.04 kg/mol) and to provide extra water for good workability in the plastic state. The water required for dissolving sodium hydroxide was 48 kg/m^3, while the extra water was 52 kg/m^3.

Table 3. Properties of fine aggregate

Sieve Size (mm)	Cumulative Passing (%)	Limits of IQS No. 45 for Zone II [17]
10	100	100
4.75	94	90-100
2.36	82	75-100
1.18	68	55-90
0.6	51	35-59
0.3	27	8-30
0.15	8	0-10
Material passing from sieve 75 µm (%)	3	≤5%
Sulfate content (%)	0.085	≤0.5%
Fineness modulus	2.71	--
Absorption (%)	1.8	--
Specific gravity	2.6	--
Bulk density (kg/m^3)	1744	--

Table 4. Properties of coarse aggregate

Sieve Size (mm)	Cumulative Passing (%)	Limits of IQS No. 45 [17]
10	97	85-100
5	12	0-25
2.36	--	0-5
Material passing from sieve 75 µm (%)	0.3	≥3
Dry density (kg/m3)	1627	--
Specific gravity	2.62	--
Absorption (%)	0.6	--
Sulfate content (%)		

A high-range water reducer with the commercial mark of Flocrete SP33 [18] was used. It is free from chlorides and agrees with ASTM C494 [19] types A, and F. Table (5) shows its main properties.

Silica fume from Sika Company [20], compatible with the American standard ASTM C 1240 [21], was also used in geopolymer concrete mixtures. Table (6) presents the physical and chemical properties of the silica fume used.

The calcium oxide used in this study was from the Karbala factory for the production of cement and Al Noora. The physical and chemical properties of calcium oxide are given in Table (7).

Table 5. Properties of the high-range water reducer*

Property	Description
Appearance	Dark brown liquids
Specific gravity	1.17-1.21
Chloride content	Nil
PH	6.5
Recommended dosage	0.8-2.8 L/100 kg binder

* *According to the manufacturer [18].

Table 6. Properties of silica fume

Physical properties		
Property	Results	Requirements of ASTM C1240
Specific surface area (m^2/kg)	19200	≥15000
Strength activity index with Portland cement at 7 days (%)	122	≥ 105
Retained on sieve 45 µm, max (%)	9	≤ 10
Specific gravity	2.2	--
Color	Grey	--
Chemical properties		
Oxide's composition	Results (%)	
SiO_2	88.593	≥85
Al_2O_3	--	--
Fe_2O_3	5.564	--
K2O	4.777	--
TiO2	--	--
CaO	0.666	--
SO_3	0.027	--
MnO	0.276	--

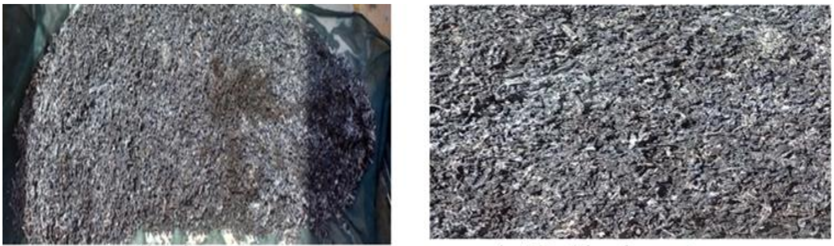
Waste tires were collected and cleaned, and the rubber from these waste tires was cut off to different sizes, starting from 0.3 to 18 mm, by the Al-Diwaniyah plant for cutting car tires in Al-Diwaniyah governorate, Iraq. The wastes were collected, washed and screened on standard sieves to obtain a gradation that matched the Iraqi specification No. 45/2016 [17], and the natural coarse aggregates used in this study. Then, the prepared crumb rubber particles were treated with a solution of 5% $Ca(OH)_2$ for 48 hours, according to previous studies [22–24]. This treatment makes the rubber particle surfaces rough and thus improves their bond strength with the geopolymer matrix. Figure 1 illustrates the preparation process for crumbed rubber waste aggregate. At the same time, Table (8) shows the properties and the sieve analysis of the rubber waste aggregate, corresponding to the sieve analysis of natural coarse aggregate based on Iraqi specification No. 45/2016 [17].

Table 7. Properties of calcium oxide

Physical properties	
Property	Results
Specific surface area (m2/kg)	16350
Specific gravity	3.3
Color	White
Chemical properties	
Oxides composition	Results (%)
SiO2	4.314
Al2O3	--
Fe2O3	0.461
K2O	1.667
TiO2	--
CaO	93.40
SO3	0.10
MnO	0.025

Table 8. Properties of the Waste Rubber Tier After Preparation

Properties	Results	Specifications
Loose bulk density (kg/m3)	--	ASTM C 29-15 [25]
Compacted bulk density (kg/m3)	494	ASTM C 29-15 [25]
Specific gravity	1.10	ASTM C127-15 [26]
Water absorption (%)	4.8	ASTM C 127-15 [26]
Sieve analysis		
Sieve size (mm)	Passing (%)	IQS No.45/2016 Limits for max. size (10 mm) [17]
14	100	100
10	97	85-100
5	12	0-25



a- Collecting b- Washing by water

c- Treatment by Ca (OH)₂ solutions d- Sieving through standard sieves

Fig. 1. Rubber waste preparation process

2.2 Selection of Geopolymer Concrete Mix Proportion

The preliminary selection of the geopolymer mixture was based on previous studies [5,10,11,27,28]. First, superplasticizer (SP), extra water, and mix proportion dosages were accurately calculated. The high fineness of metakaolin requires SP and extra water 1.1, 14% by weight of metakaolin, to improve workability with slump value (180±10 mm). Many trial mixes, including modifying metakaolin as a base material in GPC by partially substituting its weight with a binary mix of silica fume and calcium oxide and selecting the optimum proportions for other materials used in the production of GPC, were carried out. Finally, the selected GPC mixture had a binder content (metakaolin) of 372 kg/m^3 modified by silica fume and calcium oxide of 21 kg/m^3 for both of them, sodium oxide concentration of 13 molarity, sodium silicate/sodium hydroxide of 2.5, fine and coarse aggregate of 603 kg/m^3 and 911 kg/m^3, SP of 4 kg/m^3, extra water of 52 kg/m^3, and ratio of the alkali solution/binder of 0.65 to get M50 grade of GPC with compressive strength not less than 50 MPa. The alkaline liquid used in this study was a combination of sodium hydroxide (SH) and sodium silicate (SS). After placing the water in a container (48 kg/m^3), sodium hydroxide is weighed (35 kg/m^3) and added to the water to achieve the appropriate molarity (13 M) in the presence of the molecular weight of NaOH to be its sum (83kg/m^3) as a solution material. As the sodium hydroxide pellets dissolve in the water, they release heat. After sodium hydroxide was added and cooled, sodium silicate was added. Table (9) shows these trials and the optimum mix proportion at seven days with the curing condition at an average temperature of 46°C in the day and 29°C at night until the test age to produce GPC with a compressive strength of 58.0 MPa.

Table 9. Compressive strength of geopolymer concrete at seven days of age

Mix No.	Variables	MK*	SF	CaO	CA*	FA*	SS*	SH*	SP*	W*	Compressive strength (MPa)
		(kg/m^3)									
M1	SH=12, SS/SH=2.5, AL/B= 0.55	372	21	21	955	632	162	71	8.3	85	33.4
M 2	SH=12, SS/SH=3, AL/B= 0.65	372	21	21	912	603	201	74	4	50	43.4
M 3	SH=12, SS/SH=3.5, AL/B= 0.75	372	21	21	870	575	241	75	4	28	44.0
M 4	SH=13, SS/SH=2.5, AL/B= 0.65	372	21	21	911	603	192	83	4	52	58.0
M 5	SH=13, SS/SH=3, AL/B= 0.75	372	21	21	869	575	232	84	4	30	57.3
M 6	SH=13, SS/SH=3.5, AL/B= 0.55	372	21	21	956	633	176	57	8.3	66	53.1
M 7	SH=14, SS/SH=2.5, AL/B= 0.75	372	21	21	868	574	221	95	4	32	57.0
M 8	SH=14, SS/SH=3, AL/B= 0.55	372	21	21	956	632	170	63	8.3	85	53.5
M 9	SH=14, SS/SH=3.5, AL/B= 0.65	372	21	21	913	604	209	66	4	54	57.4
R	SH=12, SS/SH=2.5, AL/B=0.55	414	--	--	911	574	193	83	4.8	50	44.4

* MK: Metakaolin, SF: Silica foam, Cao: Calcium oxide, CA: Coarse aggregate, FA: Fine aggregate, SS: Sodium silicate, SH: Sodium hydroxide, SP: Superplasticizer, W: Water, Al/B: Alkaline solution/binder.

2.3 Sample Preparation and Processing Methodology

The process of mixing and preparing GPC specimens can be summarized as follows:

- Water was used to wet the electric rotating mixer, which had a 0.1 m^3 capacity.
- Calcium oxide, silica fume, and metakaolin were manually blended for two minutes.
- Dry materials, including modified metakaolin, natural fine aggregate, natural coarse aggregate for the reference mixture without wastes and crumbed rubber as a replacement to natural coarse aggregate by volume of 10, 20, and 25% for other mixes, were blended for two minutes in the mixer.
- During the mixer's rotation, the alkaline solution was added, and the mixer continued to mix all the ingredients for three minutes.
- The superplasticizer and extra water were gradually added to the mixture.
- The mixing process was stopped for one minute to give the mixture time to rest and clean the mixer arms, and then it was restarted for one minute. The total mixing duration was between 9 and 10 minutes.

Because geopolymer mixtures are more viscous than cementitious concrete, they need greater care during mixing, handling, casting, and compaction. The interior surfaces of the moulds were coated with grease to prevent concrete from sticking to the surfaces of the mould. After levelling the top surfaces of the GPC specimens, they were covered with nylon sheets and left in the laboratory for 24 hours. Then, the moulds of different sizes, based on various test methods, were opened and cured in the summer season at a temperature range of 46 °C during the day and 29 °C at night.

3. Results and Discussion

Initially, the selected crumbed rubber waste aggregate (CRWA) content as a volumetric replacement to natural coarse aggregate was 10, 20, and 30% in the geopolymeric concrete mix. Since the compressive strength of geopolymer concrete, which contains 30% replacement content of rubber waste aggregate, dropped to 15.6 MPa, the replacement percentage to a maximum value of 25% was selected to maintain an acceptable compressive strength value. Coarse aggregate is an important indicator of concrete strength. Therefore, recycled crumb rubber waste aggregate from damaged tires was substituted for natural coarse aggregate at 0, 10, 20, and 25% in the geopolymer concrete mixture in this study.

3.1 Fresh Properties

3.*1.1 Workability*

The slump test was used to determine the workability and consistency of concrete in accordance with ASTM C143 [29]. Figure 2 shows the slump value findings for the reference geopolymer concrete without wastes and geopolymer concrete with crumbed rubber waste aggregate with different proportions to replace the natural coarse aggregate of 10, 20, and 25% by volume. The slump decreased as the amount of crumbed rubber used to replace natural coarse aggregate in the geopolymer concrete mixtures increased. Compared with the reference mix, the slump values of the geopolymer concrete containing rubber waste aggregate decreased by 5.56%, 8.34%, and 11.11% for (CRWA) contents of 10, 20, and 25%, respectively. This decrease in the slump may be explained by the mechanically shredded crumb rubber having a rough surface and texture. As a result, there was an increase in the interparticle friction between the crumb rubber particles and the other geopolymer concrete components [30]. Additionally, the rough texture of the rubber surface may need more water to fill the void than natural aggregate with less rough surfaces. In addition, the higher absorption of rubber with respect to natural aggregate was cited by Su Haolin [31].

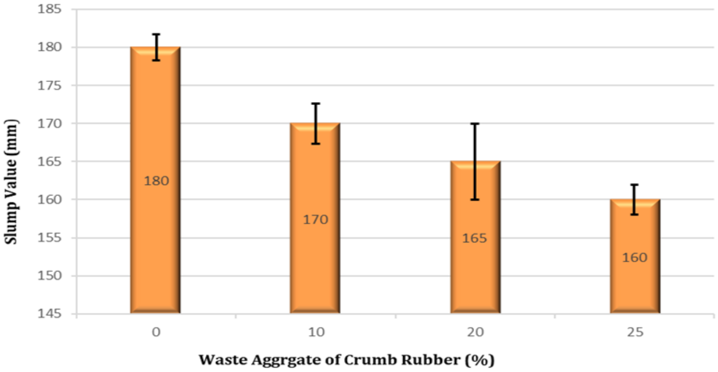


Fig. 2. Effect of crumb rubber content as a replacement to coarse aggregate on the workability of geopolymer concrete

3.1.2 Fresh Density

The fresh density of GPC was determined directly after mixing according to ASTM C138 [32]. The data in Figure 3 illustrate that using 10%, 20%, and 25% crumbed rubber waste aggregate as a volume substitute for natural coarse aggregate reduces the fresh density of geopolymer concrete. The reference mix not containing CRWA has a higher density than all GPC mixes with different contents of CRWA. The fresh density for GPC with CRWA was decreased by 2.0%, 2.6%, and 4.0% for 10, 20, and 25% crumb rubber aggregate content, respectively. This is because of the low specific gravity of the rubber waste, which is 1.1, while for natural coarse aggregate, the specific gravity is 2.62 [33,34]. Siddique and Naik reported similar findings about the density of rubber concrete [35]. They hypothesized that since rubber particles are nonpolar in nature, they may have the capacity to deflect the flow of water and entrap air on the surface of the rubber. This would lead to an increase in the number of air voids and cause a reduction in the density of the geopolymer concrete.

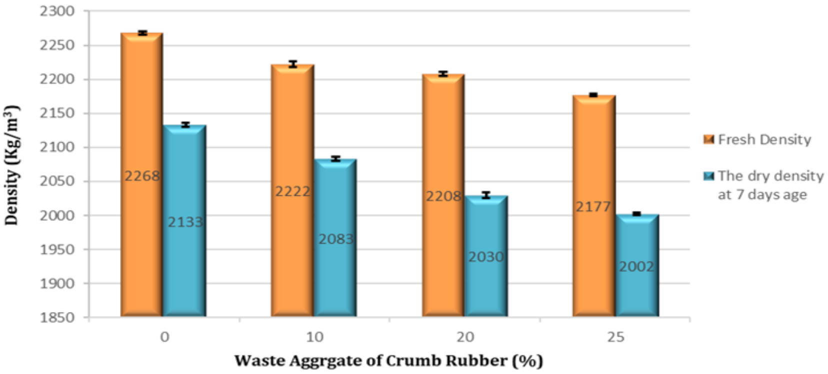


Fig. 3. Effect of crumb rubber content as a replacement to coarse aggregate on the density of geopolymer concrete

3.2 Hardened Properties

3.2.1 Dry Density

The oven dry density of GPC was determined according to ASTM C642[36]. Figure 3 shows a decrease in geopolymer concrete dry density at seven days of age as CRWA content increases. This is attributed to the lower specific gravity of crumbed rubber waste aggregate (1.1) than the specific gravity of natural coarse aggregates (2.62).

3.2.2 Compressive Strength

The compressive strength is the most significant indicator when assessing geopolymer concrete. The compressive strength of every mixture was determined using the average of three cubic samples with dimensions of 100×100 mm according to BS1881:part116. Compressive strength data for different GPC mixtures at seven days of age are shown in Table (10) and Figure 4.

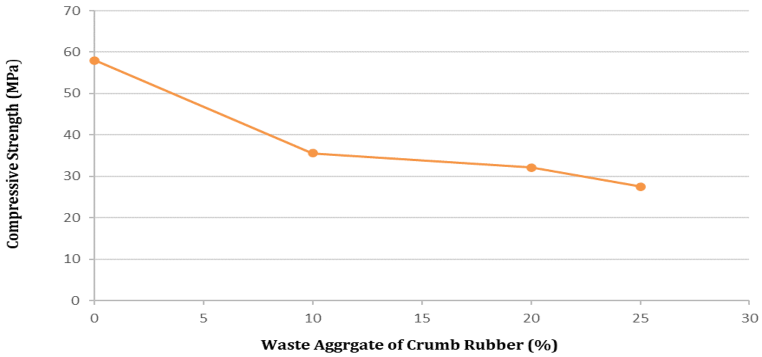


Fig. 4. Influence of crumbed rubber waste aggregate on the compressive strength of geopolymer concrete

Table 10. Mechanical properties of different geopolymer concrete mixtures

Mix Symbol	Comp. Strength (MPa)	Change Perc. in Comp. Strength (%)	Splitting Tensile Strength (MPa)	Change Perc. in Splitting Tensile Strength (%)	Flexural Strength (MPa)	Change Perc. in Flexura Strength (%)	Absorption (%)	Change Perc. In absorption (%)
R	58	--	3.3	--	4	--	4.99	--
10%T	35.6	- 38.6	2.95	-10.6	3.75	- 6.25	5.07	+ 1.60
20%T	32.1	-44.6	2.8	-15.2	3.49	- 12.75	5.62	+ 12.6
25%T	27.5	- 52.6	2. 6	-21.2	3.34	- 16.5	6.23	+ 24.8

Most of the reasons behind the negative effect on the mechanical properties of geopolymer concrete are (1) the large difference in modulus of elasticity between natural aggregate and CRWA, resulting in a large incompatibility between geopolymer paste and CRWA; (2) the weak bond between the rubber aggregate and geopolymer paste, resulting in the formation of weak areas in the interfacial transition zone (3), the CRWA has an inhomogeneous distribution due to its low weight relative to the natural aggregate, which causes inhomogeneity due to compaction. (4) the water-repellent property of the CRWA, which leads to the trapping of air bubbles within the mixture and the creation of weak zones, loss of stiffness owing to the inclusions of crumb rubber waste aggregate, and lower density as the crumbed rubber content increased [7,31,37]. All these factors contribute to the loss of the mechanical properties of geopolymer concrete containing crumbed rubber waste aggregate.

3.2.3 Ultrasonic Pulse Velocity

The UPV test is used to assess the uniformity, quality, and existence of voids in geopolymer concrete using the average of three cubic specimens 100 mm according to ASTM C 597 [38]. Figure 5 depicts the relationship between ultrasonic pulse velocity and varying proportions of CRWA. According to this Figure, the pulse transmission of the investigated specimens decreases linearly as the content of CRWA increases. Incorporating crumb rubber waste aggregate by 10%, 20%, and 25% reduces the UPV results to 8.8%, 17.4% and 19.7% at 7 days of age, respectively.

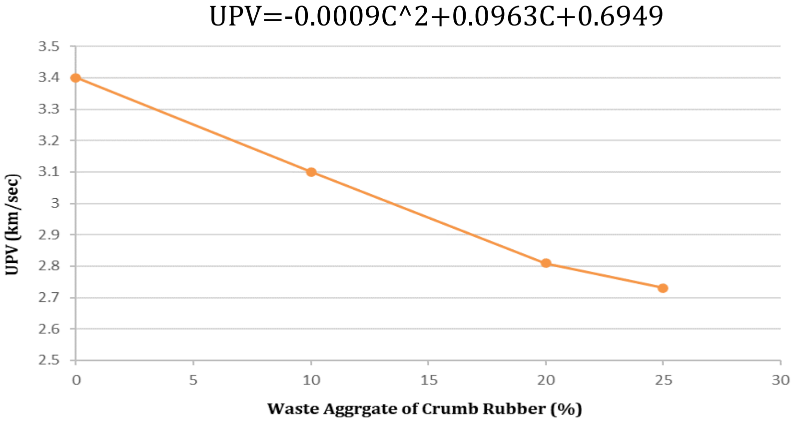


Fig. 5. Effect of crumb rubber waste aggregate recycling on the upv of geopolymer concrete

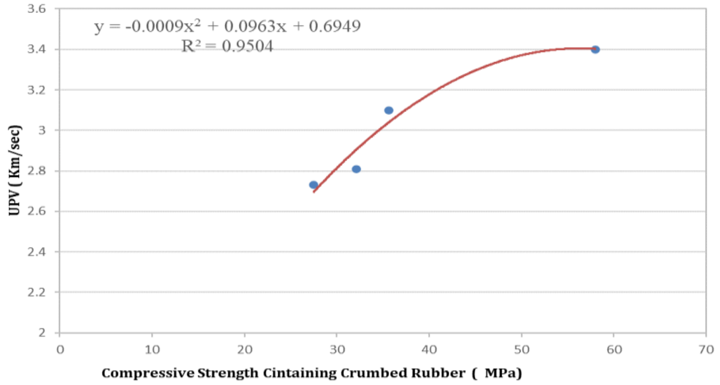


Fig. 6. The Relationship between the Compressive Strength and UPV for GPC with Crumbed Rubber Waste Aggregate

This reduction is attributed to the porous structure of geopolymer concrete containing rubber and the lower wave conductivity of rubber compared to natural aggregate, thus delaying the time required for waves to travel through the geopolymer concrete matrix

[39,40]. There is a strong correlation with R2=0.9504 between the compressive strength (C) of geopolymer concrete containing crumbed rubber waste aggregate and the ultrasonic pulse velocity (UPV), as shown in Figure 6. The following equation can illustrate these two essential properties:

3.2.4 Splitting Tensile Strength

Figure 7 and Table (10) display the results of the splitting tensile strength for different geopolymer concrete mixtures at seven days of age using the average of three cylindrical specimens 100 mm in diameter and 200 mm in height according to ASTM C 496[41]. The results illustrate that the splitting tensile strength for GPC decreases by about 10.6%, 15.2%, and 21.2% for GPC with 10%, 20%, and 25% CRWA, respectively. This is due to the reduction in the bond between the geopolymer matrix and rubber aggregate surfaces and the low stiffness of the CRWA compared with the natural coarse aggregate [33,42,43].

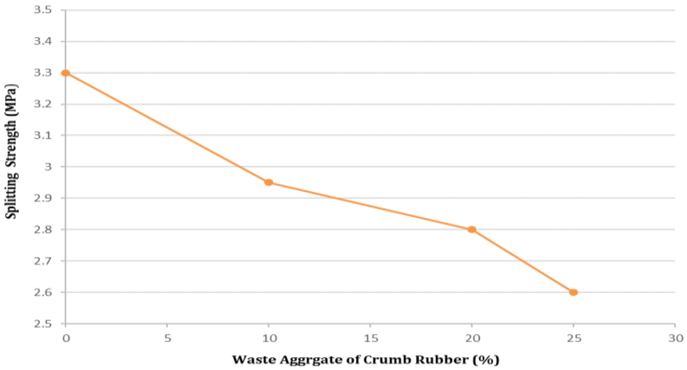


Fig. 7. Effect of recycled crumb rubber waste aggregate on the splitting tensile strength of geopolymer concrete

3.2.5 Flexural Strength

The flexural strength of every mixture at seven days of age was determined using the average of three prismatic samples with dimensions of 100*100*400 mm according to ASTM C 78 [44]. The results of GPC without and with different contents of crumbed rubber waste aggregate are shown in Figure 8 and Table (10).

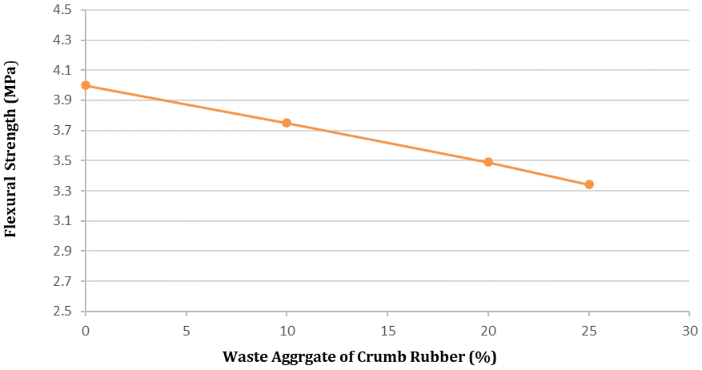


Fig. 8. Influence of crumb rubber waste aggregate recycling on the flexural strength of geopolymer concrete

The flexural strength of GPC decreases marginally, with crumb rubber aggregate waste increasing the flexural tensile strength decreased by 6.25%, 12.75% and 16.5% for the10%, 20% and 25% crumb rubber substitutions, respectively. The reason for the low flexural strength is due to the weak bond strength between the rubber surface and the geopolymer paste and as a result of the high Poisson's ratio, which is approximately 0.5, and the low stiffness of rubber compared to natural coarse aggregate [33,45]. The high value of Poisson's ratio gives a clear indication that as soon as internal tensile stresses occur in the concrete, the rubber will compress in the perpendicular direction to those stresses faster than the concrete itself and the aggregates and thus increase the bond failure [46,47].

3.2.6 Water Absorption

Table (10) shows the water absorption capability of different GPC mixes with or without crumb rubber waste aggregate at seven days of age. The average of three cubic specimens 100 mm in size was used according to ASTM C 642[36]. It can be concluded that the water-absorption capacity of rubberized geopolymer concrete increases with increasing crumb rubber content. This is because the number and size of voids in the geopolymeric concrete microstructure increased [48]. The evaporation of water content and the lower degree of mix compaction due to the light weight of rubber lead to the formation of more voids in the interfacial transition zone between the geopolymer matrix and the rubber waste aggregate compared with the geopolymer concrete mix not containing crumbed rubber waste aggregate. All concrete mixes have a water absorption rate of less than 10%, considered good concrete [49].

3.2.7 Permeability (Depth of Penetration Water Under Pressure)

Water penetration was applied according to BSEN12390-8:2000[50] on cubic geopolymer concrete specimens (150 mm) under pressures of 500-+50 kPa for 72-+2 hr. The permeability results for geopolymer concrete mixes at seven days of age, including crumb rubber waste aggregate, are shown in Figure 9.

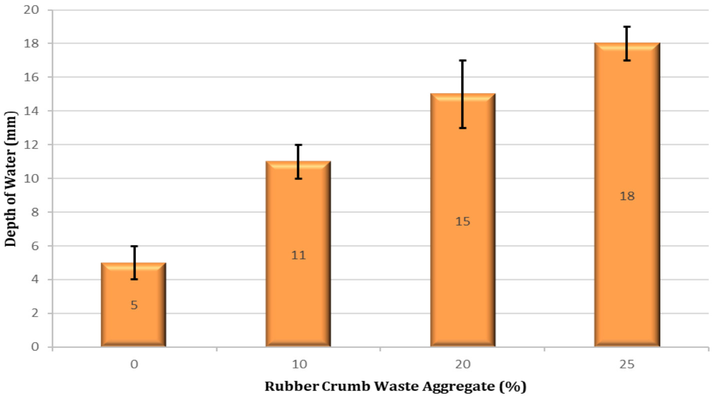


Fig. 9. Effect of crumb rubber waste aggregate recycling on the permeability of geopolymer concrete

It can be shown that the inclusion of crumb rubber waste increases the water penetration depth from 5 mm for the reference mix without rubber waste to 11, 15, and 18 mm for GPC with crumb rubber waste aggregate as a substitute for the natural coarse aggregate of 10, 20, and 25%, respectively. The detrimental effect created by the inclusion of rubber waste is due to the initiation of more pores and microcracks in the microstructure of the geopolymer matrix. The increase in pores is due to the poor workability of the mixtures containing a larger volume fraction of rubber waste, which made the compaction process difficult and caused low bonding between the geopolymer matrix and rubber, thus producing more voids in the interfacial transition zone between the geopolymer matrix and the surfaces of the crumbed rubber waste aggregate and increasing the permeability of the geopolymer concrete [33,51]. In all cases, the average water penetration depth is less than 50 mm (5-18 mm) for all specimens, consistent with what was mentioned by Skutnik [52]; therefore, the geopolymer concrete tested is considered impermeable.

3.2.8 Thermal Conductivity

The thermal conductivity of any material is influenced by a wide variety of characteristics, such as its structure, the elements' proportion in the mixture, the aggregate type, density, and porosity [53]. Previous studies have shown that the type of aggregate has a significant impact on the thermal conductivity of the material [54]. According to ASTM C1113[55], the average thermal conductivity of three 100 mm cubic samples was determined. Figure 10 shows the experimental thermal conductivity values for the geopolymer concrete with different crumbed rubber waste aggregate contents measured under dry conditions at seven days of age. It has been discovered that including rubber particles in a geopolymer concrete matrix decreases the heat conductivity of geopolymer concretes. The values declined from 0.9229 W/m. K for the reference mix without rubber waste to 0.6153 W/m. K for a specimen with 25% rubber particles as a volume substitute for natural coarse aggregate with a reduction of 33.3% relative to the reference GPC. The reduction in the heat conductivity of the composite is due to the insulating effect of the rubber particles, which have lower thermal conductivity than the geopolymer matrix and natural coarse aggregate [56].

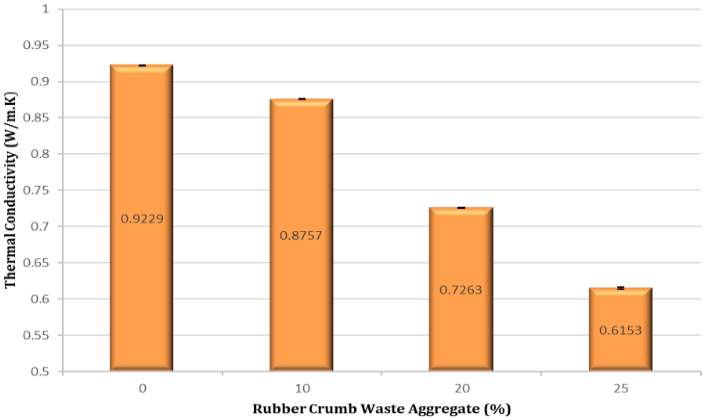
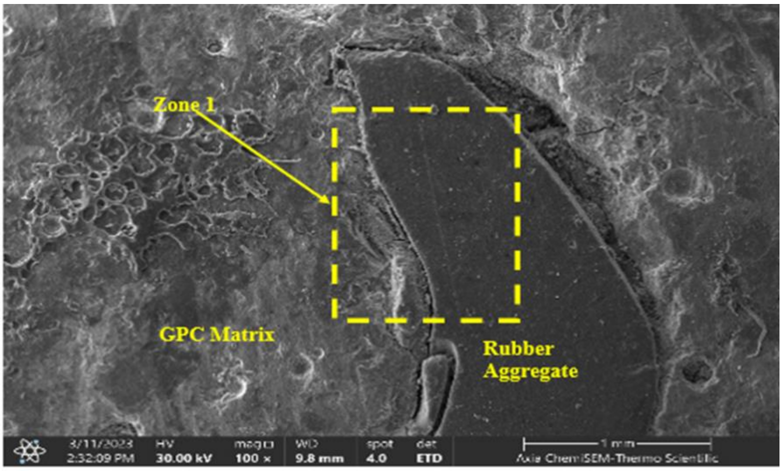


Fig. 10. Effect of the crumbed rubber waste aggregate content on the thermal conductivity of geopolymer concrete

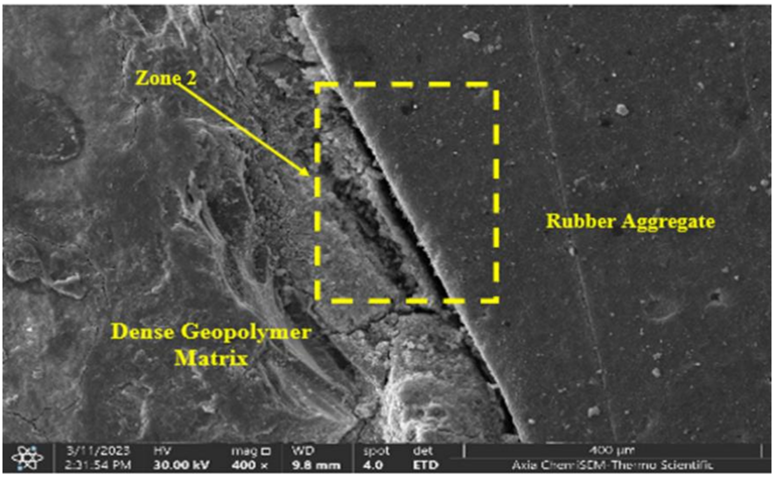
3.2.9 SEM for GPC with Crumbed Rubber Waste Aggregate

A compacted dense geopolymer paste with tiny holes and a limited number of microcracks is observed in the GPC microstructure with 10% crumbed rubber waste aggregate, as illustrated in Figure 11. The microscopic images with different magnifications show a weak bond between the geopolymer matrix and the rubber waste aggregate particle. It is clear from these images that there is a continuous gap between the geopolymer matrix and the rubber waste aggregate. This enhances the experimental results obtained in this investigation, including the reduction in the strength and thermal conductivity and the increase in the water absorption and permeability of GPC-containing crumbed rubber waste aggregate.

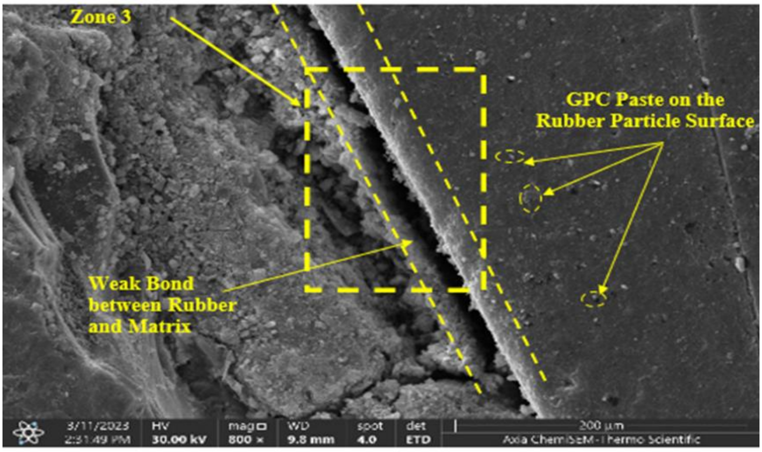
However, Figure 12 (a-f) show various (6) microscopic scales of the SEM micrographs of the fracture surface of hardened GPC specimens with natural coarse aggregate. The GPC matrix in Figure 12 (GPC without wastes) has a fairly uniform distribution of well-adhered aggregates; in contrast, Figure 11 (GPC with rubber) exhibits less uniformity and slightly more pore matrices with wider cracks. This is to be anticipated since the addition of CRWA often decreases concrete's mechanical strengths [7,57,58]. At increased magnification, the aggregate/matrix interaction may be seen in more detail in Figure 11 and 12 (d, e, f). It can be seen that cracks propagated throughout the microstructure of the samples. However, GPC without wastes exhibited fewer and narrower fractures, while GPC with rubber had greater propagation and broader cracks.



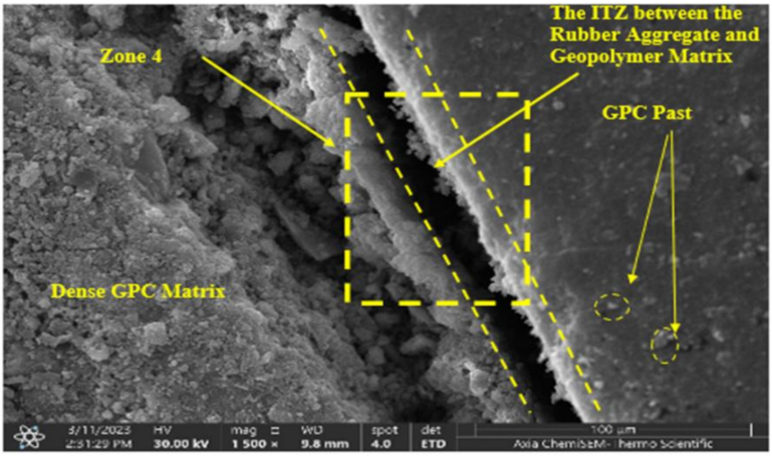
a- SEM for GPC with Crumbed Rubber waste Aggregate



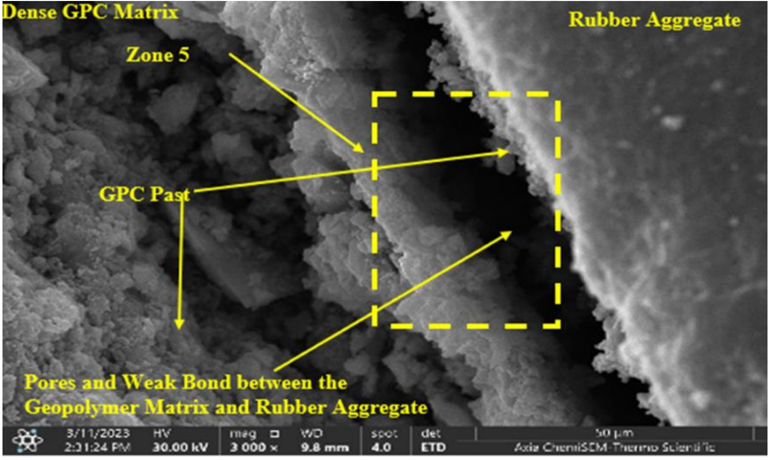
b- SEM for GPC with Crumbed Rubber waste Aggregate (Zone 1)



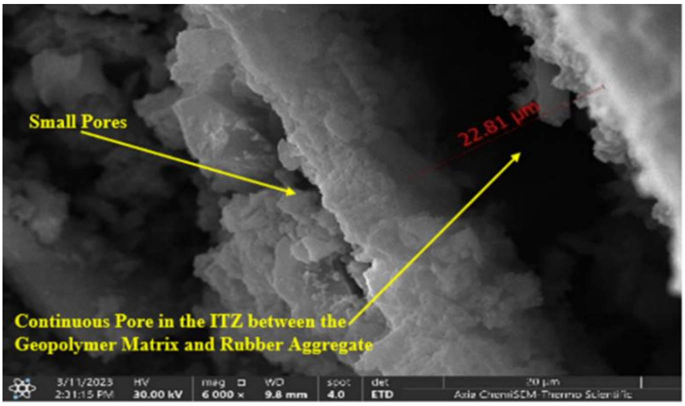
c- SEM for GPC with Crumbed Rubber waste Aggregate (Zone 2)



d- SEM for GPC with Crumbed Rubber waste Aggregate (Zone 3)

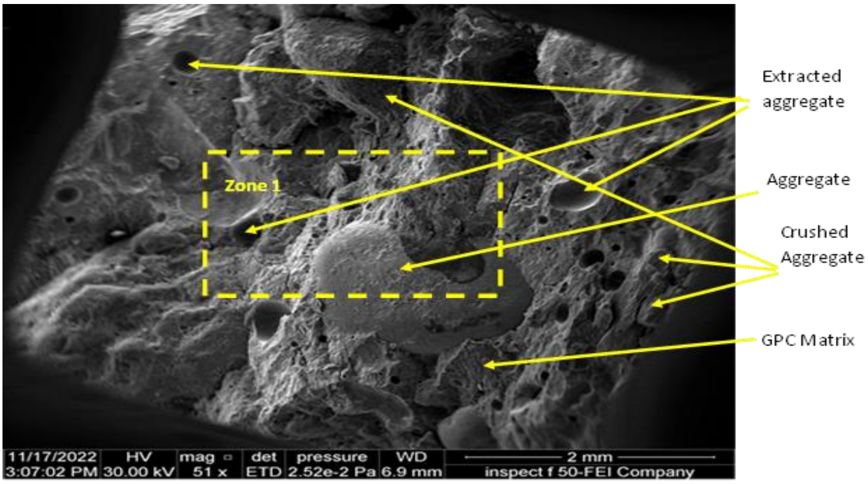


e- SEM for GPC with Crumbed Rubber waste Aggregate (Zone 4)

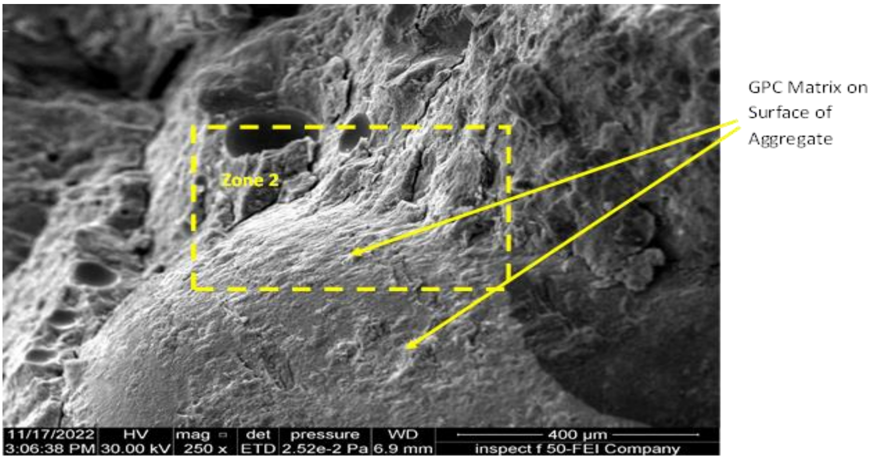


f- SEM for GPC with Crumbed Rubber waste Aggregate (Zone 5)

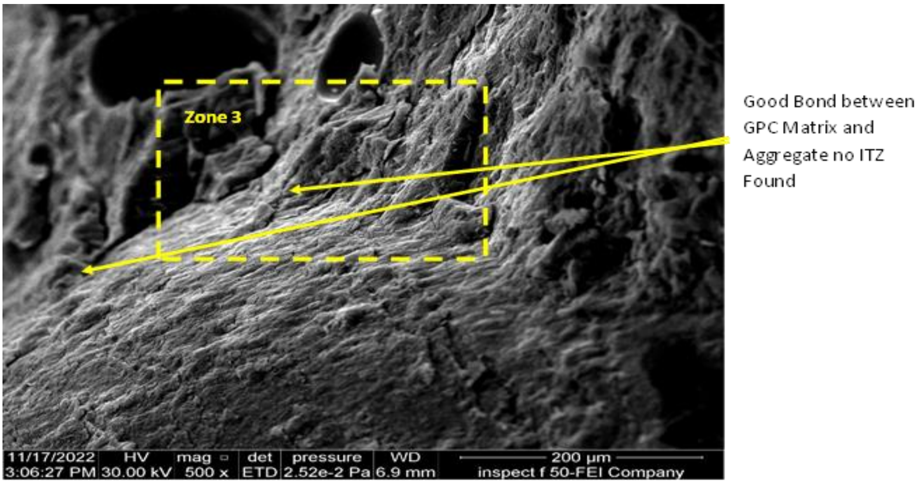
Fig. 11. (a-f) SEM images for GPC containing 10% crumbed rubber waste aggregate with different magnifications



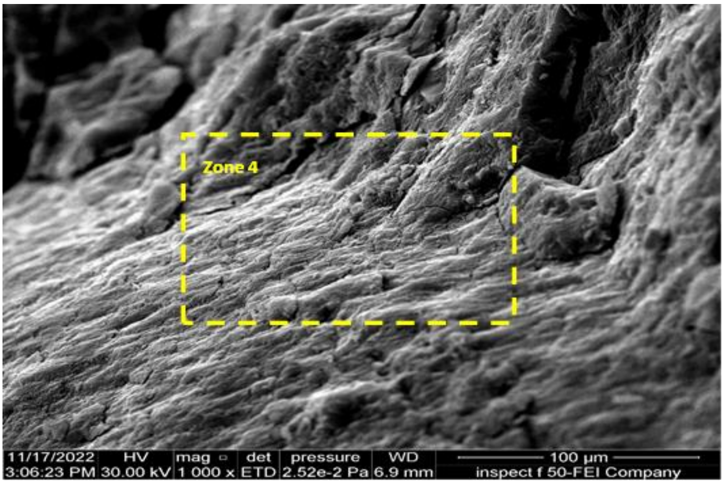
a-SEM for GPC with natural coarse aggregate



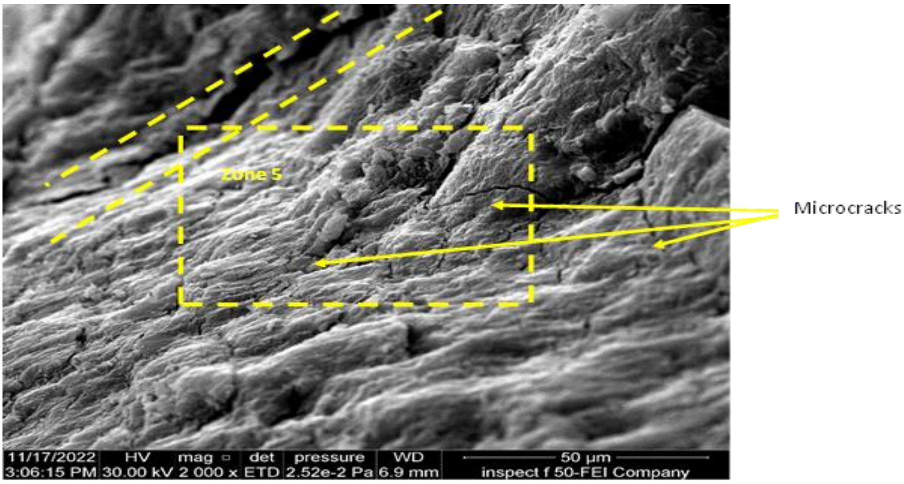
b- SEM image of GPC with natural coarse aggregate (Zone 1)



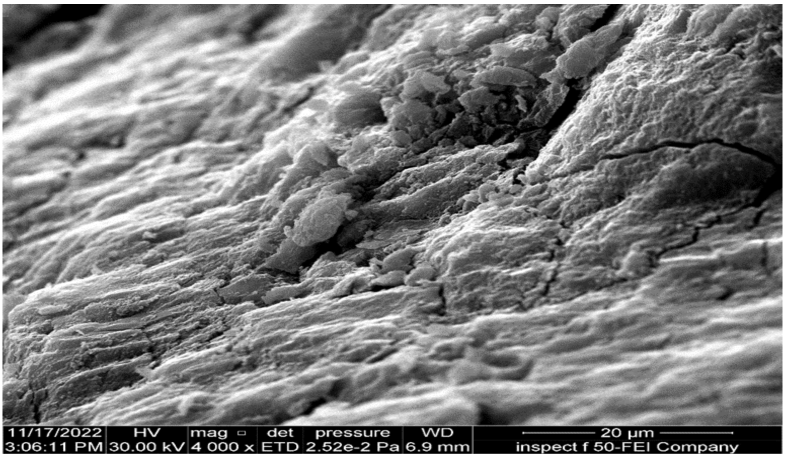
c- SEM image of GPC with natural coarse aggregate (Zone 2)



d- SEM image of GPC with natural coarse aggregate (Zone 3)



e-SEM image of GPC with natural coarse aggregate (Zone 4)



f- SEM image of GPC with natural coarse aggregate (Zone 5)

Fig. 12 (a-f) SEM images for GPC without waste aggregate with different magnifications

The interfacial transition zone (ITZ) can be observed in the geopolymer concrete with 10% rubber, while this distance is unclear in the geopolymer concrete without rubber. The lack of clarity of the ITZ of geopolymer concrete is probably due to the limited use of water in geopolymer concrete compared to cement concrete[57,59].

4. Conclusions

In addition to not utilizing cement in the concrete industry, GPC with CRWA reduces carbon dioxide emissions, energy consumption, and natural resource preservation. Furthermore, based on the findings and experimental work reported in this study, the following conclusions may be drawn:

- The fresh and dry densities of modified metakaolin-based GPC decreased when natural coarse aggregate was replaced with crumb rubber waste. This will be beneficial in reducing the weight of concrete (dead load) on the load-bearing concrete members, which is reflected positively in the design of concrete sections.
- Using coarse aggregates from rubber waste substantially reduces the compressive strength of geopolymer concrete. The compressive strength of geopolymer concrete specimens containing 10, 20, and 25% rubber waste coarse aggregate decreases by 38.6%, 44.6%, and 52.6%, respectively, compared to concrete specimens without rubber waste. In addition to reducing splitting and flexural strengths, the maximum reductions in splitting and flexural strengths are 21.2% and 16.5% for geopolymer concrete specimens containing 25% CRWA, respectively. Despite the decrease in the mechanical properties, geopolymer concrete produced in this investigation with 10% and 20% crumbed rubber waste aggregate (CRWA) can be used in different structural applications with compressive strengths of 35.6 MPa and 32 MPa, respectively. Geopolymer concrete with 25% CRWA can be used for non-structural purposes.
- The inclusion of rubber waste as coarse aggregate in geopolymer concrete increases the water absorption of geopolymer concrete compared with the reference GPC without wastes. However, the average water penetration depth was less than 50 mm (11–18 mm) for all of the tested geopolymer concrete specimens. This means that the geopolymer concrete is considered to be impermeable.

- The thermal conductivity and ultrasonic pulse velocity decrease significantly as the rubber waste aggregate content increases.
- The microscopic images for geopolymer concrete containing crumbed rubber waste aggregate enhance the experimental results obtained in this study in terms of strength reduction, thermal conductivity reduction, and the increase in water absorption and permeability.

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