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Properties of modified metakaolin-based geopolymer concrete with two types of waste aggregate

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HIGHLIGHTS

- A sustainable metakaolin-based geopolymer concrete was developed with crumb rubber and plastic waste.
- Sustainability was achieved by using cement-free GPC that reused tire and plastic waste.
- Enhancement the binder by replacing 5% of metakaolin with calcium oxide and silica fume by weight.
- Recycled materials (10% crumb rubber, plastic waste) reduced strength: compressive 25–34%, tensile 17–41%, and modulus of elasticity by 10 and 33%

Keywords:
Crumbed rubber
Geopolymer concrete
Modified metakaolin
Shredded plastic
Recycled aggregate

ABSTRACT

The widespread use of cement in construction contributes significantly to carbon dioxide (CO_2) emissions, creating an urgent need for environmentally friendly alternatives. Geopolymer concrete (GPC), which contains no cement, offers a sustainable solution. The focus is on developing a modified metakaolin-based GPC that incorporates recycled materials to improve sustainability while assessing its mechanical and durability properties. The research involved enhancing the binder by replacing 5% of metakaolin with calcium oxide and silica fume by weight. Additionally, to reduce environmental impact, 10% of the natural coarse aggregate volume was substituted with crumb rubber and shredded plastic waste. A detailed mix design was conducted using specific proportions of materials, including metakaolin, coarse aggregates, fine aggregate, sodium hydroxide, sodium silicate, water, and superplasticizer in particular proportions (372, 910, 603, 83, 192, 7, and 56 kg/m³, respectively). The study evaluated mechanical properties, including compressive strength, splitting tensile strength, and modulus of elasticity, alongside durability metrics such as water absorption, permeability, abrasion resistance, and shrinkage. The incorporation of recycled materials, including 10% crumbed rubber and plastic waste aggregate, resulted in performance reductions, with compressive strength decreasing by 25 and 34%, tensile strength by 17 and 41%, and modulus of elasticity by 10 and 33%, respectively. Despite some declines in performance, the modified geopolymer concrete demonstrated improved permeability, abrasion resistance, and shrinkage while remaining within acceptable limits. Microstructural analyses confirmed the beneficial effects of recycled materials on matrix integrity. The findings support the use of geopolymer concrete as a sustainable, low-carbon construction material.

1. Introduction

Over the last fifty years, ordinary Portland cement (OPC) concrete has become the most widely used construction material worldwide, with its consumption increasing at a rate that exceeds population growth. However, the production of OPC is energy-intensive, heavily dependent on fossil fuels, and generates significant CO_2 emissions [1]. These environmental issues have prompted the construction sector to seek sustainable alternatives that support global initiatives aimed at reducing greenhouse gas emissions and enhancing energy efficiency. In this regard, geopolymer cement and concrete have emerged as viable substitutes, offering the potential to significantly lower the environmental impact associated with construction materials [2,3]. In particular, geopolymers are created from precursors rich in aluminosilicates, such as metakaolin, fly ash, and slag, and are activated using alkaline solutions. These binders not only exhibit enhanced durability and chemical resistance but also facilitate the incorporation of various industrial and post-consumer waste materials. Additionally, the integration of waste products, particularly discarded tires and plastics, addresses two pressing issues: the ecological burden of concrete production and the environmental hazards of improper solid waste disposal [4,5]. To this end, numerous studies have demonstrated the feasibility of using waste-derived materials in geopolymer concretes. For example, Kurek [6], investigated the effects of substituting sand with rubber granules from end-of-life tires (0.0–0.8 mm and 1–4 mm) at replacement levels of 12.5 and 25%. Although the addition of rubber reduced abrasion resistance, it improved compressive strength at the 25% substitution level, indicating its potential to conserve natural

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aggregates and enhance sustainability. Moreover, numerous studies have shown the practicality of using waste-derived materials in geopolymer binders. For instance, the feasibility of replacing natural aggregates with rubber and plastic wastes in cementitious and geopolymer matrices was examined. Similarly, Katti et al. [7], examined the use of high-density polyethylene (HDPE) plastic granules as partial or full replacements for fine aggregate in GGBS-based geopolymer concrete. Using alkaline activators of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) at concentrations of 1.5 and 6 M, they tested six mixtures, including (0, 20, 40, 60, 80, and 100% plastic substitution) for compressive and tensile strengths over 7–28 days. Their results showed that replacing cement entirely with GGBS in a six-molar alkaline solution produced high early-strength geopolymer concrete. Moreover, a blend of sand and plastic granules at a 40:60 ratio delivered the most effective performance, demonstrating the practicality of integrating plastic waste into geopolymer matrices. Furthermore, Al Obeidy and Khalil [8], investigated the use of crumbed rubber waste aggregate (CRWA) in geopolymer concrete (GPC) as a partial volumetric replacement, replacing natural coarse aggregate at varying percentages (0, 10, 20, and 25%). The rubber was processed to match the gradation of natural aggregate, and metakaolin (MK) was modified with 5% calcium oxide and 5% silica fume. The experimental results showed that increasing the CRWA content reduces compressive, splitting tensile, and flexural strengths. However, GPC with CRWA offers benefits such as no water curing, rapid early strength development, and improved thermal properties, including lower thermal conductivity and dry density compared to conventional GPC (without CRWA). In addition, Hassan et al. [9], proposed a sustainable approach for reusing waste tires in construction by partially substituting Portland cement with geopolymer concrete (GPC) and incorporating crumb rubber (CR) as a partial replacement for natural aggregates.

The geopolymer concrete mixtures, including crumb rubber geopolymer concrete (CRGPC), were formulated using fly ash, alkaline solutions (sodium hydroxide and sodium silicate), riverbed sand, broken stone, crumb rubber, ground granulated blast furnace slag (GGBFS), a superplasticizing additive, and tap water. Two types of CRGPC mixtures were developed, namely, untreated and pretreated. For the pre-treatment process, crumb rubber was soaked in a sodium hydroxide solution for 24 hours and then air-dried before being incorporated into the mix. The study evaluated the mechanical properties of the developed mixtures, including compressive strength, stress–strain behavior, and elastic modulus, and compared the results with existing material models. The findings indicated that increasing the crumb rubber content resulted in a reduction in both compressive strength and elastic modulus. Notably, a 33% reduction in compressive strength was observed when 25% of the fine aggregate was replaced with crumb rubber. However, the pretreatment of rubber particles was found to mitigate these reductions to some extent. Furthermore, stress–strain models for both GPC and CRGPC were developed and proposed.

After surveying the literature, it becomes clear that most existing studies on GPC have focused on incorporating individual types of waste aggregates. Despite the increasing interest in sustainable construction materials, the existing research on GPC remains largely disjointed and lacking, especially regarding the simultaneous use of various types of waste aggregates. More precisely, most current studies have focused on rubber or plastic waste individually, overlooking the potential advantages or difficulties that may arise from their combination as partial substitutes for natural coarse aggregates. This issue creates a significant gap in research, particularly in light of the urgent global need to minimize environmental pollution and preserve natural resources. To alleviate this problem, this study directly addresses that gap by pioneering the joint use of crumb rubber and plastic waste in geopolymer concrete, utilizing Iraqi metakaolin modified with silica fume and calcium oxide to enhance the performance of the binder. In particular, the research provides an in-depth examination of how these waste materials influence the mechanical strength, elastic properties, and durability of GPC, focusing on aspects such as compressive and tensile strength, modulus of elasticity, permeability, abrasion resistance, and shrinkage. Furthermore, advanced scanning electron microscopy (SEM) is used to uncover essential microstructural details and the interaction between the binder and the waste particles. By integrating multiple waste materials into an optimized binder matrix, this study presents a groundbreaking and highly sustainable concrete alternative that not only addresses environmental issues but also surpasses the current performance standards of conventional materials. The results are expected to establish crucial benchmarks for future design protocols and the standardization of geopolymer concrete technologies worldwide. Additionally, a key objective of this research is to develop geopolymer concrete that meets established structural performance standards, thereby making it suitable for real-world engineering applications.

2. Experimental work

2.1 Materials

Kaolin clay was heated to 700 degrees Celsius for two hours to convert it into metakaolin, which was then ground to conform to the American Standard ASTM C618 [10], as a natural pozzolanic material, class N. It was used as a source of aluminum and silica for the production of geopolymer concrete. Tables 1 and 2 present metakaolin's physical and chemical properties, respectively.

Table 1: Physical properties of metakaolin

Physical properties	MK	Requirements of ASTM C 618, [10]
Strength activity index at 7 days, (%)	113	≥75%
Retained on 45 µm, (%)	18.5	≤34%
Specific surface area (m^2/kg)	14300	--
Specific gravity	2.64	--
Color	White –pinky powder	--

Table 2: Chemical properties of metakaolin

Oxide composition	Weight (%)	Requirements of ASTM C 618, [10]
SiO_2	62.410	$SiO_2+Al_2O_3+Fe_2O_3=98.327\geq70$
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 was used as an activator in the manufacturing process of geopolymer concrete. More specifically, it was prepared from 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 4.75 mm. The sieve analysis and fine aggregate characteristics are presented in Table 3, which adheres to Iraqi Standard No. 45/2016, gradation zone No. 2 [11]. Additionally, crushed gravel with a maximum size of 10 mm was utilized in this research as a natural coarse aggregate. The sieve analysis and characteristics of the coarse aggregate are presented in Table 4, according to Iraqi Standard No. 45/2016 [10]. To dilute sodium hydroxide granules (with a molecular weight of 40.0 g/mol) to 13 molar, potable water was used, in addition to its property to improve workability in the plastic state, as extra water during mixing.

Table 3: Properties of fine aggregate

Sieve size (mm)	Cumulative passing (%)	Limits of IQS No. 45 for Zone II [11]
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	2.63	--
Bulk density (kg/m^3)	1744	--

Table 4: Properties of coarse aggregate

Sieve size (mm)	Cumulative passing (%)	Limits of IQS No. 45 [11]
10	97	85-100
4.75	12	0-25
2.36	--	0-5
Material passing from sieve 75 µm, (%)	0.3	≥3
Dry density (kg/m^3)	1627	--
Specific gravity	2.62	--
Absorption, (%)	0.6	--
SO_3, (%)	0.059	≤ 0.1

A high-performance water-reducing agent with the KUT PLAST SP 400 [12], was used. It is free from chlorides and complies with ASTM C494 [13], Type F. Table 5 lists its main properties. Silica fume from CONMIX Company [14], compatible with the American standard ASTM C 1240 [15], was also used in geopolymer concrete mixtures. Tables 6 and 7 present the physical and chemical properties of the silica fume used. The calcium oxide used in this investigation is from the Karbala cement mill in Al Noora. Table 8 illustrates the physical and chemical properties of calcium oxide.

In this study, two types of waste materials were utilized as volumetric replacements of coarse aggregate. The first one is crumbed rubber waste from tires, which was gathered, cleaned, and then sliced into various sizes, ranging from 0.3 mm to 18 mm. The Al-Diwaniyah facility provided this waste type for damaging vehicle tires in Iraq's Al-Diwaniyah governorate. The second type of waste consisted of plastic accumulated from various high-density polyethylene (HDPE) sources, including vegetable cartons, garbage cans, plastic jerrycans, shampoo and dishwasher cleaning bottles, and other similar items. The gathered plastic garbage has been cleaned before being crushed and reduced to tiny flaky bits resembling chips. Finally, the waste plastic particles were sorted by size, similar to the grading of natural coarse aggregate. To enhance the bond strength between the rubber particles and plastic waste surfaces and the geopolymer matrix, these particles were treated with a solution of 5% $Ca(OH)_2$ and water for 48 hours, as per previous studies [16-19]. Figure 1(a and b) shows the two types of waste aggregate used in geopolymer concrete, while Tables 9 and 10 illustrate the properties of the crumbed rubber and the mixed plastic waste aggregate, respectively.

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

Property	Description
Appearance	Dark brown liquids
Specific gravity	1.24-1.26 @20º
Chloride content	Nil
Recommended dosage	1.00-2.00 L/100 kg cementitious

*According to the manufacturer [12].

Table 6: Physical properties of silica fume

Property	Results	Requirements of ASTM C1240 [15]
State	Amorphous sub-micro powder	--
Strength activity index with Portland cement at 7 days, (%)	122	≥ 105
Retained on sieve 45 µm, max, (%)	9	≤ 10
Specific gravity	2.00 -2.40	--
Color	Grey to medium grey powder	--

Table 7: Chemical properties of silica fume

Oxide's composition	Results (%)	Requirement of ASTM C1240 [15]
SiO_2	88.593	≥85
Al_2O_3	--	--
Fe_2O_3	5.564	--
K_2O	4.777	--
TiO_2	--	--
CaO	0.666	--
SO_3	0.027	--
MnO	0.27	

Table 8: Properties of calcium oxide

Property	Results
Specific surface area (m^2/kg)	16350
Specific gravity	3.3
Color	White
Oxide's composition	**Results (%)**
SiO_2	4.314
Al_2O_3	--
Fe_2O_3	0.461
K_2O	1.667
TiO_2	--
CaO	93.40
SO_3	0.10
MnO	0.025

(a)

(b)

Figure 1: Waste aggregate a) crumbed rubber, b) mixed plastic

Table 9: Properties of crumbed rubber waste aggregate after preparation

Properties	Results	Specifications
Loose bulk density (kg/m^3)	--	ASTM C 29-15 [20]
Compacted bulk density (kg/m^3)	494	ASTM C 29-15 [20]
Specific gravity	1.10	ASTM C127-15 [21]
Water absorption (%)	4.8	ASTM C 127-15 [21]
Sieve analysis		
Sieve size (mm)	**Passing (%)**	**IQS No.45/2016 Limits for max. size (10 mm) [11]**
14	100	100
10	97	85-100
5	12	0-2

Table 10: Grading and physical properties of mixed plastic waste aggregate

Sieve size (mm)	Cumulative passing, %	Limits of IQS No. 45 [11]
20	100	100
14	95	90-100
10	60	50-85
5	3.5	0-10
Physical properties	**Values**	**Limits of IQS No. 45 [11]**
Absorption, (%)	0.00	-----
SO_3	Nil	≤0.1%
Thickness (mm)	Max.3	---
The particles range in shape from flaky to lamellar.		

2.2 Proportions of geopolymer concrete Mix

The initial geopolymer mixture was formulated using insights from a prior study [19]. Specifically, superplasticizer (SP), extra water, and mix proportion dosages were accurately calculated at the beginning. In particular, several test mixtures were prepared by varying the metakaolin base in GPC, partially replacing it with a mixture of silica fume and calcium oxide, and determining the optimal amounts of the other materials used in GPC production. Finally, the GPC mixture consisted of 372 kg/m³ of metakaolin, 54 kg/m³ of silica fume and calcium oxide, 13 molar sodium oxide, 2.5 sodium silicate/sodium hydroxide, and 603 kg/m³ and 911 kg/m³ of fine and coarse aggregate, respectively.

To produce GPC with a compressive strength of at least 50 MPa, the mix included an SP of 4 kg/m³, extra water of 56 kg/m³, and a ratio of the alkali solution to the binder of 0.65. The alkaline solution used in this study consisted of a mixture of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). This solution is prepared by placing the water in a container (50 kg/m³), weighing the sodium hydroxide (33 kg/m³), and adding it to the water to achieve the appropriate molarity (13 M) in the presence of the molecular weight of NaOH to be its sum (83 kg/m³) as a solution material. When the sodium hydroxide pellets were dissolved in water, they released heat. Therefore, it should be left for at least one hour before adding sodium silicate, and the solution should be prepared 24 hours in advance for use. Tables 11 and 12 present all the trials and the selected optimum mix proportion. In this context, GPC specimens can be cured by oven heating, sunlight exposure, or a combination of the two. Compared to other procedures, trial mixes have demonstrated that heating in an oven at 60 °C for 4 hours, followed by exposure to sunlight until the end of the testing period, produces the most outstanding results. This combination method guarantees the specimens' maximum strength.

Table 11: Compressive strength of geopolymer concrete at seven days of age

Mix No.	MK*	SF*	CaO	CA*	FA*	SS*	SH*	SP*	W*	Compressive strength (MPa) at 7days	Curing regime
						kg/m^3					
M1	372	21	21	911	603	192	83	4	52	27.6	Sunlight
M 2	372	21	21	911	603	192	83	4	52	29.8	60 °C for four h.
M 3	372	22	22	911	603	192	83	4.5	50	36.4	Sunlight
M 4	372	22	22	911	603	192	83	4.5	50	37.7	60 °C for four h.
M5	372	29.4	29.4	911	603	192	83	5	56	42.5	60 °C for four h. then sunlight
M6	372	42	42	911	603	192	83	6	56	27.5	60 °C for four h. then sunlight
M7	372	50	50	911	603	192	83	7	56	60.0	60 °C for four h. then sunlight

*Mk =metakaolin, SF=silica fume, CA=coarse aggregate, FA= fine aggregate, SS=sodium silicate, SH= Sodium hydroxide, SP= Superplasticizer, W= water, Al/B: Alkaline solution/binder. Note: SH=13, SS/SH=2.5 and AL/B= 0.65 for all mixes.

Table 12: The selected mixes with waste aggregate

Mix No.	MK	SF	CaO	CA	FA	SS	SH	SP	W	R	PL	Compressive strength (MPa) at 7days
						kg/m^3						
GP*	372	50	50	911	603	192	83	7	56	0	0	60.0
GPL*	372	50	50	820	603	192	83	7.5	58	0	38	39.5
GR*	372	50	50	820	603	192	83	8	58	38	0	45.4

*GP=GPC without waste aggregate, GPL= GPC with mixed plastic waste and GR= GPC with rubber waste. Note: all mixes were cured at 60 °C for 4 h., then in sunlight.

2.3 Sample preparation and processing methodology

It is worth noting that GPC requires more care than ordinary concrete, particularly in terms of curing temperature, as it is more sensitive to thermal fluctuations. Particularly, the steps of mixing and preparing the GPC specimens can be summarized as follows:

- The electric rotating mixer, which has a 0.1 m^3 capacity, was wetted by water.
- Natural coarse and fine aggregates and waste mixes (e.g., waste rubber or plastic) were considered for 2-3 minutes. The mixer then came to a standstill.
- Calcium oxide, silica fume, and metakaolin were manually blended for two minutes.
- The modified metakaolin was added to the mixer and mixed for 2-3 minutes.
- Half of the alkaline solution was combined with the dry materials in the mixer.
- Extra water and superplasticizer were manually mixed with the remaining alkaline solution and progressively added.
- After two minutes, the electric mixer was turned off for one minute, and the blades were cleaned.

The total mixing time ranged from 9 to 10 minutes. The internal surfaces of the molds were lubricated to prevent concrete from adhering to them. The GPC mixture was then put into the molds, following the requirements for each test. After levelling, the top surfaces of the GPC specimens were covered with nylon sheets and kept in the lab for 24 hours. After that, the molds varied in size and were released and cured in an electric oven at 60 °C for four hours before being placed under sunlight.

2.4 Test Methods

Several experiments were conducted, including:

1. A workability test was conducted in accordance with ASTM C143 [22].
2. The compressive strength test was conducted according to BS 1881: Part 116, using three cubic samples with dimensions of 100 × 100 mm^2, and their average was taken [23].
3. The splitting tensile strength was measured according to ASTM C 496 [24], and the average of three cylinders with dimensions of 100 × 200 mm was calculated.
4. Water absorption: This test was performed in accordance with ASTM C 642 [25].
5. Permeability: Cubic geopolymer concrete specimens (150 mm) under pressures of 500–50 kPa for 72–2 h were used to find the water penetration depth of GPC mixes according to BSEN12390-8:2000 [26].
6. This test was conducted in accordance with BS EN 1338 [27] for abrasion resistance. Specifically, a specimen measuring 100 × 100 × 70 mm^3 was used.
7. The static modulus of elasticity test was conducted according to ASTM C 469-15 standards [28] using cylinders measuring 150 × 300 mm^2.
8. Drying shrinkage is a test done by ASTM C157-03 [29] to measure how much the length of cured geopolymer concrete samples that are 75 ×75 × 300 mm^3 changes.

3. Results and discussion

The first GPC mixture in this research was selected based on prior research and practical experience, as there is no established mixing proportion procedure for geopolymer mixtures [19, 30-32]. Initially, the amount of crumbed rubber waste and plastic waste used as a replacement for natural coarse aggregate in the geopolymeric concrete was set at 10%. This content was selected to prevent the high reduction in the property of GPC that appeared due to the high content of these types of waste aggregate.

3.1 Workability

Slump values are presented in Figure 2. In practice, the lubricating properties of the silicate solution improve the flowability and slump characteristics of fresh geopolymer concrete. Typically, sodium silicate and sodium hydroxide solutions, which have higher viscosities than water, are used to enhance the cohesiveness of the geopolymer concrete. Specifically, adding water and superplasticizers to the metakaolin (MK) in the blended mixtures has improved their workability [33]. Figure 2 shows that using waste materials reduces the slump of GPC. In this regard, the rough texture of waste materials, such as plastic and rubber, may require more water to fill the voids compared to the natural aggregate with less roughness. Additionally, interparticle friction between waste aggregate particles and other geopolymer concrete components might also contribute [34]. This issue may result in a decrease in slump values after using waste aggregate. The slump values for the mixtures varied from 230 to 210 millimeters. More precisely, slump values were adjusted to 230 ± 5 mm from the basic GPC mix by increasing the superplasticizer dosage and adding extra water to the waste aggregate mixes.

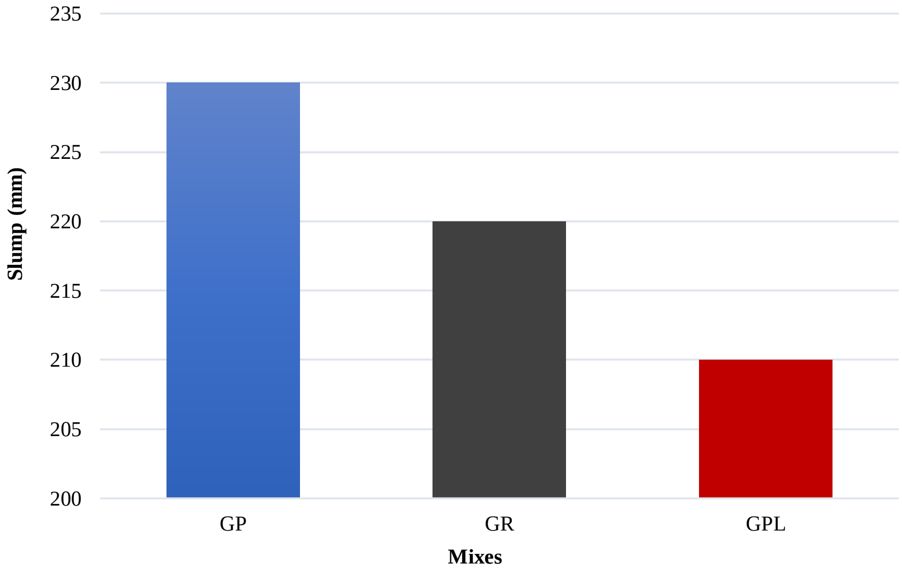


Figure 2: Slump results of GPC mixes

The slump results indicate that the mixture containing the plastic waste aggregate recorded a lower slump value of 210 mm (GPL), compared to 220 mm for the mixture with the rubber waste aggregate (GR). This difference may be attributed to the smooth surface of the plastic, which enhances the adhesion process between the waste and the water when in contact.

3.2 Compressive strength

Table 13 and Figure 3 present data on the compressive strength and other properties of various GPC mixtures at a seven-day age. The compressive strength results show that using waste plastic and rubber aggregate lowers the compressive strength by 25 and 34%, respectively, compared to GPC mixes that do not have any waste materials.

Table 13: Properties of GPC mixes

Mixes symbol	Compressive strength at 7 days (MPa)	Tensile strength at 7 dayes (MPa)	Absorption at 7 dayes (%)	Permeability at 28 days (mm)	Abrasion (mm) at 7adys	Static modulus (GPa) at 7 days	Shrinkage at 7 days (%)
GP*	60	2.9	5.09	10	19	20	0.0012
GR*	45.4	2.4	5.11	18	17.05	18	0.0015
GPL*	39.5	1.7	5.30	16	20.43	13.45	0.0016

Note: *GP, plain mix without waste aggregate, GR, mix with 10% crumb rubber waste aggregate, GPL, mix with 10% plastic waste aggregate.

It can be observed that the compressive strength varies with changes in the type of aggregate, regardless of the base material. Particularly, the incorporation of waste materials leads to a decrease in the compressive strength, even when they are partially replaced with coarse aggregate. This decrease occurs because the natural aggregate and the waste materials have different properties, resulting in a significant mismatch between the geopolymer paste and the waste aggregate. In this regard, the lightweight of the waste aggregate led to an uneven mixture, which trapped air bubbles and created weak spots, reducing the density and negatively impacting the properties of the geopolymer concrete [24, 35, and 36].

The mixture incorporating 10% plastic waste aggregate (GPL) exhibited the weakest performance among the tested samples. Moreover, the result revealed a significant difference between the properties of the geopolymer paste and those of the waste aggregate, primarily due to the lightweight characteristics of the plastic waste. This difference caused the mixture to be uneven, trapping air bubbles inside and creating weak spots, which reduced the density and the overall quality of the GPC [36,37]. It is worth noting that plastic waste typically has a more flexible and less rigid composition compared to that of conventional aggregates or crumbed rubber, which further exacerbates the issue. The lower stiffness of plastics means that the concrete does not receive sufficient support, making it more likely to deform when subjected to heavy weights. This deficiency ultimately reduces the compressive strength of the concrete. Moreover, the reduced density of plastic particles contributes to a less robust overall concrete structure. In addition to these issues, the composite material may become weaker because plastics do not bond well with other materials, making it challenging to create strong connections [38]. As a result, the use of plastic waste aggregates in concrete formulations necessitates careful consideration to mitigate these inherent limitations.

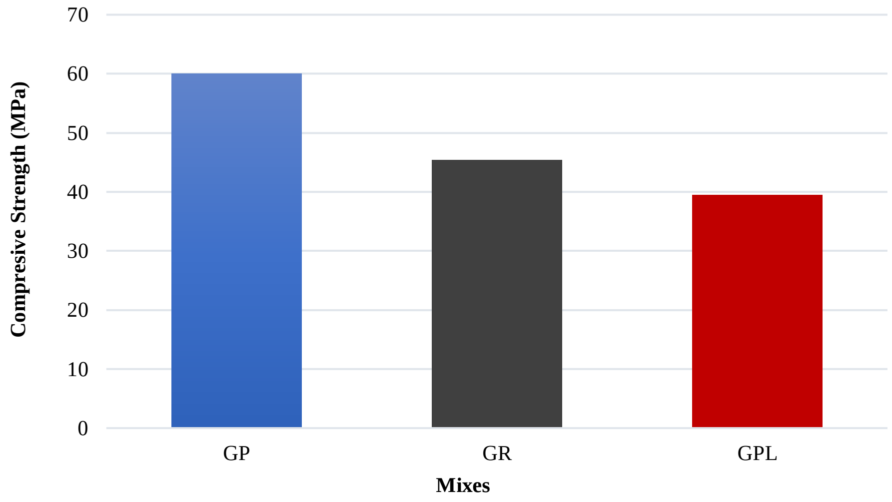


Figure 3: Compressive strength values of GPC mixes

3.3 Splitting tensile strength

Table 13 and Figure 4 show that the splitting tensile strength of the GPC mixes decreases by approximately 17% for the GPC with 10% crumb rubber waste and by 41% for the GPC with 10% plastic waste aggregate. The reduction in strength may be related to the weak bond between these waste aggregates and the geopolymer matrix due to its low stiffness or may be related to the difference in shape, stiffness, and roughness between the waste aggregates and the natural aggregate, because the waste aggregate has a planar and flaky shape with a smooth surface, unlike gravel, which is angular and rigid [39].

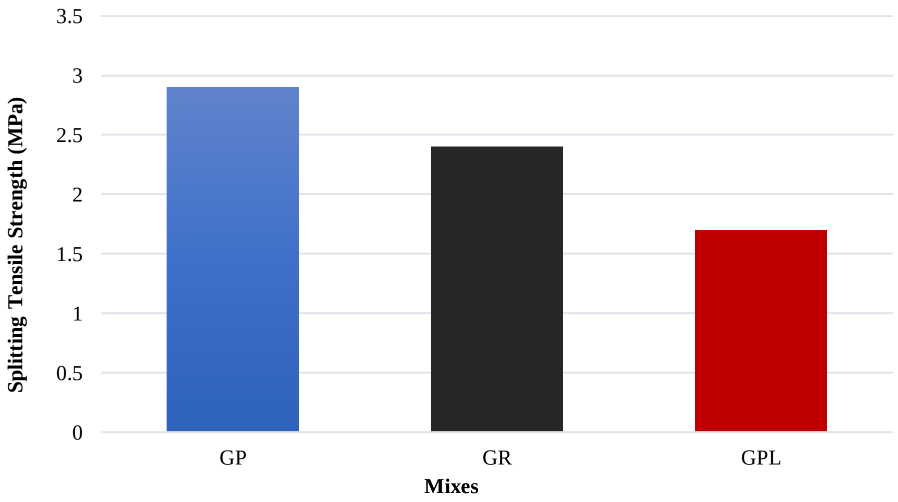


Figure 4: Tensile strength results of GPC mixes

The splitting tensile strength of the GPC mixtures that incorporate the plastic waste aggregate (GPL) is lower than that of mixtures containing the crumbed rubber waste aggregate (GR). The decrease is attributed to the lower stiffness of the plastic waste aggregate, which may lead to weaker bonding with the geopolymer matrix. Additionally, plastic is a hydrophobic material, requiring less water for curing. Consequently, the observed reduction in strength can be attributed to the hydrophobic nature and the smooth surface of the plastic aggregates, resulting in poor interfacial interaction with the geopolymer binder [2].

In contrast, rubber is more flexible and possesses better elastic properties, which may contribute to a stronger bond with the geopolymer binder. This extra flexibility can make the GPC stronger and more durable under pressure, resulting in better performance than that of mixtures that use plastic waste aggregates. According to Yajish et al., the crumbed rubber was covered with a paste, indicating that the NaOH treatment improved the performance of the crumbed rubber. This enhancement leads to better stress transfer at the interfacial transition zone (ITZ), resulting in increased mechanical strength of the mixes [40].

3.4 Water absorption

Table 13 presents the water absorption results for various GPC mixes, both with and without crumb rubber and plastic waste aggregate, after seven days. These results represent the values of three cubic specimens, each measuring 100 mm in size. The water absorption observed in samples with crumb waste rubber and plastic waste aggregate content is slightly higher compared with mixes without waste aggregate. In this regard, the higher water absorption in mixes with crumb rubber might be due to the way these lower-quality materials allow water to move through them. Furthermore, evaporation of water from the mix and the reduced level of compaction due to the lightweight rubber resulted in a greater number of voids in the interfacial transition zone between the geopolymer matrix and the rubber waste aggregate, in comparison to the geopolymer concrete mix that does not include crumbed rubber waste aggregate, and this is another reason for increasing water absorption of the mixes with 10% crumb rubber waste [41]. This higher water absorption can lead to changes in the mechanical properties of the concrete, potentially affecting its overall durability and strength. Consequently, further research is necessary to investigate the long-term implications of incorporating crumbed rubber waste into construction materials.

The flaky and angular shape of the plastic aggregate waste resulted in increased pores within the matrix due to difficulty in compaction. As a result, the porosity of the geopolymer concrete increased. Additionally, the poor particle size distribution of the plastic waste aggregate reduced the compatibility of the geopolymer. Moreover, the impermeable nature of plastic caused free water deposition surrounding the plastic particles, resulting in more pores in the boundary transition zone between the waste aggregate and the surrounding matrix [32]. Consequently, this outcome explains the increase in water absorption. All concrete mixtures exhibit a water absorption rate of less than 10%, which is considered a good quality of concrete [42], indicating that they maintain their structural integrity and durability over time. This low absorption rate also suggests that the incorporation of plastic particles does not significantly compromise the overall performance of the concrete mix.

3.5 Permeability (Depth of Water Penetration Under Pressure)

The permeability results for the geopolymer concrete mixes at 28 days of age, including those with crumb rubber waste aggregate and plastic waste aggregate, are presented in Table 13 and Figure 5. In this regard, the inclusion of crumb rubber and plastic waste aggregate increases the water penetration depth from 10 mm in plain GPC mixes without waste to 18 mm and 16 mm, respectively, for GPC mixes with crumb rubber and plastic waste. In particular, the addition of rubber waste created more tiny holes and cracks in the geopolymer mix, which increased its water absorption capacity. This outcome was also linked to the difficulty in mixing the concrete when there was a lot of waste, resulting in weak connections between the geopolymer and the rubber, which created more gaps in the area where they meet and increased the permeability of the GPC [43, 44, and 45]. These challenges underscore the importance of carefully considering proportions and mixing techniques to optimize the overall performance of geopolymer concrete. Accordingly, future research could focus on optimizing these factors to improve durability and reduce water absorption. In all cases, the average water penetration depth is less than 50 mm (10-18 mm) for all specimens; therefore, the geopolymer concrete tested is considered impermeable, according to Skutnik et al.'s findings. This characteristic suggests that the geopolymer concrete could be a viable option for construction in environments where moisture resistance is critical, potentially extending the lifespan of structures exposed to harsh conditions [46]. In the case of the GPC incorporating plastic waste aggregates, it exhibits higher permeability compared to that of the GPC without waste materials. In essence, the smooth surface texture and the irregular shapes of the plastic waste obstruct adequate bonding with the surrounding matrix, leading to this phenomenon. In the sequel, the resulting poor mechanical interlocking creates gaps and channels that facilitate water movement. These gaps and channels enable water to flow more easily through the concrete, resulting in increased permeability. Consequently, these variables can affect the overall durability and performance of the geopolymer concrete in various environmental conditions. In practice, this characteristic can pose challenges in applications where water retention is crucial, but it also presents opportunities for innovative drainage solutions in construction projects.

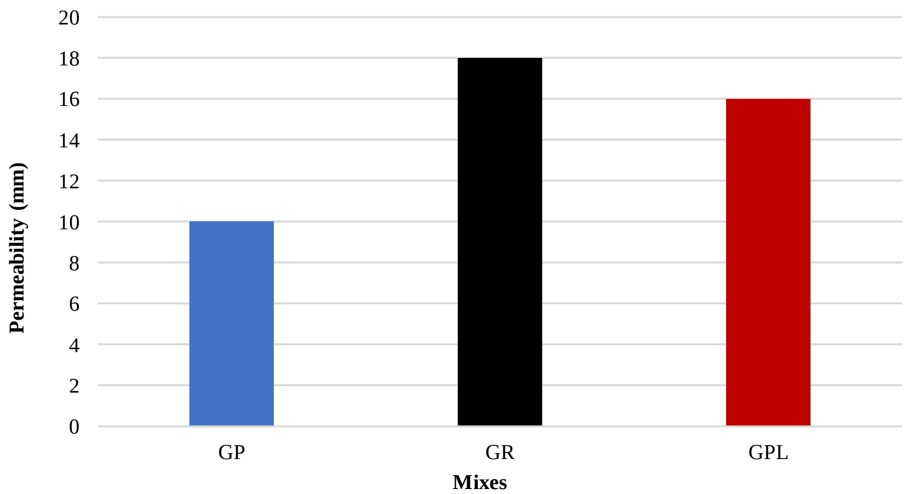


Figure 5: Permeability (water penetration depth) results of GPC mixes

3.6 Abrasion resistance

Figure 6 illustrates the superior abrasion resistance obtained from the geopolymer concrete with the rubber waste aggregate (17 mm). According to BS EN 1338, this number corresponds to class 2 (groove width smaller than 20 mm, typically used in high-traffic areas). Specifically, the abrasion width for the reference concrete without rubber was 19 mm, indicating that the GPC without rubber has a greater surface wear value than the rubber variant. This difference can be attributed to the rubber granules on the concrete's surface, which help decrease friction and act like a brush. Additionally, the effective resistance of the rubber-enhanced concrete to ground friction may be due to its superior energy absorption and crack resistance properties [47, 48, and 49]. As a result, the incorporation of rubber enhances the durability of the concrete and improves its overall performance in demanding environments. Subsequently, this innovation could lead to longer-lasting surfaces and reduced maintenance costs in various construction applications.

The lower abrasion resistance was recorded for the mixture with plastic waste aggregate (20.43 mm). In this respect, the results were consistent with compressive and splitting tensile strength [50]. Particularly, the GPC's abrasion resistance increased with the increasing strength, indicating that incorporating higher-quality aggregates could further enhance the durability of the concrete. As such, the finding suggests potential avenues for future research aimed at optimizing the balance between sustainability and performance in construction materials [51].

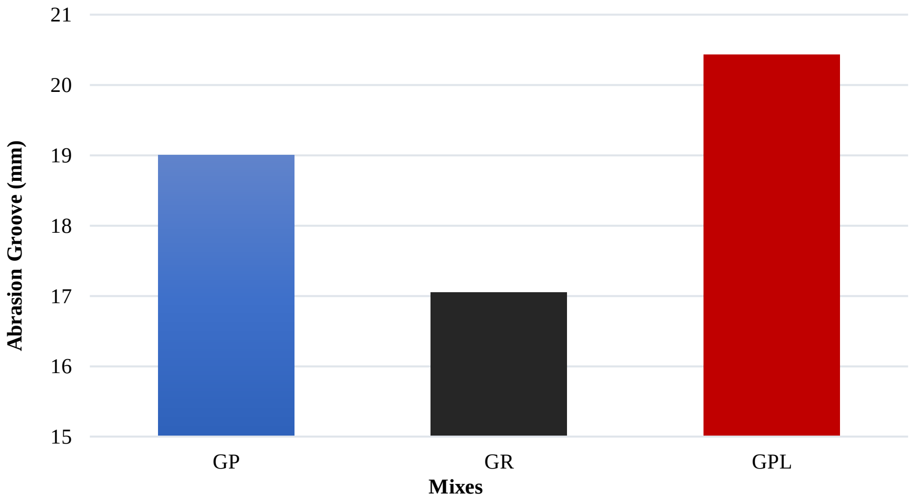


Figure 6: Abrasion results of GPC mixes

3.7 Static modulus of elasticity

The metakaolin-based geopolymer concrete exhibits a low static elastic modulus, regardless of the type or quantity of the waste material used. Compared to OPC, the compressive strength and the static modulus are linked. In particular, the lamellar structure of the kaolinite clay causes the MK-geopolymer paste to have a low modulus of elasticity, making it more deformable under stress [52]. In this context, other studies [53, 54, and 55] found similar behavior patterns.

According to Table 13 and Figure 7, the highest modulus of elasticity for a plain mix with no waste aggregate was 20 GPa. In contrast, the lowest value was 13.45 GPa for a mixture containing an aggregate made of plastic waste. More precisely, the reduction in the modulus of elasticity from the reference mixture is approximately 10 and 33% for the mixtures with the rubber crumb waste aggregate and the plastic waste aggregate, respectively. Essentially, replacing the natural coarse aggregate with the PL aggregate resulted in a significant decrease in static modulus measurements. The MK-GPC mixtures with PL had lower strength than that of the control mixture, resulting in lower elasticity values. Therefore, the type of aggregate directly influenced the elasticity modulus of the concrete. Because the PL particles have a much lower modulus of elasticity than that of the natural aggregates, there is a weak connection between the concrete mix and the smooth surfaces of the PL particles, which helps explain this finding. The replacement of the rubber waste aggregate has the same behavior.

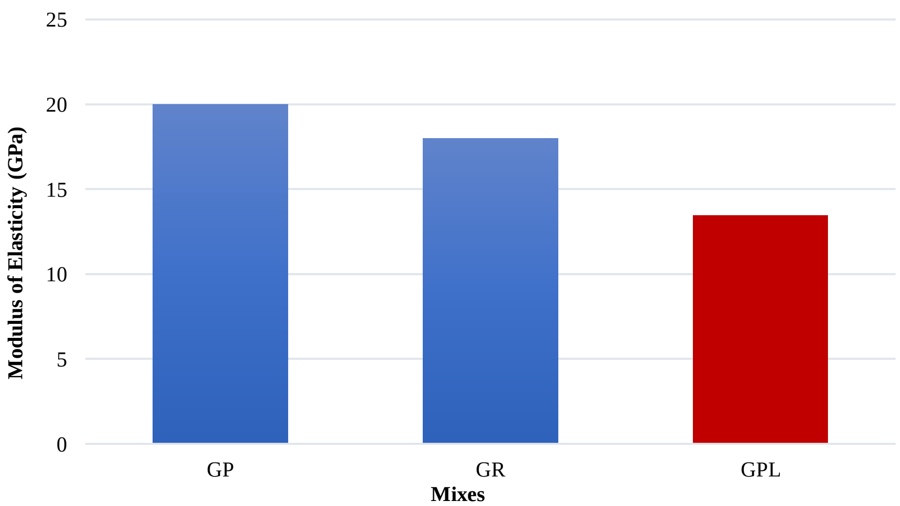


Figure 7: Static modulus of elasticity values of GPC mixes

Based on the above results, further research is necessary to investigate potential methods for improving the strength and elasticity of mixtures that incorporate waste materials. Investigating alternative additives or reinforcing techniques could provide valuable insights into optimizing these properties. Additionally, studying the long-term durability and performance of such mixtures in various environmental conditions will be essential for practical applications.

3.8 Drying shrinkage

Table 13 and Figure 8 present the results regarding the shrinkage of the GPC mixes when the waste aggregate is included compared to the case when it is not included. The data clearly indicate a significant difference in shrinkage rates, suggesting that the addition of waste aggregate may impact the durability and stability of the GPC mixes. Accordingly, further analysis is necessary to understand the long-term implications of using recycled materials in construction applications. Specifically, the results indicate that the use of recycled aggregate increases drying shrinkage, which aligns with the findings of Alonso et al. [56]. In this regard, many causes may contribute to the rising drying shrinkage in combination with the presence of the recycled aggregate:

- Recycled aggregates often absorb more water than natural aggregates. This more excellent absorption causes increased internal moisture, which, when evaporated, contributes to more significant drying shrinkage.
- Weaker Interfacial Transition Zone (ITZ): The connection between the recycled aggregate and the geopolymer matrix is often weaker because the recycled aggregate has a rough and porous surface, which leads to greater shrinkage and a higher chance of cracking. As a result, it is essential to improve the mix design and consider the use of additives or alternative materials to mitigate these effects and enhance the overall performance of the concrete [57].

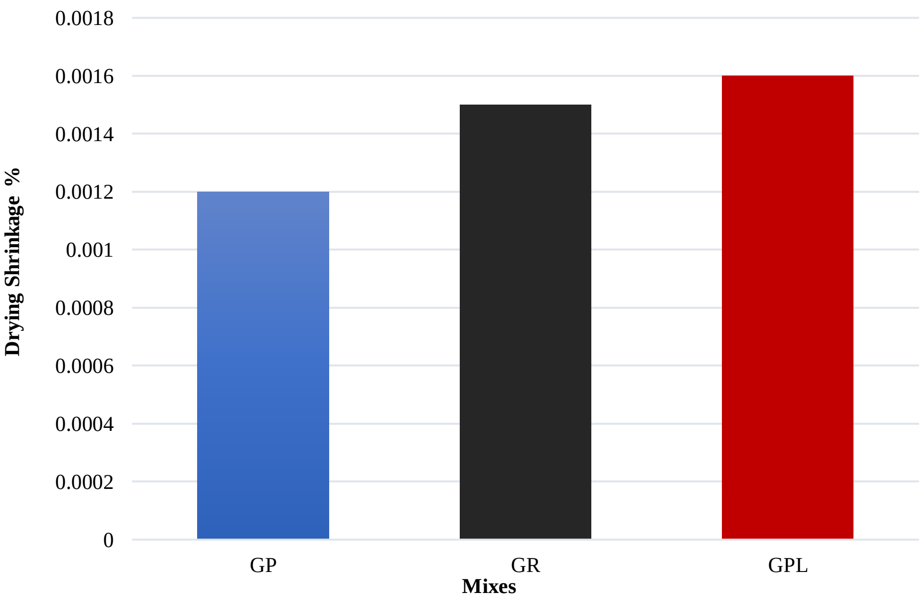


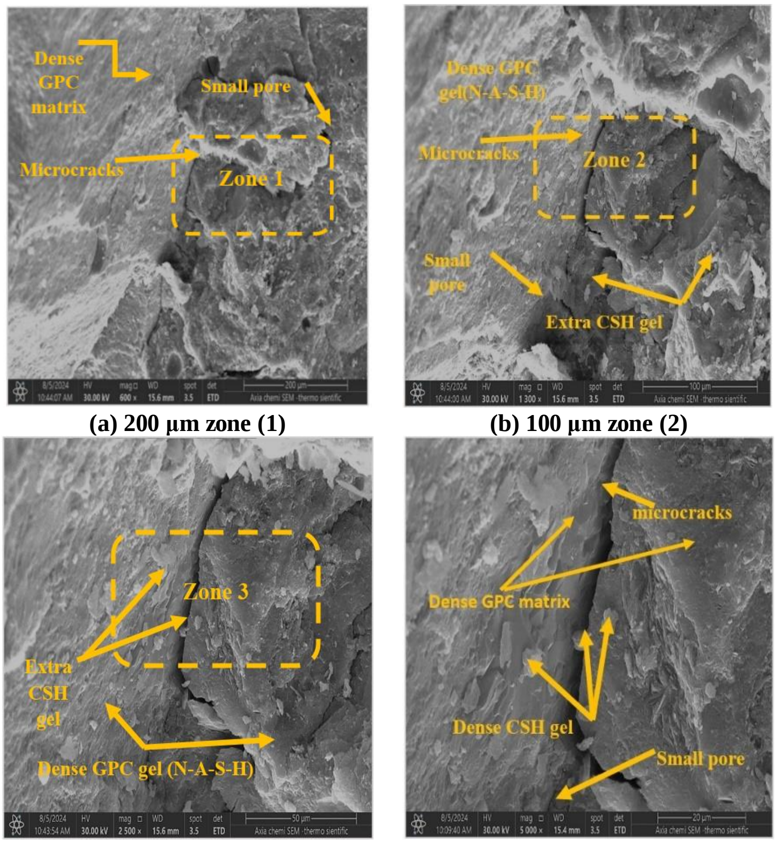
Figure 8: Drying shrinkage of GPC mixes

Figure 7 shows that the concrete containing 10% plastic waste exhibits greater drying shrinkage than the concrete with the rubber waste aggregate. As mentioned previously, plastic aggregates tend to be stiffer and less compressible than rubber. This increased stiffness results in less stress relaxation during the shrinkage process, causing a larger portion of the shrinkage strain to be transferred to the matrix. Conversely, rubber aggregates, being softer and more flexible, can absorb a portion of the shrinkage stress, which helps to minimize the overall deformation [40,58]. To this end, this distinction highlights the importance of selecting appropriate materials for specific engineering applications. In this sense, by understanding the properties of different aggregates, engineers can better predict the performance and the durability of the concrete mixtures in various environmental conditions.

3.9 Microstructure analysis

The SEM graphics provide a clear picture of how the geopolymer reacts during the polymerization process, highlighting the GPC microstructure, the distribution of the GP gel matrix, and the presence of pores, cracks, and other materials within the concrete structure.

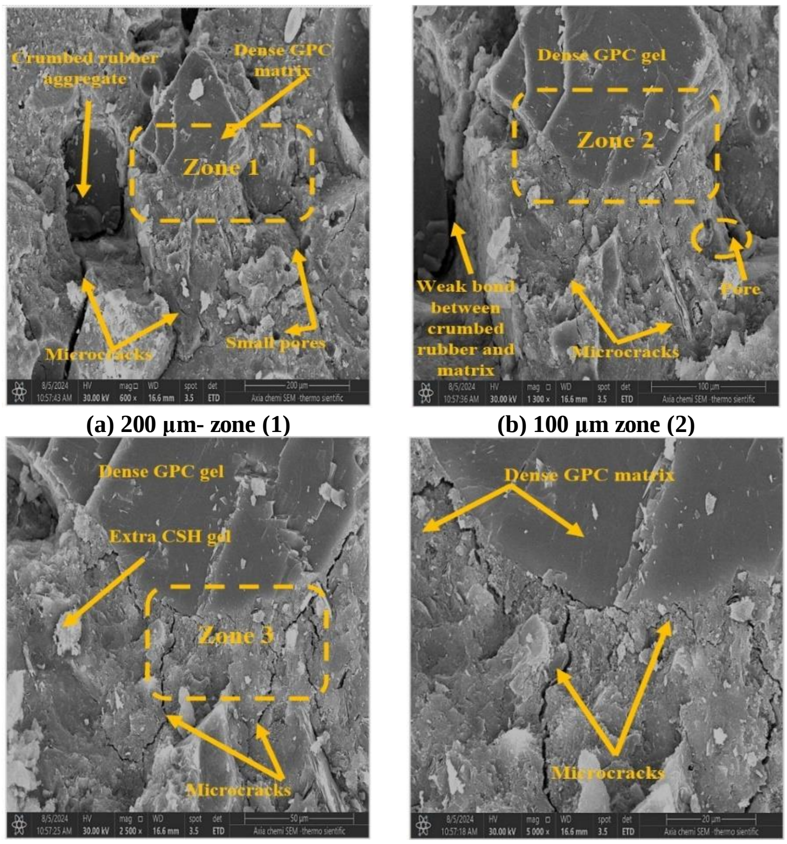
From Figure 9 (a-d), which shows the SEM image of samples without any waste aggregate, we can see that the matrix is closely packed, with just a few tiny holes and cracks, indicating a strong structure. Particularly, the concrete's strength derives from the geopolymer binder, which forms a thick, interconnected web of alumina-silicate gel (similar to N-A-S-H gel). This dense network enhances the durability and the mechanical properties of the concrete produced, providing resistance to environmental factors and physical stress. On the other hand, the samples incorporating the waste aggregates may exhibit a different microstructure, which can potentially lead to variations in performance characteristics.



(a) 200 µm zone (1) **(b) 100 µm zone (2)**

(c) 50 µm zone (3) **(d) 20 µm**

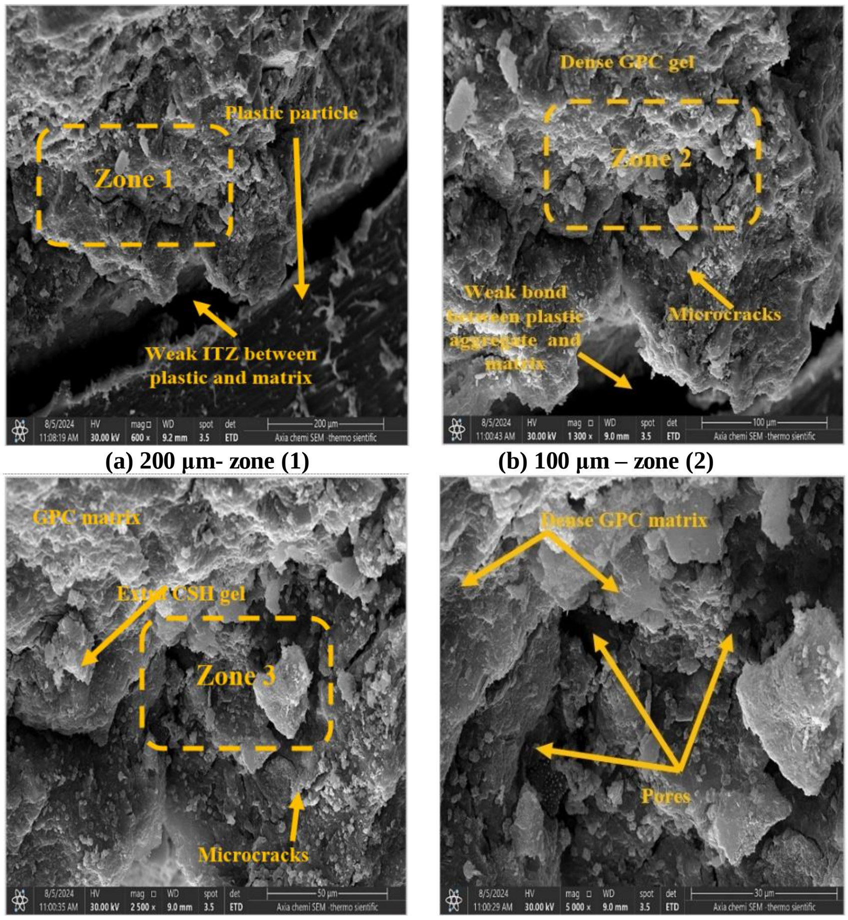
Figure 9: The SEM image of the reference GPC without the waste aggregate at different magnification levels, a) at 200 µm, b) 100 µm, c) 50 µm, and d) 20 µm



(a) 200 µm- zone (1) **(b) 100 µm zone (2)**

(c) 50 µm zone (3) **(d) 20 µm**

Figure 10: The SEM image of the GPC specimens with the rubber waste aggregate at different magnification levels, a) 200 µm- zone, b) 100 µm**,** c) 50 µm, and d) 20 µm



(a) 200 µm- zone (1) **(b) 100 µm – zone (2)**

(c) 50 µm- zone (3) **(d) 20 µm**

Figure 11: The SEM image of the GPC specimens with the plastic waste aggregate at different magnification levels, a) 200 µm, b) 100 µm, c) 50 µm, and d) 20µm

These variations in microstructure can affect the overall strength and durability of the concrete, making it crucial to understand the impact of different materials used in the mix. Consequently, the choice of aggregates plays a significant role in determining the final properties of the concrete. In this context, the densification process significantly improved the GPC properties, with a measured compressive strength of 60 MPa and a splitting tensile strength of 2.9 MPa. In the SEM images of the geopolymer concrete with crumbed rubber aggregate, the waste aggregate reveals that the geopolymer matrix has more pores and microcracks than the reference specimen, as shown in Figure 10 (a-d). Additionally, the ITZ between the crumb rubber particles and the geopolymer matrix appears fragile. These images are compatible with the experimental results, demonstrating reduced strength and increased water absorption and depth penetration (permeability).

The SEM images are used to study the microstructure of the GPC with 10% plastic waste aggregate, as shown in Figure 11(a-d). These images show that the area where the plastic waste aggregate meets the geopolymer matrix is weaker, with lower bond strength and more pores, compared to the area with crumbed rubber particles and the matrix. This condition results in the lowest strength for the geopolymer concrete sample, as indicated by the experimental findings.

4. Conclusion

1. The partial replacement (10% by volume) of natural coarse aggregates with rubber or plastic waste in the GPC led to reductions in both compressive and splitting tensile strengths. While the plastic waste caused a more pronounced decrease in strength than that of rubber, the resulting GPC still meets structural concrete standards, making it suitable for various construction applications.
2. The inclusion of rubber and plastic waste aggregates resulted in a noticeable decrease in the static modulus of elasticity, even at low replacement levels, indicating a reduction in stiffness compared to conventional GPC.
3. Water absorption and permeability increased in the GPC mixes incorporating the waste aggregates. However, despite this increase, the measured permeability remained below 50 mm, classifying the concrete as impermeable and thus still appropriate for durability-critical structures.
4. The use of recycled aggregates also led to an increase in drying shrinkage. However, the shrinkage values were still lower than those typically observed in ordinary Portland cement concrete, suggesting improved volumetric stability in geopolymer systems.
5. The SEM and the microstructural analysis supported the mechanical findings, revealing a denser and more compact geopolymer matrix in control specimens without waste. In particular, specimens containing recycled aggregates exhibited a more porous structure, which correlated with the observed reductions in mechanical performance.

6. Overall, the study demonstrated that the modified metakaolin-based GPC incorporating rubber and plastic waste can offer a sustainable alternative to conventional concrete. Although some mechanical properties are compromised, the environmental benefits and the acceptable performance make it a promising material for green construction initiatives.

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Author contributions

Conceptualization, **S. Al-Saedi**, and **W. Khalil**; data curation, **S. Al-Saedi**; formal analysis, **S. Al-Saedi**; investigation, **S. Al-Saedi**, and **W. Khalil**; methodology, **W. Khalil**; project administration, **S. Al-Saedi** and **W. Khalil**, resources, **W. Khalil**; software, **S. Al-Saedi**; supervision, **W. Khalil**;validation, **S. Al-Saedi**, and **W. Khalil**; visualization, **S. Al-Saedi**, and **W. Khalil**; writing—original draft preparation, **S. Al-Saedi**; writing—review and editing, **S. Al-Saedi**. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

Information will be provided upon request..

Conflicts of interest

The authors declare that there is no conflict of interest.

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