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Mechanical Properties of Modified Metakaolin-Based Geopolymer Concrete Containing Tires Rubber Waste and Reinforced with Recycled Steel Fibers

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Keywords:
Crumbed Rubber Wastes; Damaged Tires; Geopolymer Concrete; Metakaolin; Recycled Steel Fibers Wastes.

Highlights:

- *Waste management is essential for sustainability.*
- *Rubber waste in geopolymer concrete reduces its mechanical properties, while recycled steel fiber in specific proportions increases them.*
- *The failure mode of geopolymer concrete can change by adding these wastes.*
- *Geopolymer concrete SEM images were used to enhance the discussion of the results.*

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Abstract: Geopolymer concrete has superior physical properties and a positive environmental impact compared to conventional concrete. Waste management is one of the most essential issues. Regarding sustainable raw material management, recycling the industrial waste as much as possible and developing new technologies that reduce industrial waste landfills and generate materials with new added value is essential. Every year, people throw away about 17 million tons of tires that cannot be used again. This trash is a significant environmental threat, so recovering tires is essential. The results showed that replacing 10% of the crumbed rubber wastes with natural coarse aggregate decreased the workability, compressive strength, splitting tensile strength, flexural strength, and direct tensile strength by 5.5%, 38.6%, 10.6%, 6.25%, and 6.67%, respectively with respect to a reference without wastes. At the same time, adding 0.125% and 0.25% recycled steel fibers increased the workability reduction by 2.9% and 5.9% and improved mechanical properties, including compressive strength, splitting tensile strength, direct tensile strength, and flexural strength by 43.3%, 15.9%, 26.4%, 14.2%, 90.4%, 42.4%, 32.1%, and 17.9%, respectively, compared to a reference mixture containing 10% crumbed rubber wastes. The results also showed an increase in the total energy by 23.2%, 142.4%, and 312.1% when replacing 10% of the natural coarse aggregate with crumbed rubber wastes, including 0.125 and 0.25% recycled steel fibers, respectively. When these wastes were introduced together or individually, Brittleness of geopolymer concrete changed to ductile.

الخواص الميكانيكية للخرسانة الجيوبوليمرية المعتمدة على الميتاكاؤلين المعدل والحاوية على مخلفات مطاط الإطارات والمسلحة بالألياف الفولاذية المعاد تدويرها

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الخلاصة

تتمتع الخرسانة الجيوبوليمرية بخصائص فيزيائية فائقة وتأثير بيئي إيجابي مقارنة بالخرسانة التقليدية. في الوقت الحاضر، تعتبر إدارة النفايات من القضايا المهمة. فيما يتعلق بالإدارة المستدامة للمواد الخام، فإن إعادة تدوير النفايات الصناعية قدر الإمكان وتطوير تقنيات جديدة تقلل من مدافن النفايات الصناعية وانتاج مواد جديدة ومفيدة أمر ضروري. في كل عام، يتخلص الناس من حوالي ١٧ مليون طن من الإطارات التي لا يمكن استخدامها مرة أخرى. تعتبر هذه الاطارات نفايات حيث تشكل تهديدًا بيئيًا كبيرًا، لذا فإن إعادة تدوير الإطارات أمر ضروري. أظهرت النتائج أن استبدال ١٠٪ من مخلفات المطاط المفتت بالركام الخشن الطبيعي يؤدي إلى انخفاض في قابلية التشغيل ومقاومة الانضغاط ومقاومة الشد بالانشطار ومقاومة الانثناء ومقاومة الشد المباشر بنسبة ٥,٥٪، ٣٨,٦٪، ١٠,٦٪، ٦,٢٥٪. و٦,٦٧٪ على التوالي بالمقارنة مع الخلطة المرجعية بدون نفايات. وفي الوقت نفسه، تؤدي إضافة ٠,١٢٥٪ و٠,٢٥٪ من الألياف الفولاذية المعاد تدويرها من الإطارات التالفة إلى زيادة الانخفاض في قابلية التشغيل بنسبة ٢,٩٪ و٥,٩٪ وتحسين الخواص الميكانيكية بما في ذلك مقاومة الانضغاط والشد بالانشطار والشد المباشر والانثناء. بنحو ٤٣,٣٪، ١٥,٩٪؛ ٢٦,٤٪، ١٤,٢٪؛ ٩٠,٤٪، ٤٢,٤٪؛ ٣٢,١٪، ١٧,٩٪ على التوالي مقارنة بالخليط المرجعي الذي يحتوي على ١٠٪ من مخلفات المطاط المفتت. كما أظهرت النتائج زيادة في امتصاص الطاقة الكلية بنسبة ٢٣,٢٪ و١٤٢,٤٪ و٣١٢,١٪ عند استبدال ١٠٪ من الركام الطبيعي الخشن بمخلفات المطاط المفتت، واضافة ٠,١٢٥ و٠,٢٥٪ ألياف فولاذية معاد تدويرها على التوالي. ان شكل الفشل يتغير من قصيف إلى مطيلي عند إضافة هذه النفايات معًا أو بشكل منفصل.

الكلمات الدالة: نفايات المطاط المتفتت، الإطارات التالفة، الخرسانة الجيوبوليمرية، الميتاكاؤلين، الالياف الفولاذية المعاد تدويرها.

1.INTRODUCTION

Geopolymer concrete is a successful alternative to cement concrete, as it enhances sustainability by reducing carbon dioxide emissions. At the same time, it has properties equal to or higher than cement concrete [1–3]. The increasing quantity of non-biodegradable old tires poses an environmental risk and requires effective management. Iraq has a significant accumulation of used tires that has remained unresolved for an extended period. The country imports more than ten million tires annually [4], and about 1.5 billion tons of used tires are thrown out annually worldwide [5]. Therefore, tire disposal is a serious waste management issue worldwide, especially in Iraq. There is an increasing need to find possible applications for waste tires due to environmental concerns regarding their management and treatment. It is possible to decrease the amount of waste going to landfills using materials recovered from tires to produce rubberized fiber-reinforced concrete. Burning or dumping old tires in landfills may take a long time and cause severe harm to groundwater and the environment [6]. The easiest way to get rid of damaged tires is to use them after preparation in concrete, whether asphalt, cement, geopolymer, tire-derived fuel (TDF), or as ground materials like rubber flooring tiles. As a result, these wastes were managed by incorporating them into different types of concrete, which improved some of the concrete properties while also helping to preserve the environment [7,8]. Generally, car tires comprise 46-48% rubber, 25-28% carbon, 10-12% oil, vulcanizing agents, and 3-6% textiles [9]. The distinguishing feature of cement concrete is the high compression resistance, while the tension resistance is very low because of the concrete structure's brittleness. Therefore, once the elastic limit is reached, the microcracks occur, and then macrocracks lead to failure. Additionally, the ratio between tensile and compressive strengths is very low. Hence, the addition of fibers not only improves ductility but also improves the post cracks phase [10], which also applies to geopolymer concrete. Fibers perform a significant function by improving toughness and transferring the stresses through concrete between cracks, and there will be multiple cracks instead of one [11-14]. When the fibers' volume fraction is sufficient, strain hardening occurs, while strain softening is prominent [15,16]. The area under the curve is affected by the fiber's quantity, type, diameter, length, shape, and stiffness [17,18]. The advantage of steel fibers is that they improve toughness after cracking. The addition of local industrial macrofibre to geopolymer concrete, as well as crumbed rubber wastes from damaged tires considered waste, will be studied in this research. Few studies have used rubber waste as a volumetric substitute for natural coarse aggregate in geopolymer concrete to preserve natural resources and the environment and improve some geopolymer concrete properties. In addition, few researchers focused on using recycled waste in geopolymer concrete, such as steel fibers from damaged car tires, which is a source of concern because of the continuous increase and must be disposed of to protect the environment and improve some geopolymer concrete characteristics. Gailitis et al. [19] investigated the properties of geopolymer concrete using fly ash and containing an alkaline content of 10 M after adding 2% and 3.5% waste steel fibers derived from old tire parts. The specimens were exposed after sealing to a temperature of 75℃ for 24 hours. Scanning electron microscopy (SEM) showed good adhesion between the matrix and the fiber. The results recorded the highest increase of 33.8% and 21.8% in the compressive and tensile strengths for concrete with 3.5% fiber. This strength decreased to around 5% and 15% for 2% and 3.5% waste steel fibers, respectively, when the fiber content was reduced to 2% compared to the reference geopolymer concrete without fiber. Amran et al. [20] comprehensively reviewed the fibers' effect on the geopolymer concrete (GPC) properties. It was found that the steel fibers enhanced the mechanical characteristics of GPC compared with cement concrete. The fibers showed greater bonding strength with the geopolymer concrete matrix. The results showed that the good dispersion of the fibers gave a good interaction between the fibers and the geopolymer matrix. Also, the tensile strength of geopolymer concrete with fiber was superior to t cement concrete. The bonding strength increased with increasing the fiber surface roughness, geometric shape, and concrete grade. Previous studies [21,22] have proven that fibers' type and volume fractions were generally taken as (0-1) %. Also, the geometric shape and fiber strength substantially impacted the geopolymer concrete performance. The effect of adding different percentages of rubber waste (crumb rubber that was recycled from damaged tires) as a replacement of fine and coarse natural aggregates (0, 10, 20, and 30%) on the hardening characteristics of geopolymer concrete based on slag as a binder was studied by Aly et al. [23]. The natural aggregate consists of crushed dolomite with a maximum size of 12mm at 65% and sand with a maximum size of 0.5mm at 35%. The waste rubber aggregate was mechanically separated into No. 40 and 1-4 mm sieves, then blended at 70% and 30%, respectively. Then, it was used as a substitute for natural fine and coarse aggregate together. The researcher's main finding was that the compressive strength was improved slightly by 7% for 28- and 60-days age, as the rubber percentage increased to 10%. However, when the rubber contents exceeded 10%, the compressive strength decreased by 24% and 34% for 20% and 30% rubber percentages, respectively, at the age of 28 days. Similarly, at 60 days, the compressive strength decreased by 21% and 28% for rubber percentages of 20% and 30%, respectively. The flexural and splitting strengths decreased as the rubber content replacement increased by 20%, 30%, and 30% for splitting strength, and 34.6%, 23%, and 35.5% for flexural strength for concrete with rubber content of 10, 20, and 30%, respectively. The inclusion of rubber in geopolymer concrete significantly improved its resistance. These enhancements resulted in a 50%, 150%, and 200% increase in ductility and energy absorption for rubber waste percentages of 10%, 20%, and 30%, respectively, compared to geopolymer concrete without rubber waste.

Yeluri and Yadav [24] reported a review of the mechanical properties when using rubber tire waste as aggregate in geopolymer concrete. This review's main conclusions were that including rubber waste in geopolymer concrete enhanced the workability and reduced the flow value. The compressive strength decreased by increasing the rubber content for concrete or mortar. The compressive strength was reduced by 60% for specimens, with 15% rubber for concrete and 10% for mortar. The splitting and flexural strengths increased with increasing rubber content. It was noted that the highest flexural strength was at a 30% replacement content of fine aggregate with rubber. Based on the above, the studies that studied the effect of rubber from damaged tires on the geopolymer concrete properties, especially those based on metakaolin, are still few and limited. Also, previous research evaluated the combined effect of using rubber and recycled steel fibers from damaged tiers on the geopolymer concrete properties based on metakaolin. Therefore, this research studies the effect of combining steel fibers and crumbed rubber wastes on the geopolymer concrete properties based on modified Iraqi metakaolin.

2.EXPERIMENTAL WORK

2.1.Materials

Iraqi kaolin from the Al-Anbar region was used as a source of silica and alumina to produce geopolymer concrete. It was subjected to several processes, including grinding by iron balls (like cement plant softener balls) in a Los Angeles device and burning in A furnace powered by electricity at 700 °C for 2 hr. to make metakaolin with particle size, as shown in Fig. 1. Metakaolin (MK) was preserved in plastic containers to avoid air humidity. The chemical and physical properties of metakaolin are shown in Tables 1 and 2, respectively. The results showed that the metakaolin used in this study considered natural pozzolana complies with the American specification ASTM C618 [25].

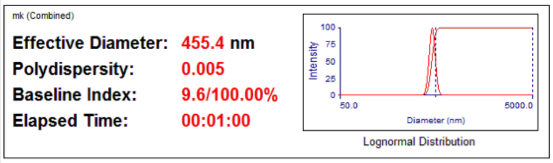

mk (Combined)
Effective Diameter: 455.4 nm
Polydispersity: 0.005
Baseline Index: 9.6/100.00%
Elapsed Time: 00:01:00

Fig. 1 Particle Size for Metakaolin After Grinding and Burning.

Table 1 Chemical Characteristics of Metakaolin.

Oxide Composition	Content by Weight (%)	Requirements of ASTM C 618 [25]
SiO_2	62.410	SiO_2+ Al_2O_3+ Fe_2O_3= 98.327 ≥ 70
Al_2O_3	35.026	
Fe_2O_3	0.891	
K_2O	0.9080	
TiO_2	0.5310	
CaO	0.1430	
MnO	0.0020	≤4 percent
SO3	0.0270	
LO I	0.7110	≤10 percent
LOI: Loss of ignition.		

Table 2 Physical Characteristics of Metakaolin (MK).

Physical Characteristics	MK	Requirements of ASTM C 618 [25]
Strength activity index at 7 days (%)	113	≥75 percent
Retained on sieve 45µm (%)	18.40	≤34 percent
Fineness (m^2/kg)	14301	--
Specific gravity	2.630	--
Color	Pink-white powder	--

The alkaline solution used in this study consisted of sodium hydroxide (NaOH) from Mahaco Industrial Company [26] with 99% purity and sodium silicate (Na_2SiO_3) from DUBAI CHEM Company [27]. The sodium silicate and sodium hydroxide properties are shown in Table 3 and Table 4, respectively.

Table 3 Properties of Sodium Silicate.

Description	Value [27]
Na_2O (%) by weight	13.10-13.70
SiO_2 (%) by weight	32.00-33.00
SiO_2/ Na_2O ratio	2.4±0.05
Specific gravity	1.534-1.551
Viscosity (CPS) 20°C	600-1200
Appearance	Hazy

Table 4 Properties of Sodium Hydroxide.

Chemical Composition	Results [26]	Specification [28]
Sodium hydroxide content	99.5%	99.0% wt. min.*
Na_2CO_3	0.54%	0.94% wt. max.
NaCl	0.02%	0.022% wt. max.
Iron	1.3 ppm	5 ppm wt. max.
Na_2So_4	0.003%	0.038% wt. max.
Appearance	white, flaky to pellet shape	

* On dry basis.

The natural fine aggregate used in this study was brought from the Al-Ukhaidir area / Iraq, with a maximum size of 4.75 mm. The sieve analysis and the properties of the fine aggregate are shown in Table 5. The results illustrated that the used fine aggregate complied with the Iraqi specification (IQS) No. 45/2016, zone II [29]. Natural crushed coarse aggregate from the Al-Badrah region/ Iraq, with a maximum size of 10 mm, which agrees with the Iraqi specifications No. 45 / 2016 [29], was used in this study. The natural coarse aggregate properties are presented in Table 6.

Table 5 Properties of Fine Aggregate.

Sieve size (mm)	Passing (%)	Limits of IQS No. 45 for Zone II [29]
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
75 um of material passed through sieve (percent)	3	≤50%
Sulfate percentage (percent)	0.084	≤0.50%
Fineness modulus	2.72	--
Absorption (percent)	1.80	--
Specific gravity	2.60	--
dry density (kg/m^3)	1745	--

Table 6 Properties of Coarse Aggregate.

Sieve size (mm)	Passing (%)	Limits of IQS No. 45 [29]
10	97	85-100
5	12	0-25
2.36	--	0-5
Material passing from sieve 75 μm (percent)	0.30	≥3
Density (kg/m^3)	1626	--
Specific gravity	2.620	--
Absorption (percent)	0.60	--
Sulfate percentage (percent)	0.059	0.1

Potable water (tap water) was used to dissolve the sodium hydroxide and as extra water in the mixture. A high-range water-reducing admixture (HRWR) with the commercial mark of Flocrete SP33 [30] was used. It was free from chlorides and complies with ASTM C494 [31] Types A and F. Table 7 shows the main characteristics of HRWRs.

Table 7 Characteristics of the High-Range Water Reducing Admixture.

Property	Description [30]
Appearance	Fluid with a dark brown colour
Specific gravity	1.170-1.210
Chloride percentage	Nil
PH	6.50
Typical dose	0.80-2.80 L/100 kg binder

Sika company [32] produces the silica fume used in this study. Table 8 shows the physical characteristics, strength activity index, and chemical composition of silica fume. The results show that the silica fume used meets ASTM C1240 [33] chemical and physical requirements. The Karbala plant in Iraq provided the calcium oxide employed in this investigation [34]. The physical and chemical properties of calcium oxide are given in Table 9.

Table 8 Characteristics of Silica Fume.

Physical Characteristics		
Property	**Results**	**Requirements of ASTM C1240** [33]
Fineness (m²/kg)	19200.0	≥15000
Strength activity index (percent)	122.0	≥ 105
Retained on sieve 45 µm, max (percent)	9.00	≤ 10
Specific gravity	2.200	--
Color	Grey	--
Chemical Characteristics		
Oxides composition	**Results (%)**	
SiO_2	88.59300	≥85
Al_2O_3	--	--
Fe_2O_3	5.5640	--
K_2O	4.7770	--
TiO_2	--	--
CaO	0.6660	--
SO_3	0.0270	--
MnO	0.2760	--

Table 9 Characteristics of Calcium Oxide.

Physical Characteristics	
Property	**Results**
Specific surface area (m²/kg)	16350
Specific gravity	3.30
Color	White
Chemical Characteristics	
Oxides Composition	**Results (%)**
SiO_2	4.3140
Al_2O_3	--
Fe_2O_3	0.4610
K_2O	1.6670
TiO_2	--
CaO	93.300
SO_3	0.100
MnO	0.0250

The rubber waste was prepared after collection from the Al-Diwaniya plant for recycling tires, whose grains vary from 0.3 mm to 14 mm. It was created by removing the steel belts and fabric from tires and cutting them before they were mixed with concrete. This rubber was cleaned and graded using standard sieves so that its gradation was like the natural coarse aggregate used in the present investigation. The rubber aggregates were submerged in a 0.5% concentration of calcium hydroxide solution for two days to increase the surface roughness, then washed with tap water and dried in air. Plate 1 shows the carried-out steps to prepare the crumbed rubber aggregate, while Table 10 lists the properties of this waste.

Table 10 Characteristics of the Rubber Waste Tier after Preparation.

Properties	**Results**	**Specifications**
Loose bulk density (kg/m³)	--	ASTM C 29-15 [35]
Compacted bulk density (kg/m³)	494	ASTM C 29-15 [35]
Specific gravity	1.100	ASTM C127-15 [36]
absorption (%)	4.8	ASTM C 127-15 [36]
Sieve analysis		
Sieve size (mm)	**Passing (%)**	**IQS No.45/2016 Limits for (10 mm) maximum size** [29]
14	100	100
10	97.5	85-100
5	12.4	0-25

a- Collection b- Washing by water

c- Treatment by Ca $(OH)_2$ solution d- Sieving through slandered sieves

Plate 1 Process of Preparing Rubber Waste from Damaged Tiers in this Investigation.

Plate 2 displays the recycled steel fibres that were obtained from the Diwaniya tires recycling plant. The length and diameter of the fibres were determined using statistical analysis [37]. A total of 1000 fibres were randomly selected from the fibres used in this study, and their lengths and diameters were measured using electronic tweezers with error rates of 0.01 mm. The lengths and diameters were then separated into seven and five groups, respectively. The findings are displayed in Fig. 2 and Fig. 3.

Plate 2 Recycled Steel Fibers Used in this Investigation After Preparation.

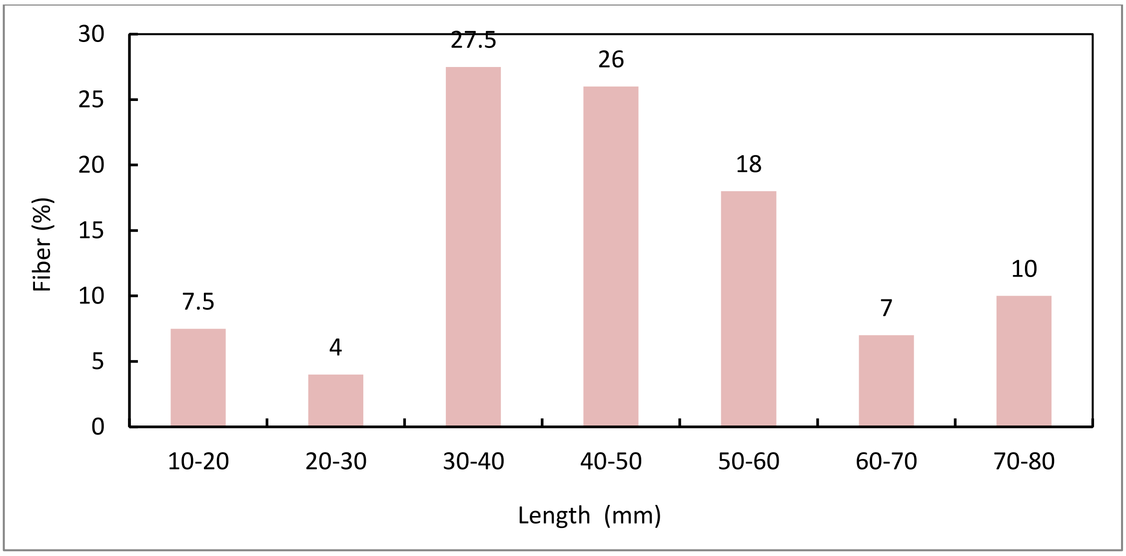


Fig. 2 Relative Frequency of Fibers Length.

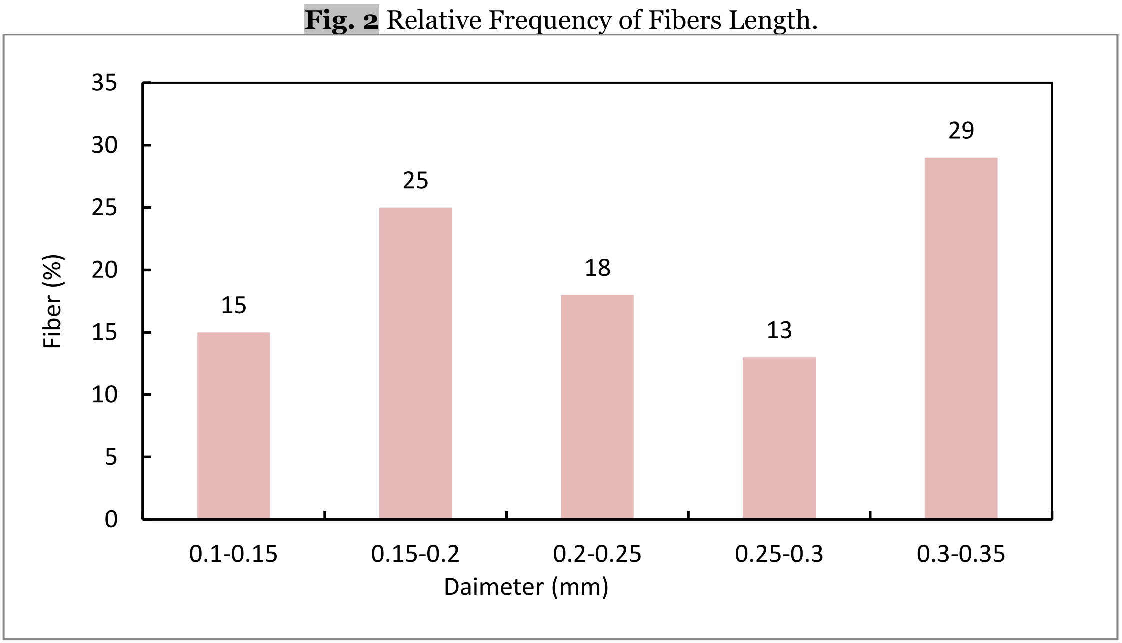


Fig. 3 Relative Frequency of Fibers Diameter.

The fibers' lengths varied from 4 to 37mm, with a 67% coefficient of variation. The reported length, which included the most fibre, was within the 30-40 mm range by 27.5%, implying that the average length of the fibre utilised in this investigation was 35 mm. The fibre diameter ranged from 0.2-0.35 mm, with a 74% coefficient of variance. About 29% of the fibers had a diameter of 0.3-0.35 mm, resulting in an average diameter of 0.33 mm. By dividing the fiber length by the fiber diameter, the fiber aspect ratio was obtained. The fiber's useful aspect ratio ranged from 60 to 100, and its length spanned from 4mm to 76mm [38]. Raising the aspect ratio of fibre enhances the flexural strength of concrete; nevertheless, it reduces the workability of the mixture. [39]. The aspect ratio of the recycled fiber wastes in this study was about 35/0.33≈ 106. Table 11 presents these recycled steel fiber properties.

Table 11 Physical and Chemical Properties of Recycled Steel Fibers.

Properties	**Recycled steel fiber**
Color	Gray
Shape	Irregular
Density (kg/m^3)	7850
Average length (mm)	35
Average diameter (mm)	0.33
Average aspect ratio	106
Surface texture	Invisible
Tensile strength (MPa) [40]	2239-2578
Chemical Properties [4]	
Iron (Fe)	97.24
Manganese (Mn)	0.97
Carbon (C)	E
Copper (Cu)	0.57
Cobalt (Co)	0.26
Silicon (Si)	0.2
Zinc (Zn)	0.11
Chrome (Cr)	0.06

2.2.Selection of Mix Proportion, Mixing Process, and Specimens Preparation

The preliminary selection of the geopolymer mixture was based on previous studies [41–45]. A 7-day age was chosen initially for the geopolymer mixture since it was the appropriate age based on Table 12. Several experimental mixtures were prepared to change metakaolin by adjusting the value of Si/Al (R) by the inclusion of different percentages of silica foam and calcium oxide as a partial replacement of metakaolin by weight, either together or separately, at ratios of (5, 10, and 15%). By adjusting the R-value from (1.781) to (1.914), it was found that adding 5% silica foam and 5% calcium oxide produced the best compressive strength with a value of 53.3 MPa. After several attempts with different concentrations of sodium hydroxide, alkali-to-binder ratios, and sodium silicate-to-sodium hydroxide ratios, it was found that the compressive strength was 58.6MPa. The binder content (modified metakaolin) was 372 kg/m^3 and had been modified with silica fume and calcium oxide at 21 kg/m^3 each as a partial replacement. The sodium hydroxide concentration was 12 molarity, the sodium silicate/sodium hydroxide was 2.5, and the alkali solution/binder ratio was 0.55. Many trial mixes were conducted to determine the mix proportion that produced the greatest compressive strength at the practical design age. Table 13 shows that mix 4 gives the highest compressive strength under curing conditions in the sun during August. The average temperature was 46°C during the day and 29°C at night until the test age was reached with a compressive strength of 58 MPa.

1- Metakaolin, silica foam, and calcium oxide were mixed by hand for two minutes.

2- As a partial replacement for natural coarse aggregate, all dry materials, including gravel, sand, modified metakaolin, and 10% crumbed rubber waste, were mixed with a mixer of 0.1 m^3 volume for two minutes.

3- The alkaline solution and extra water with the superplasticizer were added to the dry materials during the mixer's rotation and mixed for three minutes.

4- The mixing process was stopped for one minute to add the recycled steel fibers, which were spread manually over the mixture, and then the mixing process was resumed for 1-2 minutes.

5- The molds were coated with grease to prevent the mixture from adhering to the surface of the molds, and then they were transferred to the vibrating table for compaction for one minute.

6- To prevent evaporation, the samples' surfaces were leveled and covered with nylon.

7- The specimens were left in the laboratory for 24 hours. Different-sized molds were opened based on various test methods, and the specimens were cured in the summer under an average temperature of 46°C during the day and 29°C at night until the test date. Plate 3 details specimens prepared in the present study according to each stranded test.

Table 12 Compressive Strength of Geopolymer Concrete at Different Ages.

Curing age (days)	**Compressive Strength (MPa)**
7	43.3
14	50.3
28	50.8

Table 13 Proportions of Geopolymer Concrete Mixtures and Compressive Strengths.

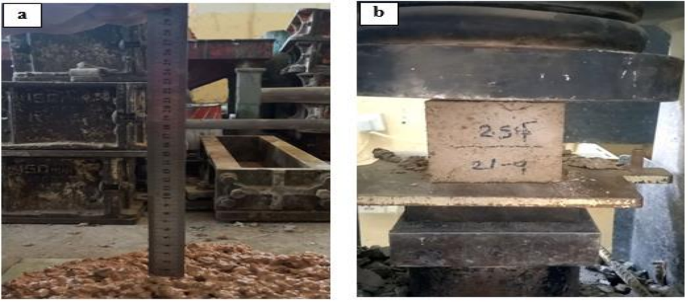
Mix No.	**Variables**	**MK***	**SF**	**CaO**	**CA***	**FA***	**SS***	**SH***	**SP***	**W***	**Compressive Strength (MPa)**
		(kg/m^3)									
M1	SH=12, SS/SH=2.5, AL/B= 0.55	372	21	21	955	632	162	71	8.3	85	33.3
M 2	SH=12, SS/SH=3, AL/B= 0.65	372	21	21	912	603	201	74	4	50	43.5
M 3	SH=12, SS/SH=3.5, AL/B= 0.75	372	21	21	870	575	241	75	4	28	44.1
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	57.2
M 6	SH=13, SS/SH=3.5, AL/B= 0.55	372	21	21	956	633	176	57	8.3	66	53.0
M 7	SH=14, SS/SH=2.5, AL/B= 0.75	372	21	21	868	574	221	95	4	32	57.1
M 8	SH=14, SS/SH=3, AL/B= 0.55	372	21	21	956	632	170	63	8.3	85	53.4
M 9	SH=14, SS/SH=3.5, AL/B= 0.65	372	21	21	913	604	209	66	4	54	57.3
R	SH=12, SS/SH=2.5, AL/B=0.55	414	--	--	911	574	193	83	4.8	50	44.3

* MK: Metakaolin, SF: Silica foam, CaO: Calcium oxide, CA: Gravel, FA: Sand, SS: Sodium silicate, SH: Sodium hydroxide, SP: High range water reducer, W: Water, Al/B: Alkaline solution/binder.

2.3.Testing the Geopolymer Concrete Specimens

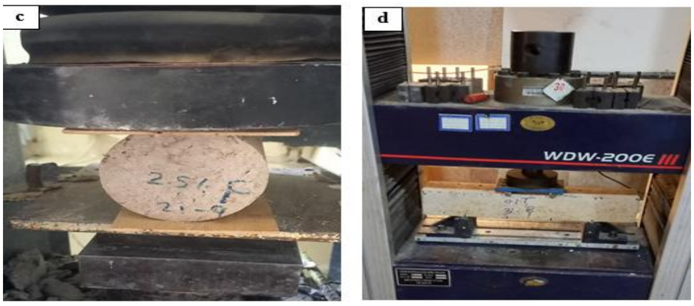
A total of 27 specimens were tested in the present study to determine the optimized grades of geopolymer concrete. Optimized mix ratios are shown in Table 13. Thirty-six 100×100mm cubes, 150mm diameter, 200mm high cylinders, and 100×100×400 mm prism were cast. Three cube, cylinder, and prism specimens were used to determine the average value of the compressive strength according to BS1881:part116 [46], split tensile strength according to ASTM C 496 [47], flexural strength according to ASTM C 78 [48], and flexural energy, for different type of geopolymer concrete (reference mixture, concrete containing 10% crumbed rubber, concrete containing 0.125 steel fiber, and concrete containing 0.25% steel fibers), respectively. Plates 3 and 4 illustrate some of the prepared specimens and different tests on GPC specimens. Slump value (workability) was found using a cone test described for cement concrete by ASTM C143 [49].

Plate 3 Some Geopolymer Concrete Specimens Prepared in this Study.



a- Slump test

b- Compressive strength test



c- Splitting tensile test

d- Flexural strength test

Plate 4 Different Tests for Geopolymer Concrete Specimens.

3.RESULTS AND DISCUSSION

Experimental tests for geopolymer mixtures consisting of reference geopolymer mixtures without waste (R), geopolymer mixtures containing 1٠% rubber waste (CR), and GPC reinforced with recycled steel fibers (RSF) were carried out to evaluate these GPC mixes properties. Initially, the RSF volume fractions selected were 0.5, 1, and 1.5%. Appropriate workability was not obtained due to the balling phenomenon with a volume fraction greater than 0.25%. This situation is consistent with that of Aiello et al. and Aghaee et al. [40,50,51] due to these wastes' different lengths, diameters, and aspect ratios. After several attempts, the ratios of adding recycled steel fiber were fixed, i.e., 0.125% and 0.25%, so they had appropriate workability.

3.1.Workability

The slump test was used to determine the workability and consistency of concrete. Fig. 4 shows the geopolymer concrete workability without wastes (R) containing 10% crumbed rubber aggregate reinforced with 0.125 and 0.25% recycled steel fibers. The results illustrated a decline in the slump values when recycled steel fibers were added to the GPC mixture and/or 10% crumbed rubber aggregate, even though the amount of plasticizer was increased to maintain the same workability. By comparing the slump values of the control mix to those of the recycled steel fiber mixes with 10% rubber aggregate, the recycled steel fibers (RSF) caused slump drops of 11.1% and 16.7% for GPC mixes reinforced with 0.125% and 0.25% RSF, respectively, which may be because of the high friction between the RSF and the other parts of the geopolymer concrete during the mixing process. The steel fibers tending to stick together while mixing reduced the workability of recycled steel fiber geopolymer concrete. This phenomenon is known as "balling." Also, the variance in the size and shape of the recycled steel fibers is one of the primary causes of the balling effect in newly formed geopolymer concrete [52].

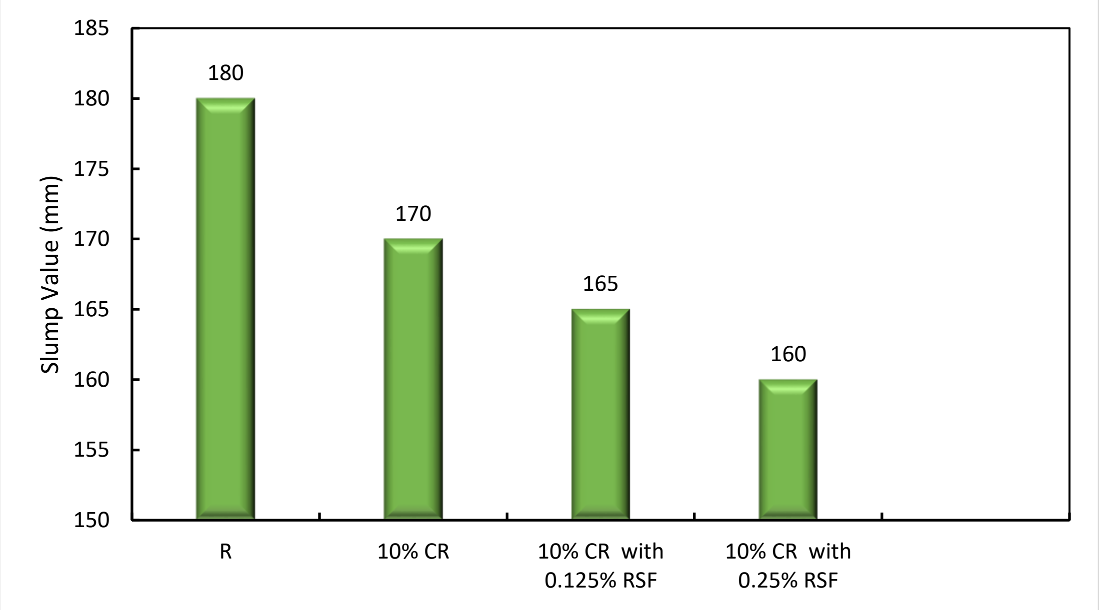


Fig. 4 Effect of 10% Crumbed Rubber Waste Aggregate and Different Recycled Steel Fibers Volume Fractions on the Geopolymer Concrete Workability.

3.2.Compressive Strength

The compressive strength of the reference geopolymer concrete (R) without any waste material, GPC with 10% rubber waste aggregate, and GPC with 10% rubber waste aggregate reinforced with 0.125% and 0.25% are shown in Table 14 and Fig. 5. The use of 10% rubber waste aggregate as a volumetric replacement for natural coarse aggregate in GPC significantly reduced the strength by about 38.6% relative to the reference GPC specimen. The strength loss may be due to the bonding loss between the crumb rubber aggregate and matrix, stiffness loss owing to the inclusions of crumb rubber aggregate wastes, and density reduction with a rise in the crumb rubber replacements [53,54]. The poor adhesion between the rubber and the matrix was attributed to the smooth texture of the crumbed rubber surface [23]. The SEM analysis, Plate 7, confirmed the bond between the rubber-geopolymer matrix interface was low. Including 0.125% RSF in GPC with 10% rubber waste aggregate improved the compressive strength by 43.3%. Including 0.25% RSF enhanced the compressive strength by 16% compared to GPC containing only 10% rubber waste aggregate. Generally, including steel fibers in any concrete improves its strength [55–57]. This enhancement in compressive strength is due to the high bond strength between the GPC and the recycled steel fibers, which leads to crackarresting capabilities and load transition to the sound matrix before failure and vice versa [55]. As well as, the inclusion of high-density recycled steel fibers in the geopolymer concrete mix increased the dry density of the mixture, resulting in a significant increase in compressive strength compared to geopolymer concrete containing 10% crumb rubber waste [58]. The decrease in compressive strength for GPC reinforced with 0.25% RSF was due to the high aspect ratio. The increase in the fiber dose beyond 0.125% volume fraction caused a less homogeneous distribution, resulting in a higher tendency to ball and, thus, improper compaction and larger voids in the microstructure of GPC [39,59].

Table 14 Compressive, Splitting Tensile, and Flexural Strengths of Different Geopolymer Concrete Mixtures.

Mix Symbol Property	R	10% CR	0.125% RSF	0.25%RSF
Compressive Strength (MPa)	58	35.6	51.0	41.25
Splitting Tensile Strength (MPa)	3.3	2.95	4.17	3.77
Flexural Strength (MPa)	4	3.75	7.14	5.34

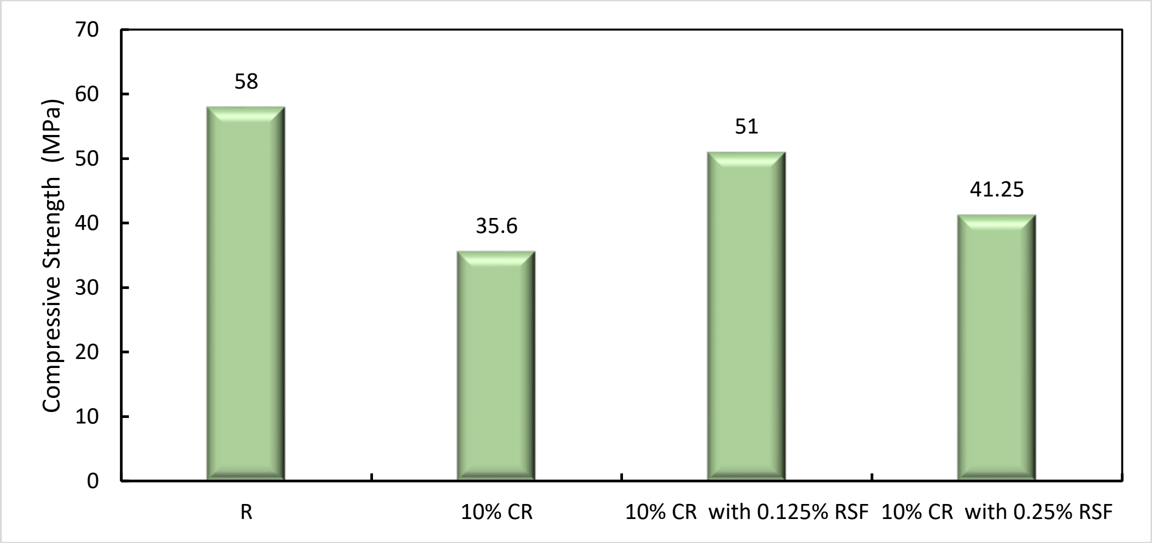


Fig. 5 Compressive Strength of Different GPC Specimens.

3.3. Splitting Tensile Strength

Table 14 presents the results of splitting tensile strength. As a volumetric substitute for natural coarse aggregate, 10% rubber waste aggregate reduced splitting tensile strength significantly by about 6.3% relative to the reference GPC specimen without waste due to the loss of bonding between the crumb rubber aggregate and matrix due to the smooth rubber particles surface, and the stiffness loss due to the inclusions of crumb rubber aggregate wastes [53,54]. However, the results showed that the splitting tensile strength increased by 26.4% and 14.2% for the 0.125% and 0.25% steel fibrous specimens, respectively, compared to reference mixtures without wastes. The increment of splitting tensile strength of rubberized geopolymer concrete containing fiber was attributed to the action of the steel fiber that was considered a bridge between the components of geopolymer concrete and between cracks as well as the considerable stiffness of the steel fiber, which increased the splitting tensile strength. Therefore, adding recycled steel fiber to rubberized geopolymer concrete specimens improved the splitting tensile strength and encouraged the addition of crumb rubber [60]. The explanation for the decrease in splitting tensile strength again when adding 0.25% steel fibers was due to the reduction in workability and, thus, increased porosity and voids.

3.4. Flexural Strength

GPCs containing different proportions of recycled steel fibers and rubber waste are shown in Table 14. Replacement of natural coarse aggregate with 10% rubber waste reduced the flexural strength by 10.6% compared to the reference GPC specimen without waste for the same reason above. Including recycled steel fibers increased the flexural strength by 78.5% and 33.5% for the 0.125% and 0.25% steel fibrous specimens compared to a reference without wastes. Similar improvements in splitting tensile and flexural strength due to recycled steel fiber inclusion were reported in previous studies [55,57]. This enhancement might be attributed to the hydrophilic character of recycled steel fiber [61], which strengthened the connection between the steel fiber and matrix. Furthermore, the high elastic modulus of steel fiber promoted stress dispersion, limited tensile fracture development, and enhanced mechanical strength [62]. Plate 5 depicts the typical failure mode of geopolymer concrete with 10% crumbed rubber and different percentages of recycled steel fibers. The brittle failure occurred in geopolymer concrete with natural coarse aggregate and without wastes. The concrete specimen was divided into two halves. Geopolymer concrete specimens with 10% rubber waste and/or recycled steel fibers failed in a ductile failure. After failure, all concrete specimens containing crumb rubber aggregate and recycled steel fibers may withstand the load for a few minutes compared to reference specimens without wastes. Adding steel fibers increased the deflection underload with flexural load resistance, which suggests that steel fibers were more ductile and acted as a bridge between the concrete components and the cracks. These findings are consistent with those reported by Eren et al. [63].

Plate 5 Failure Mode of Geopolymer Concrete Specimens with 10% Crumbed Rubber Aggregate and Recycled Steel Fibers Under Flexural Stress.

3.5.Total Flexural Energy (Toughness)

Area under a load-deflection curve indicates toughness representing the energy the material absorbs during a flexural load [64]. By ensuring sufficient toughness, a structure will prevent unexpected failures, improving safety overall. A sensor installed inside the testing machine assessed the deflection at the third mid-span during the flexural test for 100 x 100 x 400 mm prismatic specimens according to the American standards ASTM C78. This test can be used to determine a relationship between the load and deflection, allowing to compute the total flexural energy of each geopolymer concrete specimen. The toughness value was calculated from the area under the load-deflection curve after drawing the curve using the Excel program provided by a computer connected to the testing machine. Fig. 6 illustrates the total load-deflection relationship for geopolymer concrete specimens, while Fig. 7 shows the results of the total flexural energy. Using recycled steel fibers in all geopolymer concrete specimens (with 10% rubber waste coarse aggregate) generally transformed the failure mode from brittle to ductile, increasing the overall flexural energy. The results demonstrated that the total flexural energy of geopolymer concrete increased as the steel fiber content increased. The percentage increase was 142.8% and 312.1% for geopolymer concrete with 0.125% and 0.25% recycled steel fibers, respectively, compared with concrete specimens containing neither steel fiber nor rubber waste aggregate. This increase was attributable to the steel fiber's function as a connection bridging the macro and microcracks and transferring stress to sound concrete, thus increasing the failure stress and delaying the specimen's failure [63].

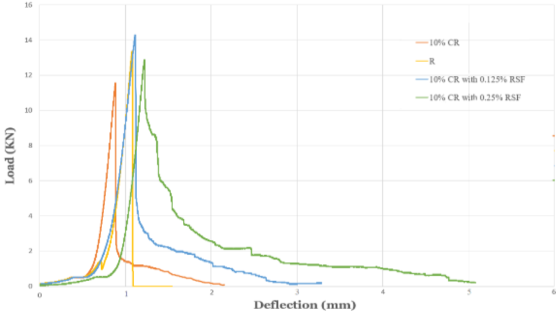


Fig. 6 Load-Deflection Relationship for Different Geopolymer Concrete Mixes.

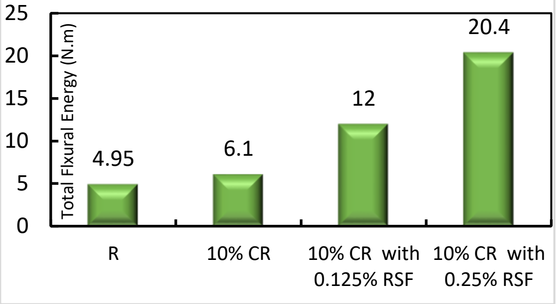
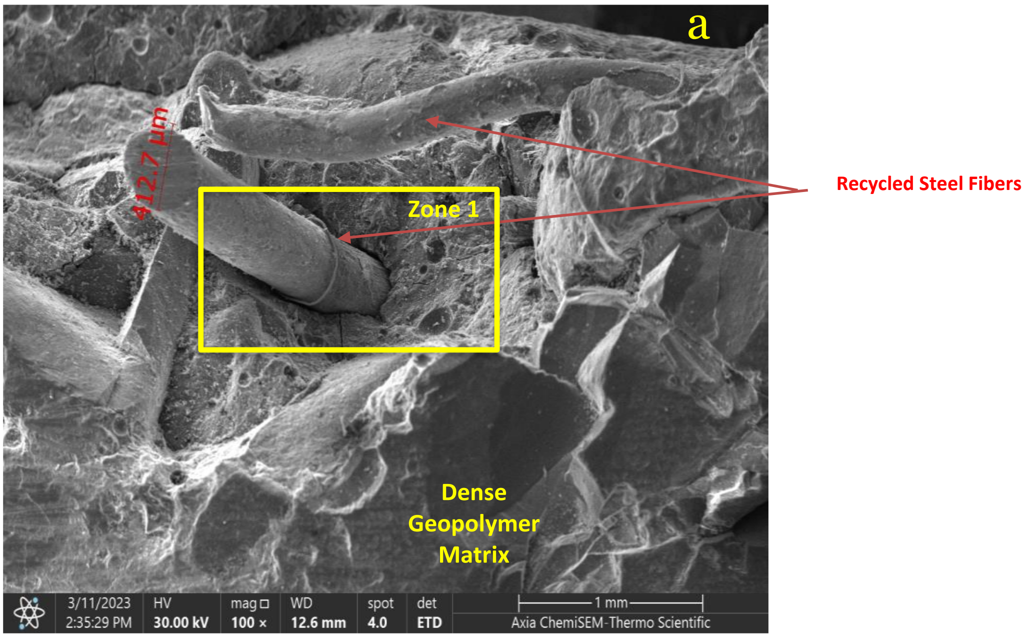


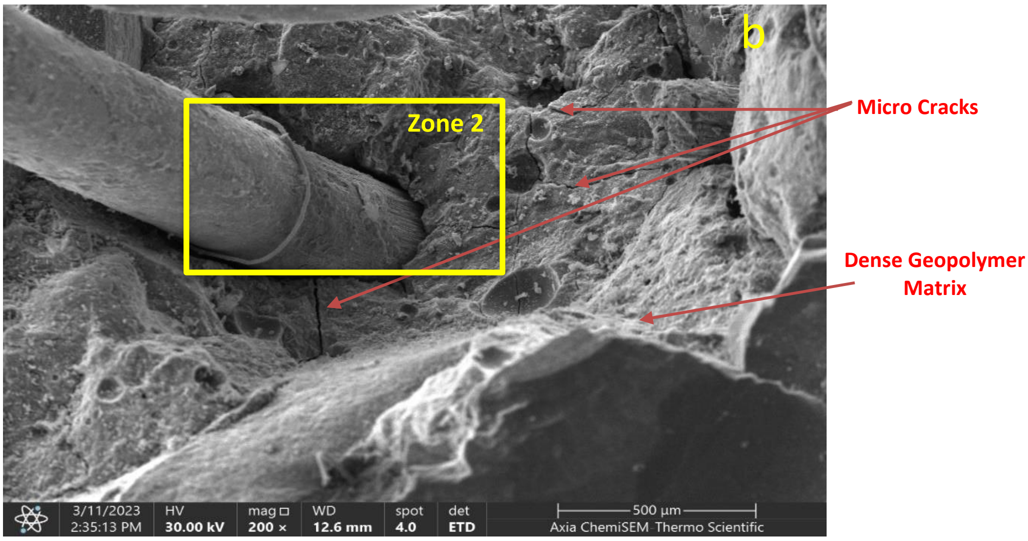
Fig. 7 Effect of 10% Rubber Waste and Different Percentages of Recycled Steel Fibers on the Total Flexural Energy of Geopolymer Concrete.

3.6.SEM of GPC with Recycled Steel Fibers

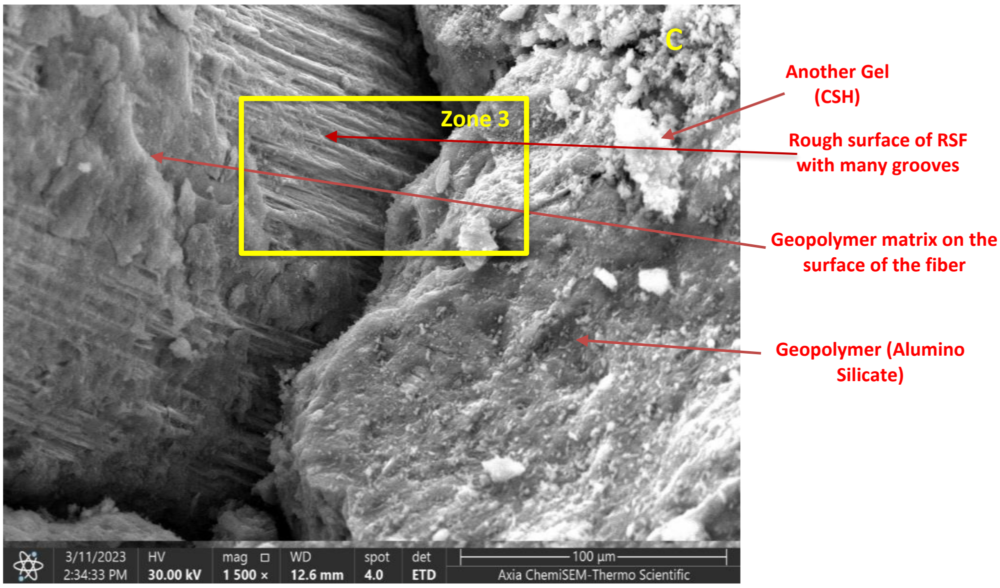
Plate 6 (a)-(f) depicts the fracture surface of a concrete specimen that contained 10% rubber waste and was reinforced with 0.125% recycled steel fibers. The geopolymer composite had a dense microstructure, as shown in all images because curing helps polymerization and fills the tiny pores, which was positively reflected in improving the mechanical characteristics of geopolymer concrete mixtures, such as the compressive, tensile, and flexural strengths, as presented previously from the experimental results. It can be noticed that the surface of the recycled steel fiber was coated with solidified geopolymer paste, which demonstrates the strong connection between the steel fibers and the geopolymer concrete matrix, implying that the recycled steel fibers surface was rougher and had deeper grooves than regular fibers [65,66]. These grooves enhanced the interface bonding by increasing the adhesion between the matrix and the fibers. Plate 6 (c)-(f) shows the RCF rough surface with many grooves. Moreover, fibers were demonstrated to arrest transverse microcracks and slow their integration into major fissures, enhancing the concrete's strength. Fiber-reinforced specimens exhibited ductile behavior when a load was applied to the composite's fracture, consistent with the experimental findings. The fibers were used as a stress-carrying bridge while limiting and delaying the expansion of fractures caused by the load, which increased this composite outstanding toughness. The GPC matrix in Plate 7 (a) (GPC without wastes) has a uniform geopolymer matrix and well-adhered aggregates with this matrix. In contrast, Plate 7 (b) (GPC with rubber) exhibited less uniformity and slightly more pores matrices with more pores and wider cracks in the geopolymer matrix, which is anticipated since the concrete mechanical strengths are often decreased by adding CRWA [23,67,68]. Cracks propagated throughout the sample's microstructure, although GPC without wastes exhibited fewer and narrower fractures, while GPC with rubber had greater propagation and broader cracks. The presence of a weak interfacial transition zone (ITZ) with a clear distance between the rubber particle and the matrix can be observed in the geopolymer concrete with 10% rubber, this implies that crumbed rubber is not bonded to the geopolymer matrix ; however, this distance was unclear in the geopolymer concrete without rubber. The non-clarity of the (ITZ) of geopolymer concrete without waste materials is probably due to the limited use of water in geopolymer concrete compared to cement concrete [67,69].



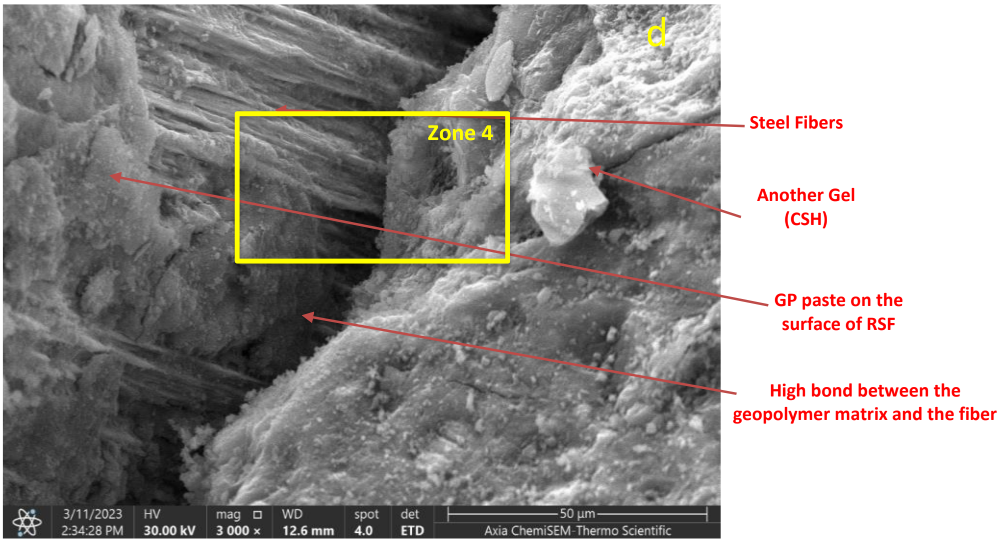
(a) SEM for GPC with 10% rubber waste aggregate and recycled steel fiber.



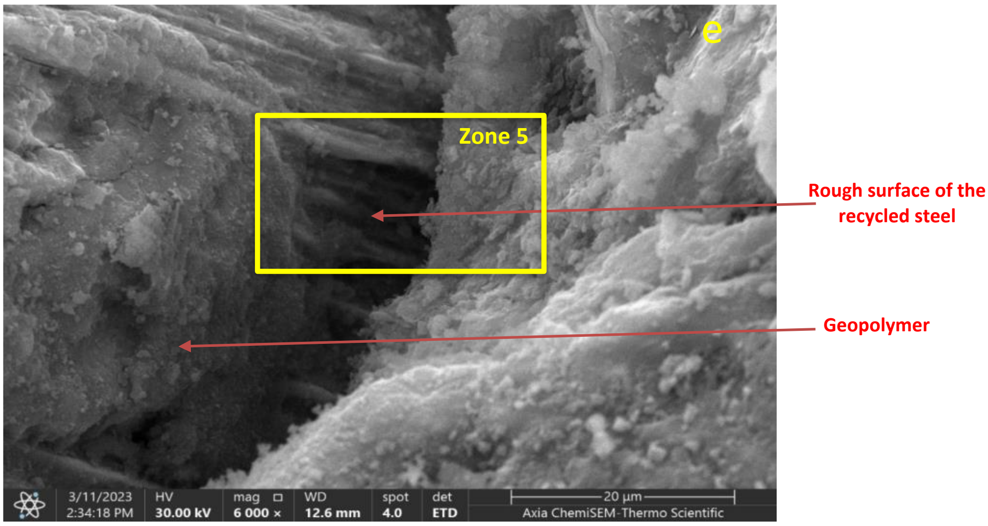
(b) SEM for GPC with 10% Recycled Crumbed Rubber and Recycled Steel Fiber (Zone 1).



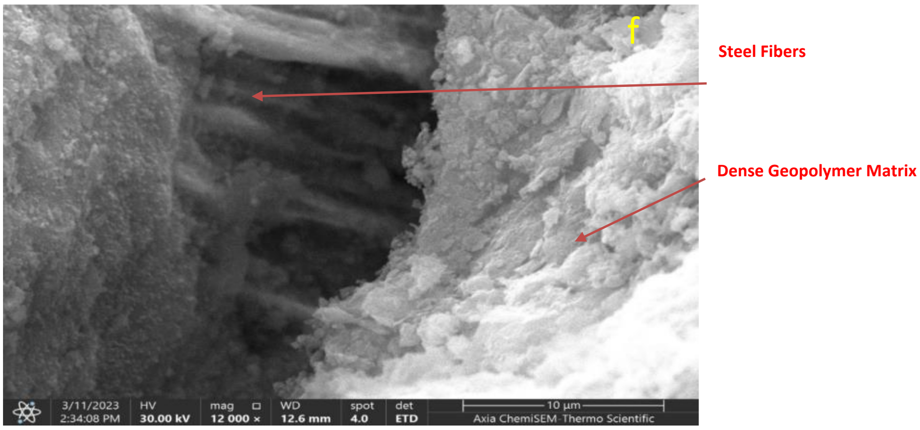
(c) SEM for GPC with 10% Recycled Crumbed Rubber and Recycled Steel Fiber (Zone 2).



(d) SEM for GPC with 10% Recycled Crumbed Rubber and Recycled Steel Fiber (Zone 3).



(e) SEM for GPC with 10% Recycled Crumbed Rubber and Recycled Steel Fiber (Zone 4).



(f) SEM for GPC with 10% Recycled Crumbed Rubber and Recycled Steel Fiber (Zone 5).

Plate 6 SEM Image of GPC Containing10% Crumbed Rubber Waste and 0.125% Recycling Steel Fibers Waste with Different Magnifications.

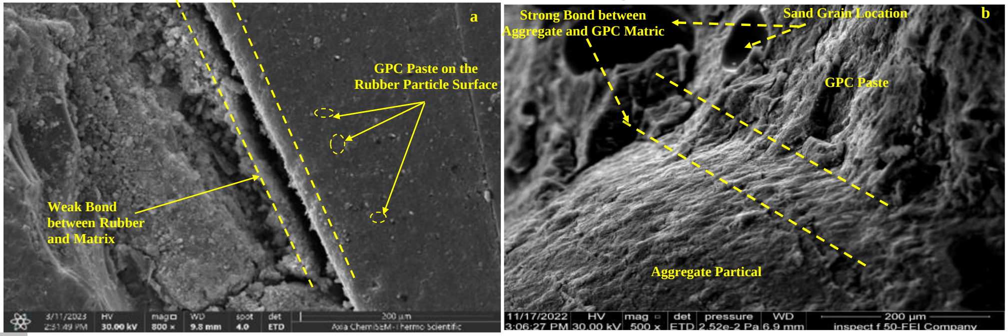


Plate 7 (a) SEM for GPC with 10% Crumbed Rubber Waste Aggregate and (b) Reference without Wastes Reference GPC without Wastes.

4.CONCLUSIONS

1- Including 10% rubber waste aggregate reduced the compressive strength of geopolymer concrete by 38.6% compared to concrete specimens without waste. While the compressive strength of geopolymer concrete increased when recycled steel fiber was added. The percentages increases were 43.3% and 15.9% for 0.125% and 0.25% volume fraction compared to a specimen containing 10% crumbed rubber only, i.e., using the fiber reduced the decrease in compressive strength due to the presence of crumbed rubber, as the percentage of decrease became 28.9% and 12.1% compared to reference specimen without wastes.

2- Using 10% rubber waste aggregate in geopolymer concrete reduced the splitting and flexural strengths. The reduction in splitting and flexural strengths were 21.2% and 16.5%; however, using the recycled steel fibers in geopolymer concrete increased the splitting and flexural strengths by approximately 78.5% and 33.5% for geopolymer concrete specimens containing 0.125% compared to the corresponding specimens without wastes.

3- The total flexural energy of geopolymer concrete increased by 23.2% with 10% crumbed rubber aggregate compared to the reference without waste. Also, the total flexural energy considerably increased by including recycled steel fibers. The percentage increase was 142.4% and 312.1% for specimens containing 10% crumbed rubber and reinforced with 0.125% or 0.25% recycled steel fibers, respectively, compared to the reference without wastes.

4- Despite the loss in mechanical characteristics, specimens containing rubber aggregate or recycled steel fibers exhibited ductile failure modes and failure that occurred without the specimen completely disintegrating.

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