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Fracture Toughness of Fibrous Concrete Incorporated with Treated Recycled Aggregates

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Abstract

This paper examines the effect of recycled concrete aggregate (RCA) on the behavior of concrete, particularly when combined with different fiber mesh and treatment techniques. Recycled concrete aggregate was treated using two treatment methods. Method 1 used a mix of cement, silica fume, and water, while Method 2 combined cement, silica fume, water, sand, and superplasticizer. Two types of fiber, glass and polypropylene (plastic) fiber mesh, were placed across the expected crack path to study their effect on crack resistance. A total of 24 prisms were cast and tested. Tests measured slump, absorption, unit weight, compressive strength, and fracture toughness. The findings indicate that using recycled concrete aggregate decreases strength and workability compared to normal aggregate. Treated recycled aggregate enhanced the strength, especially in Method 2, which provided compressive strength even higher than normal aggregate. However, fracture toughness decreased due to the sudden formation of cracks. Interestingly, concrete made with untreated recycled concrete aggregate and glass fiber exhibited better crack resistance and fracture toughness. This study compares RCA treated using two different methods and reinforced with two types of fiber mesh, showing that minor changes in the mix design can enhance the behavior of concrete made with RAC.

Keywords: Treated Recycled Aggregate Concrete; Fracture Toughness; Concrete Compressive Strength; Glass Fiber Mesh; Polypropylene Fiber Mesh.

1. Introduction

Recycled concrete aggregate (RAC) comes from sources such as demolished reinforced concrete buildings and waste concrete constructions. It contains dust, old mortar, and other materials stuck to its surface, which makes it different than the normal aggregate. RCA typically has higher water absorption and lower density and strength compared to normal aggregate. These properties affect the quality of concrete prepared with RAC, making it weaker and restricting its applicability for structural purposes [1–3]. Studies showed that replacing normal aggregate with RCA reduces both durability and strength [4, 5]. This makes it important to find a way to enhance the characteristics of RCA before incorporating it into concrete. Many researchers have examined different treatment techniques to improve the characteristics of RCA. Treatment helps in reducing water absorption, removing the adherent mortar and other material, and improving the bond with the surrounding cement paste.

Many studies examined different treatment methods. Liang et al. [6] studied three different mixing methods and two pretreatment materials to enhance the RCA quality, specifically compressive strength. Their results show that using suitable surface pretreatment and mixing approach improves the RCA properties. This enhancement may raise the compressive strength of concrete with 100% RCA to reach 43.3 MPa. Ismail & Ramli [7] examined the quality of concrete created with treated RCA and several types of fibers. They concluded that the concrete prepared with treated

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RCA gave better impact resistance. The incorporation of fibers improved this effect, resulting in concrete three times stronger compared to concrete made with normal aggregate. Srinivasa Reddy et al. [8] studied the properties of treated RAC using different treatment techniques. Their results found that treating RCA using bacteria enhanced the compressive strength by reducing the high porosity and water absorption. Garg et al. [9] evaluated the effect of incorporating several dosages of S2 glass fiber and replacement ratios of RCA on the fracture energy. Their findings indicated that incorporating S2 glass fiber changes the concrete behavior from brittle to ductile. The fracture energy exhibited a reduction by about 20% with a 60% replacement ratio of RCA.

Altun & Oltulu [10] studied the effect of using three types of fibers on the behavior of RCA: polypropylene, steel, and hybrid fibers. They found that steel fiber increased the strength, while the hybrid fibers provided the best mechanical performance. Chen et al. [11] explained different methods to treat RAC, such as polymer emulsion and pozzolanic solution. They found that the polymer emulsion technique enhances both the workability and durability of recycled concrete. Alqarni et al. [12] examined three different techniques to treat RAC. The three methods are: mechanical cleaning, acid soaking, and cement slurry coating. They found that the cement slurry coating method provided the best enhancement in both compressive and tensile strength. Li et al. [13] investigated the durability of concrete made with RAC and treated with permeable crystalline materials. The results show that the treated concrete exhibited better durability than the untreated concrete. Liu et al. [14] studied the behavior of concrete created with RAC and recycled polypropylene fiber. Their results showed that for a 100% replacement ratio of RAC, the compressive strength was almost the same compared to normal aggregate. Li et al. [15] studied the effect of using CO_2 curing as a treatment method on the properties of RAC. They found that using this technique improved the characteristics of RAC by reducing its porosity and water absorption. Dicha et al. [16] investigated the behavior of concrete made with RAC treated with a diatomaceous earth slurry reinforced with banana fibers. The results showed an improvement in the fracture energy and concrete resistance. The study also supports environmental sustainability by incorporating agricultural waste.

In the current study, RCA was treated using two different methods: Method 1, a mix of cement, silica fume, and water was used, and Method 2, a mix of cement, silica fume, water, sand, and superplasticizer was used. Two types of fiber mesh (Glass and Polypropylene) were placed so they intersect with the expected crack path of the specimens (prisms). The prisms were tested for fracture toughness. This research aims to enhance the behavior of RCA and examine its effect on concrete strength, ductility, and durability. Also, analyzing the influence of the inclusion of fiber mesh with treated recycled aggregate. Another objective is to support the ability to use treated recycled aggregate, through effective treatment solutions, in structural concrete.

2. Experimental Program

2.1. Materials

In this research, all the materials used were examined at the construction materials test laboratory at the Department of Civil Engineering in the University of Mosul.

Cement: Ordinary Portland cement, type I (Sinjar), manufactured in Iraq, was used, which meets I.Q.S requirements [17]. The physical characteristics are listed in Table 1 and the chemical characteristics are listed in Table 2.

Table 1. Cement Physical Properties

Characteristics	Value	I. Q.S Specifications [17]
Standard Consistency w/c	0.285	
Initial Setting (Minutes)	150	≥ 45
Final setting (Minutes)	276	≤ 600
Compressive Strength (2 days) (N/mm^2)	24.5	≥ 10
Compressive Strength (28 days) (N/mm^2)	34.6	≥ 32.5

Table 2. Cement Chemical Property

Chemical Components	Value %	I.Q.S Specifications [17]	Chemical Components	Value %
SiO_2	19..20	-	C_3S	54.12
AL_2O_3	5.13	-	C_2S	14.22
Fe_2O_3	3.63	-	C_3A	7.44
CaO	61.21	-	C_4AF	11.06
MgO	2.66	≤ 5.0	L.S.F	95.86
SO_3	2.17	≤ 2.5	Solid Solution	16.95
Free Lime	1.82	-		
Loss on ignition	0.14	≤ 4.0		
Insoluble residue	0.26	≤ 1.5		

Fine Aggregate (Sand): Fine aggregate, which is locally available, was used. Sieve analysis was conducted according to I.Q.S. No. 45/1984 [18] as shown in Table 3. The specific gravity and absorption were found to be 2.67 and 2%, respectively.

Table 3. Sieve analysis of fine aggregate

Sieves No.	% Passing	I.Q.S Specifications [18]
NO. 4	100.0	100-90
NO. 8	89.5	100-75
NO. 16	79.8	90-55
NO. 30	44.6	59-35
NO. 50	30.6	30-8
NO. 100	4.2	0-10

Coarse Aggregate: Normal rounded and recycled concrete aggregate were used. Sieve analysis [18], specific gravity [18, 19], and % absorption [20] tests were conducted on each type of aggregate.

- Normal rounded aggregate: Sieve analysis of the normal rounded aggregate meeting the Iraqi specification (I. Q.S) [18] was conducted as shown in Figure 1. The specific gravity was (3.26) and absorption (0.61%), as listed in Table 4.

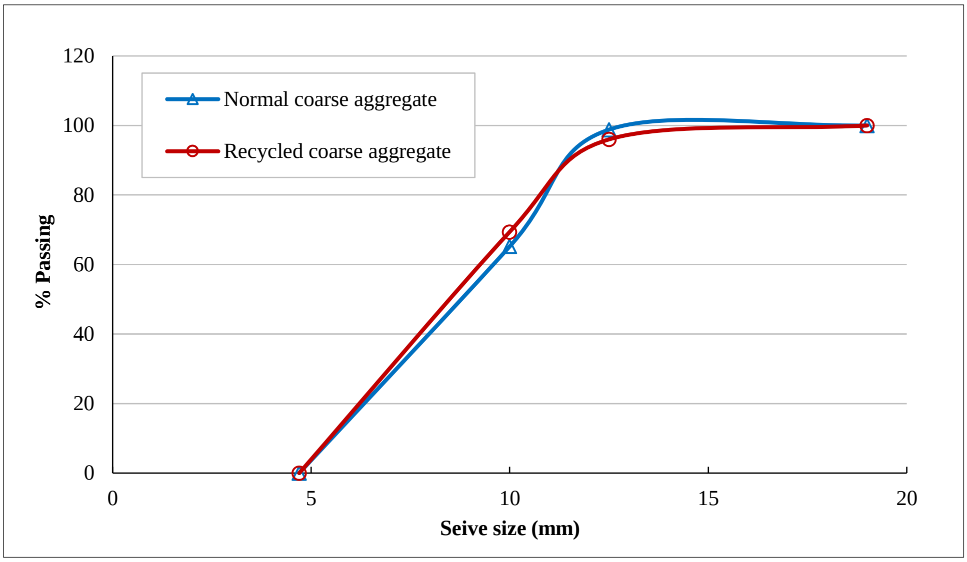


Figure 1. Sieve Analysis of Coarse Aggregate

Table 4. Characteristics of Normal and Recycled Aggregate

Tests	Normal Aggregate	Recycled aggregate		
		Untreated	T1	T2
Specific gravity [14]	3.26	3.05	2.75	3.16
% Absorption [15]	0.61	2.65	3.03	2.86

- Recycled concrete aggregate (RCA): The RCA was provided by a local factory affiliated with the Mosul Municipality. Demolished construction materials were used as a source of this aggregate.

For comparison purposes, recycled aggregate in this study was used with and without treatment.

- Recycled concrete aggregate without treatment (RC-U): The recycled aggregate without treatment (untreated aggregate) was coded as (RC-U). The sieve analysis of the untreated aggregate is shown in Figure 1. The specific gravity was 3.05 and the Absorption was 2.65 %, as shown in Table 4.

Recycled concrete aggregate with treatment (RC-T): The treated recycled aggregate was coded as (RC-T). Two different methods were used in the treatment: Method 1, coded as (RC-T1), and Method 2 as (RC-T2). The specific gravity and Absorption are listed in Table 4.

Treatment Methods: Two methods were used in the treatment of recycled concrete aggregate as follows:

- **Method 1:** In this method, cement, silica fume, and water were mixed to produce a slurry as shown in Figure 2-a. The material were mixed in a ratio of 1:0.45 (cement: w/c ratio). Silica fume with 10% replacement by cement weight was added. Six cubes 70*70 *70 mm were cast and tested as shown in Figure 2-b. The results from the test of compressive strength at 7 and 28 days are listed in Table 5.

(a) (b)

Figure 2. (a) Slurry produced from the mix (Method 1), (b) Cast cu

Table 5. Results of compressive strength for the mixture in Methods 1 and 2

Treatment Method	Compressive strength (MPa) 7 days	Compressive strength (MPa) 28 days
Method 1	25.5	29.9
Method 2	33.0	36.38

- **Method 2**: In this method, a mix of silica fume, cement, sand, water, and superplasticizer was used to make the slurry as shown in Figure 3-a. A mix ratio of 1:1:0.45 (cement: sand: w/c ratio) was used. Silica fume with 10% replacement by cement weight was added. 50 g of superplasticizer (PC200) was also used to maintain the consistency. Six cubes 70*70*70 mm were cast and tested (See Figure 3-b). The results of the compressive strength test at 7 and 28 days are listed in Table 6.

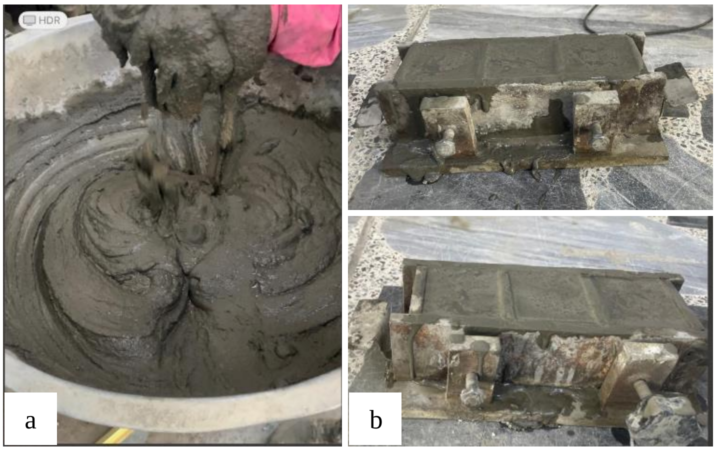


Figure 3. a) Slurry produced from the mix (Method 2), b) Cast cubes

Table 6. Cross area of fiber and equivalent area of each mesh per (50 mm length)

Fiber type	Cross section area of single fiber (mm^2)	Total area per (50 mm length) for 1-mesh (mm^2)	Equivalent area per (50 mm length) for n-mesh (mm^2)
Glass	0.175	1.94	3.88 (2 meshes)
Polypropylene (Plastic)	0.66	1.99	3.96 2 meshes)

- **Treatment procedures:** The dry materials were mixed first (cement and silica fume), then the water was added and mixed to get a slurry with the required consistency, as shown in Figure 4-a. Then, the recycled concrete aggregate was gradually added to the slurry, as shown in Figure 4-b. The aggregate was left in the slurry for one hour. After that, the aggregate was spread for 24 hours in the laboratory atmosphere as shown in Figure 4-c. The aggregate was cured in a water pan for 3 days, as shown in Figure 4-d.

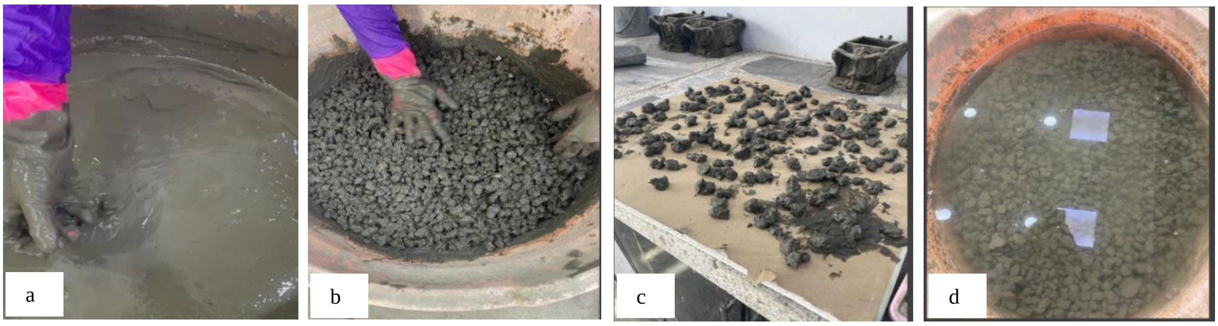


Figure 4. Treatment process: a. Preparing the slurry, b. Treating the RCA, c. Spreading the aggregate, and d. Curing

In Method 2, the treatment process was similar to Method 1, with adding sand and superplasticizer to produce the slurry.

- **Effect of Treatment on Recycled Concrete Aggregate**

Weight: The impact of the treatment using Methods 1 and 2 on the RCA weight was studied. Two samples weighing 1kg of recycled concrete aggregate before treatment were taken. The first sample was treated using Method 1 and coded as T1, and the second sample was treated using Method 2 and coded as T2. After one hour of treatment, the weight of both samples was measured every quarter of an hour, with the specified time being one hour. Then, the weight was measured after 10 hours. Figure 5 shows weight versus time for both samples. Figure 5 shows that, in both treatment methods, there was a notable increase in the sample's weight compared to the untreated (control), and then the weight started to decrease with time. Figure 5 also shows that the weight increased more when using Method 2.

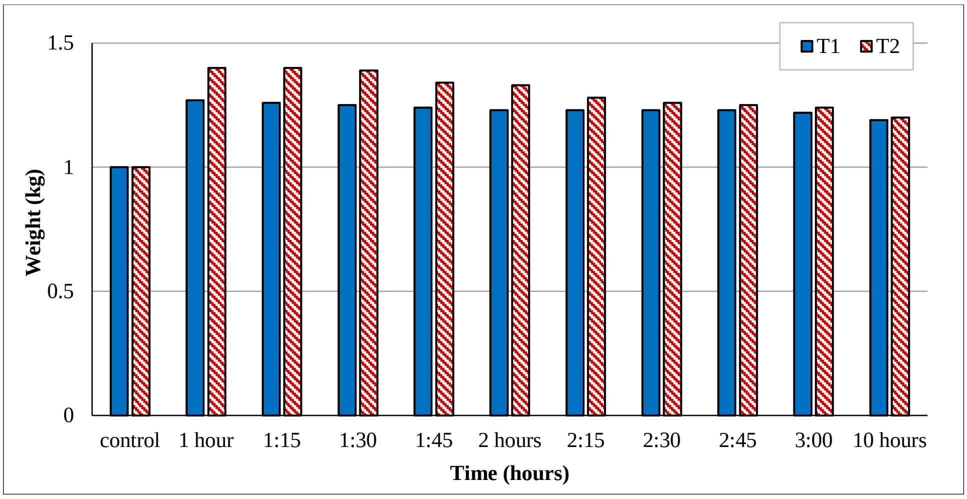


Figure 5. Weight versus time of the treated RCA

Dimensions: The impact of the treatment using Method 1 on the recycled aggregate concrete particle dimensions was studied. An arbitrary particle was selected before treatment, and the same particle was used after treatment to measure the change in dimensions. Figure 6 shows partial dimensions before and after treatment. There was a notable increase in the dimensions.

(a) Before treatment

(b) After treatment

Figure 6. Partial dimensions, a) before treatment, b) after treatment

- **Fiber mesh:** Glass and polypropylene (plastic) fiber were used, as shown in Figure 7. Table 6 show cross area of fiber and equivalent area of each mesh per (50 mm length)

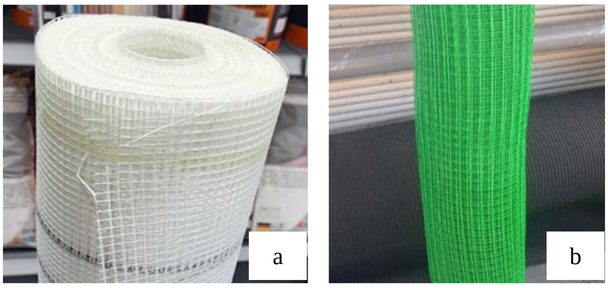
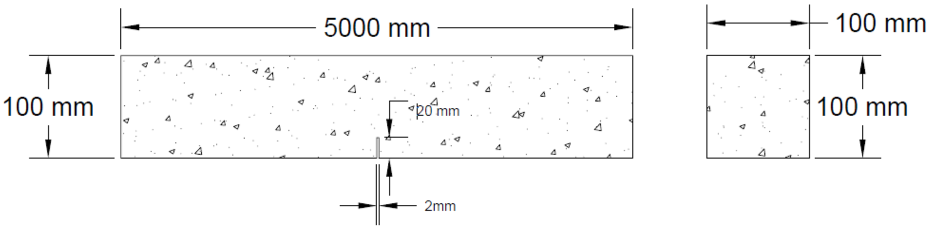


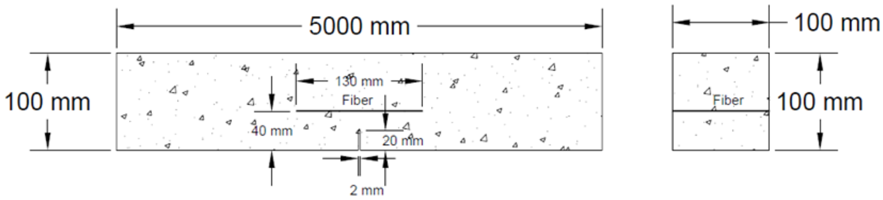
Figure 7. a). Glass fiber, b). Polypropylene (plastic) fiber

2.2. Details of Mixtures and Mixing Procedures

A total of 48 specimens, 24 prisms measuring (100*100*500 mm) with notches, with and without fiber mesh as shown in Figure 8, and 24 cubes measuring (100*100*100 mm) were prepared and cast in this research. As shown in Figure 8, the prism notch's dimensions are 20 mm in height and 2mm in width. For specimens contain fiber sheets, the fibers were placed at a 40 mm from the bottom of the specimen, with a dimension of 100*130 mm.



a) Specimen with notch and without fiber



b) Specimen with notch fiber

Figure 8. Specimens, a). Without fiber, b). With fiber

The details of the mixtures utilized in the present research are listed in Table 7. The normal mix uses normal rounded aggregate without recycled aggregate. The remaining mixtures were made with RCA (100% replacement of normal aggregate), containing RCA treated using two different methods and two types of fiber mesh.

Table 7. Details of each mix

Mixtures	Cement (kg/m^3)	Sand (kg/m^3)	Normal Aggregate (kg/m^3)	Recycled Aggregate (kg/m^3)	Water (kg/m^3)	Glass fiber	Polypropylene (Plastic) fiber
Normal	400	850	900	0.0	170	-	-
Normal-GF	400	850	900	0.0	170	with	-
Normal-PL	400	850	900	0.0	170	-	with
RC-U	400	850	0	900	170	-	-
RC-U-GF	400	850	0	900	170	with	-
RC-U-PL	400	850	0	900	170	-	with
RC-T1	400	850	0	900	170	-	
RC-T1-GF	400	850	0	900	170	with	-
RC-T1-PL	400	850	0	900	170	-	with
RC-T2	400	850	0	900	170	-	-
RC-T2-GF	400	850	0	900	170	with	-
RC-T2-PL	400	850	0	900	170	-	with

A mixing machine was used for all the mixtures. The dry materials were mixed first (aggregate (coarse and fine), and cement). Then, water was added to the dry material and mixed well to get a homogenous mixture. Before pouring the specimens, the slump test was conducted [21]. Then, 12 specimens of each mix (6 cubs and 6 prisms) were cast according to the specifications. During the cast, the fiber mesh was installed. The notches were made using a steel plate with the required dimensions. After 24 hours, the specimens were demolded and cured in water tanks. Figure 9 shows mixing procedures. The research methodology is shown in Figure 10.

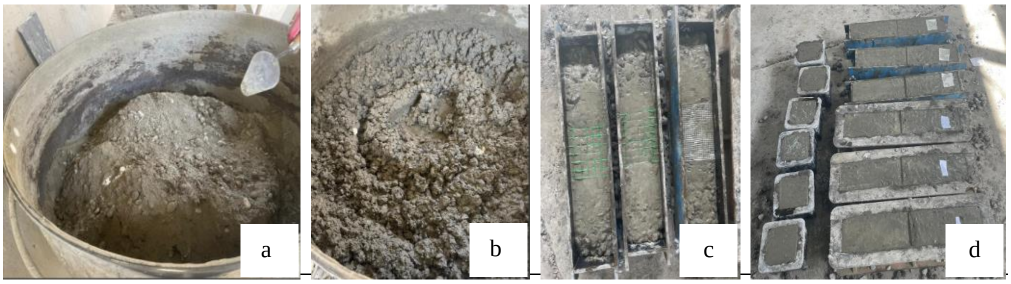


Figure 9. Mixing procedures: a). mixing dry material, b). add water, c). casting the specimens with fibers, d). cast specimens

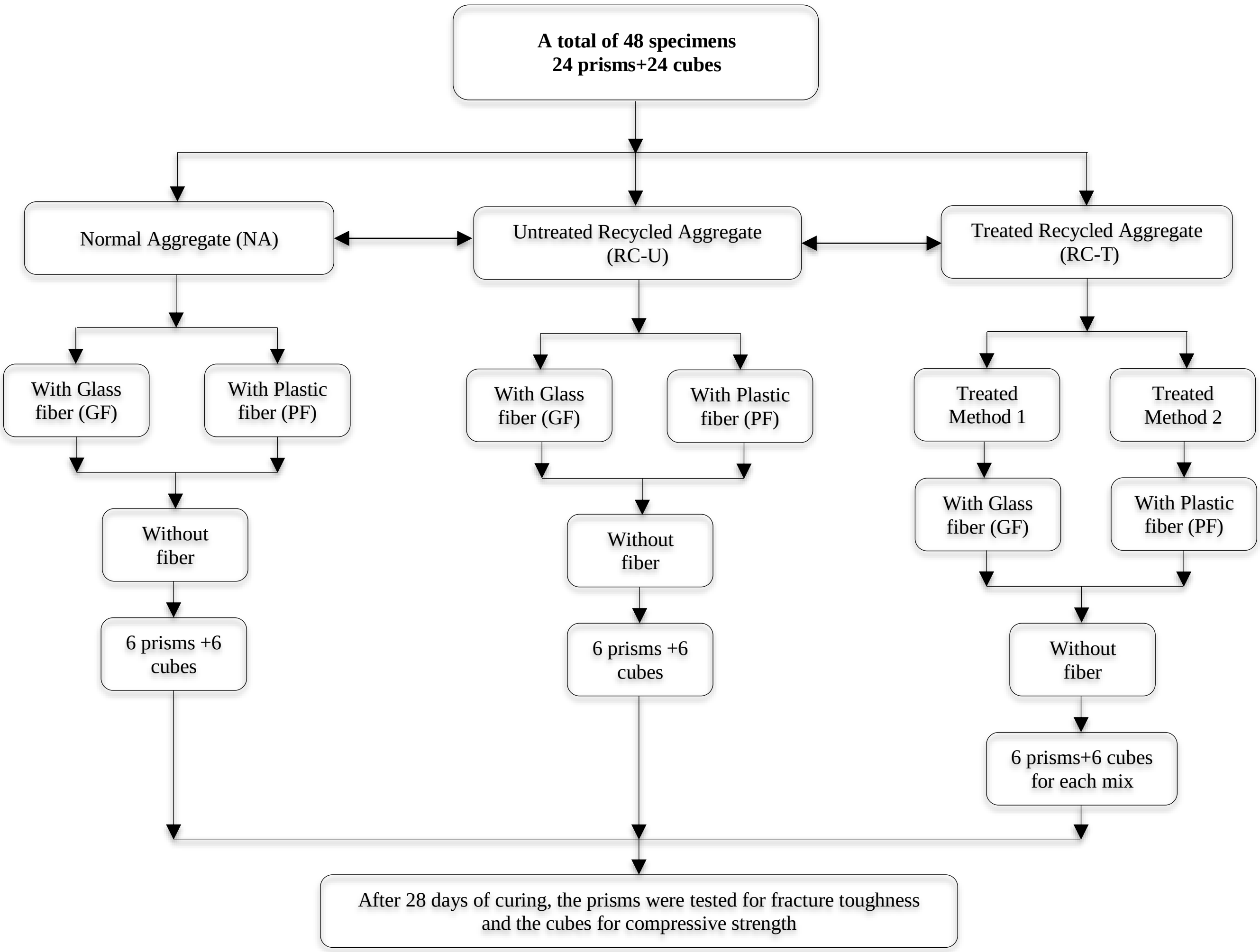


Figure 10. Research methodology

3. Experimental Findings and Discussion

3.1. Fresh Concrete Behavior

The slump test was performed following ASTM C143 guidelines [21]. Figure 11 shows slump values versus mixture from the test.

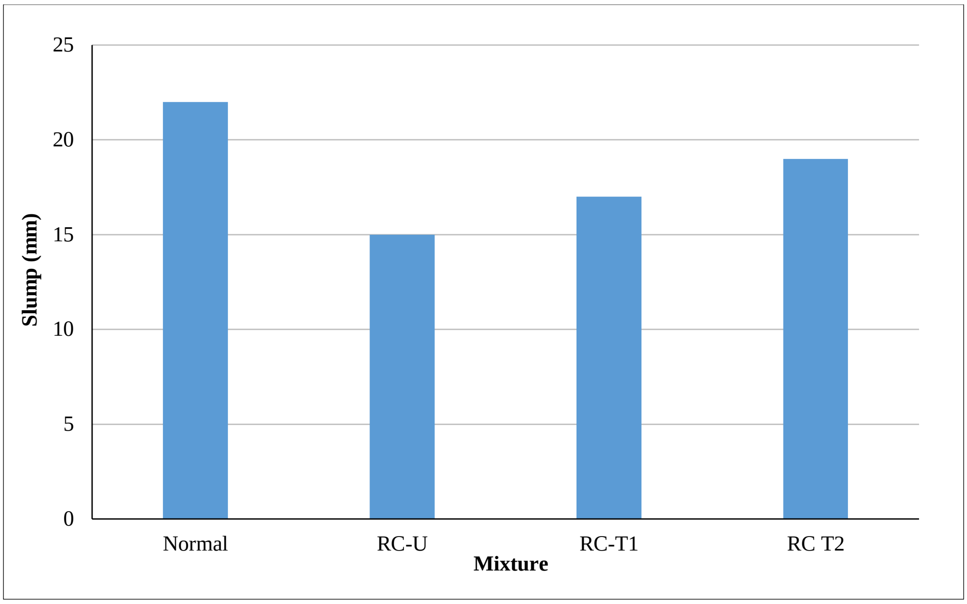


Figure 11. Slump test values versus mixtures

Figure 11 shows that concrete created with normal aggregate exhibited the highest slump value, followed by concrete prepared with treated RCA, then concrete created with untreated RCA, which shows the lowest slump value. These results are consistent with Silva et al. (2014) [22]. The properties of untreated RCA, such as a rough surface and high porosity, increased water absorption and internal friction between particles. All this tends to reduce the amount of water in the mix and provide a lower slump. These results align with Kou & Poon (2012) [23].

Compared to untreated recycled aggregate, treated aggregate using both methods showed an improvement in concrete workability. Using silica, cement, and water in the first method helped in coating the aggregate surface, filling the pores, which results in reducing the absorption of water, improving the surface texture, and improving the workability. Adding sand and superplasticizer to silica, cement, and water in the second method provided better results. The presence of sand and superplasticizer produced a denser and more uniform coating layer, resulting in less porosity and a smoother surface.

These results are consistent with the results from the current study. The water absorption test results (See Table 4) show that the aggregate treated using Method 2 exhibited a lower value compared to the aggregate treated using the first method. The better coating in the second method decreased the loss of water in the mixture and the friction between the particles, resulting in improved workability. These findings align with Wang et al. (2020) [24] and Zhao et al. (2022) [25].

Based on these observations, treating the surface of recycled RCA enhances the properties of fresh concrete and ensures a higher quality of concrete. This is important to practical applications, where the slump variation may affect the placement, compaction, and finishing of concrete. As a result, when incorporating RCA in concrete, it is important to choose an efficient treatment method to maintain workability and consistency.

3.2. Hardened Properties

3.2.1.Absorption and Unit Weight

The absorption and unit weight test were conducted according to ASTM C642-13 [26]. Figure 12 shows the absorption test results. These results indicate that the concrete prepared with untreated RCA provided a higher absorption value compared to the concrete created with normal aggregate. This is due to the high porosity and the adherent mortar on RAC particles. These results are consistent with Silva et al. (2014) [22] and Katz (2003) [27]. Compared to concrete prepared with untreated RCA, the concrete created with treated RCA exhibited lower absorption. This is due to the coating effect, which reduces the surface pores and fills the internal voids. The concrete made with recycled aggregate treated using the second method, containing silica, cement, sand, and water, provides the lowest absorption. The presence of sand helped in filling the surface pores and internal voids more uniformly and resulted in a denser coating. These results agree with Zhao et al. (2022) [25].

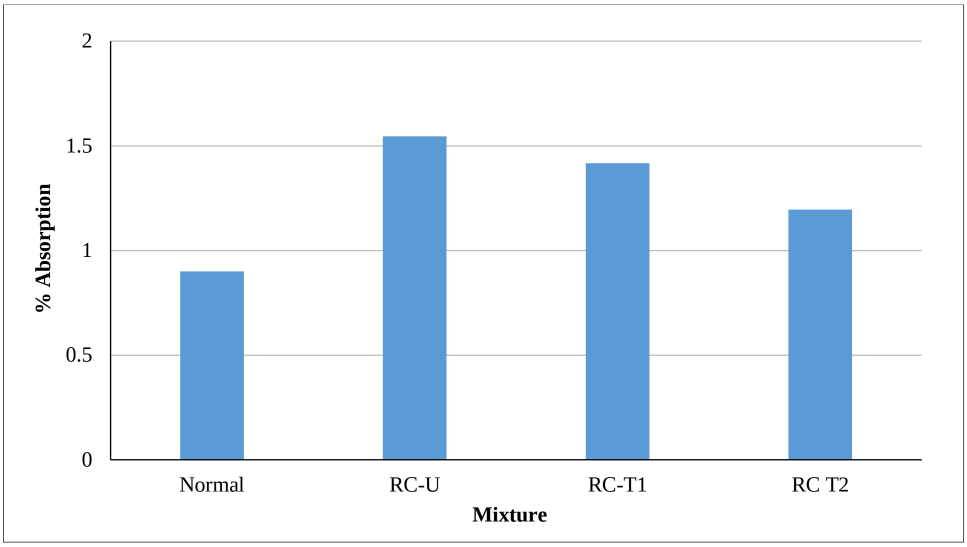


Figure 12. Absorption versus Mixtures

These results show how essential it is to treat the surface of RCA. The treatment improves the quality of recycled aggregate by reducing absorption, increasing the concrete's long-term performance, and durability. Furthermore, it limited undesired water loss from the mix. As a result, treated RAC is more suitable for structural uses where moisture resistance is crucial.

Figure 13 shows the results of dry unit weight. These results indicate that concrete constructed with RCA exhibited lower unit weight compared to concrete produced with normal aggregate. This is likely due to the lower specific gravity of recycled aggregate (See Table 4). Nevertheless, the unit weight of concrete constructed with treated aggregate RCA increased compared to the unit weight of concrete prepared with untreated RCA. This behavior is caused by the reduction of the internal void and the denser coating provided by the treatment methods. The improvement in the dry unit weight is also caused by the lower absorption values (See Figure 13). This result is align with findings in Wang et al. (2020) [24].

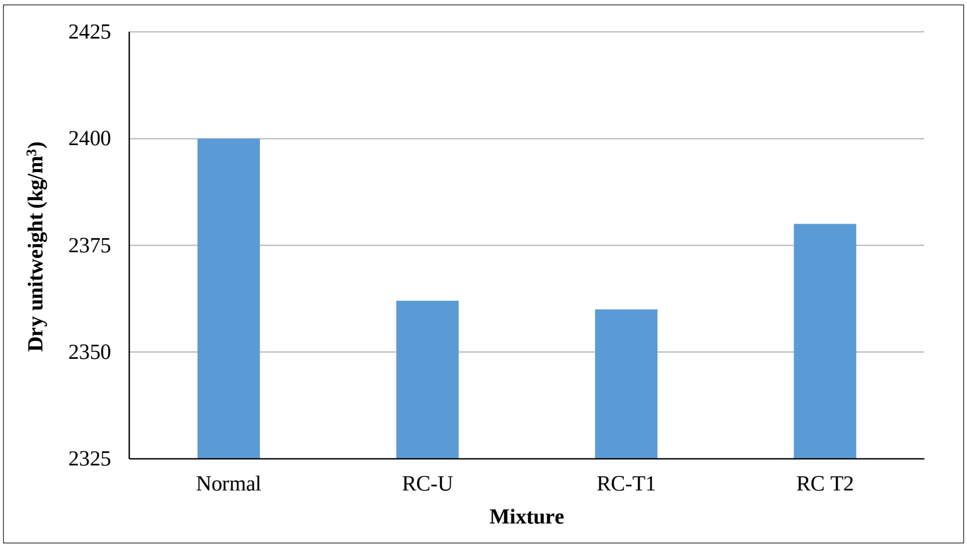


Figure 13. Unit weight versus mixtures

The increase in unit weight indicates better particle distribution and lower porosity, making the concrete stronger and more durable. Treating RCA, especially using Method 2, is promising and shows its ability to replace natural aggregate in structural applications without losing important properties.

3.3. Mechanical Characteristics

3.3.1. Concrete Compressive Strength

The compressive strength was determined following BS EN 12390-1:2000 [28]. Figure 14 shows compressive strength versus mixtures. This figure indicates that concrete created using untreated RCA had lower strength compared to the concrete created using normal aggregate. When normal aggregate was completely replaced, the strength decreased by 10%. This is caused by the weak nature of RCA, leading to a weaker bond in the transition zone (ITZ) between the RAC particles and the surrounding cement pastes. This results align with the results found by Kou and Poon (2012) [23] and Mindess et al. (2003) [29]. Figure 14 also shows that the strength of concrete created using treated RCA was higher than the strength of concrete created using untreated RCA. Among the two treating methods, Method 2 (containing silica, cement, sand, water, and superplasticizer) exhibited higher compressive strength. Further, the concrete constructed with treated RCA using the second method exhibited higher strength than the concrete prepared with normal aggregate. This indicates that the treatment of recycled aggregate produced a dense, well-bonded interface that helped in load transformation. Using silica fume and sand in the treatment reduced the porosity and filled the microcracks, producing a stronger concrete. These results align with the findings from Wang et al. (2020) [24] and Zhao et al. (2022) [25].

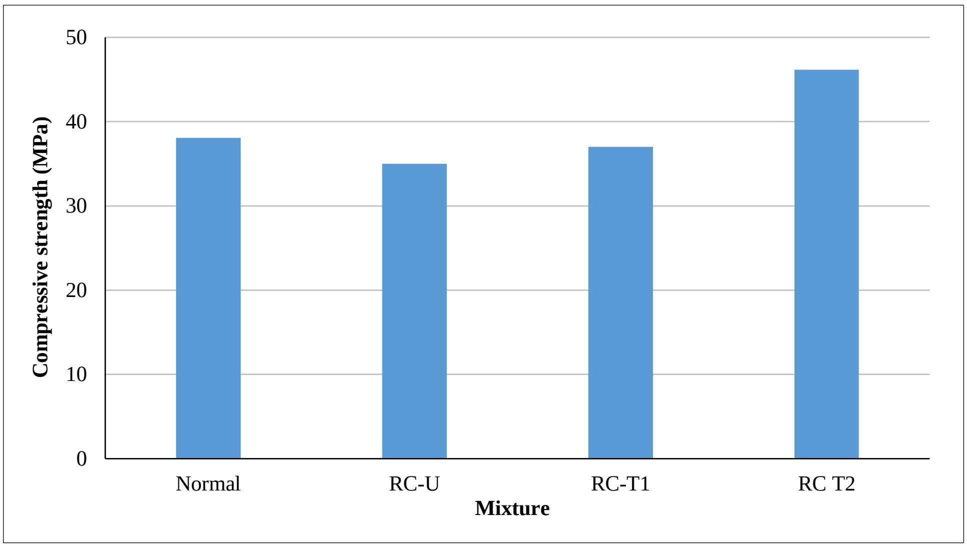


Figure 14. Compressive strength versus Mixtures

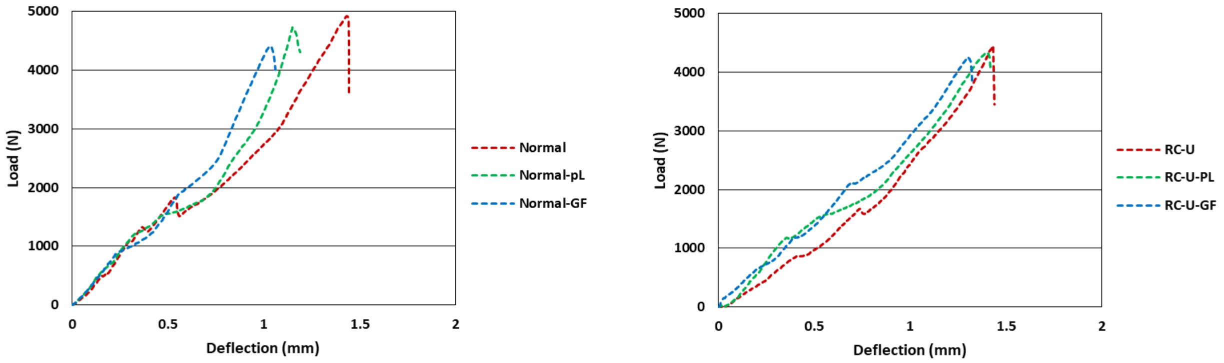
Fracture Toughness Evaluation

Fracture toughness (Gc) is defined as the energy required for a crack to spread through a unit area. It refers to the materials resistant to cracking and their ability to reabsorb energy after cracking [25]. A three-point bending test was used to measure the fracture toughness [30, 31]. Figure 15 shows the load-deflection curve of the tested prisms. Figure 15-a shows that the concrete made with normal aggregate exhibited the highest peak load. When adding fibers, either polypropylene (PL) or glass fiber (GF), the beams exhibited more stiffness but a slightly lower peak load. Figure 15-a also shows that the specimens with untreated RCA exhibited similar behavior to those with normal aggregate, both with or without fiber mesh. However, the untreated RCA specimens showed lower peak load compared to those made with normal aggregate.

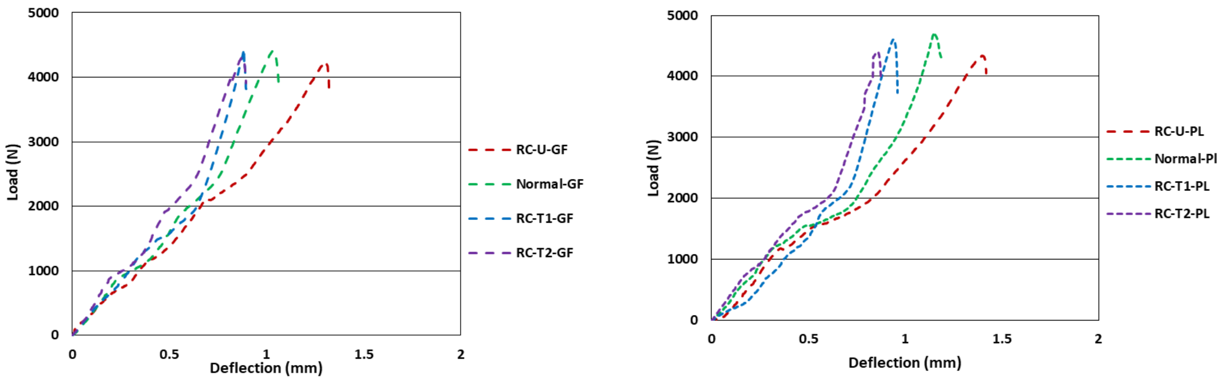
Figure 15-b shows that the beams with glass fiber (GF) exhibited higher stiffness compared to those with polypropylene fiber (PL). The specimen RC-T2-GF performed better than RC-T1-GF, showing that the treatment using Method 2 worked better. A similar pattern was observed for the specimens made with polypropylene fiber (PL), where the specimen RC-T2-PL performed better than the specimen RC-T1-PL in both stiffness and ultimate load.

Figure 15-c shows the effect of adding fiber mesh, either GF or PL, to treated RAC. Specimens with glass performed the best, followed by those with polypropylene fiber. Specimens without fiber exhibited the weakest performance. Overall, RC-T2-GF exhibited the best results, indicating that treatment using method 2 with GF mesh represents a good companion and produced stiffer and stronger beams.

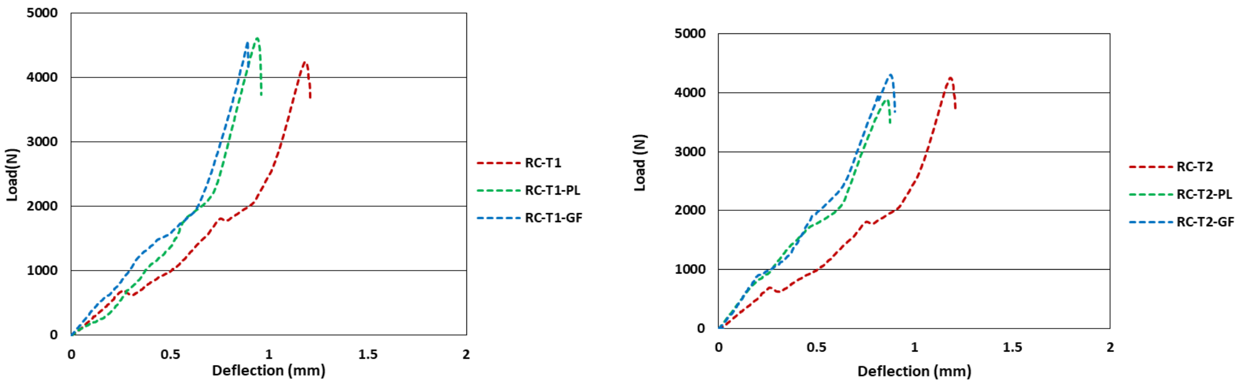
Figure 16 shows that the highest fracture toughness value was recorded in concrete prepared with normal aggregate and without fiber mesh. The concrete created with recycled aggregate exhibited lower fracture energy in all mixtures. Additionally, the untreated recycled aggregate performed better than the treated aggregate regarding the treatment methods. This behavior meets the results found by Xiao et al. (2012) [32] and Lu et al. (2024) [33], which found that the weak nature of recycled aggregate weakened the interfacial zone (ITZ). In addition, treatments may affect the surface roughness and mechanical interlock, resulting in more brittle behavior.



(a) Load–deflection curve for normal aggregate and untreated RAC with and without fiber



(b) Load–deflection curve for normal and RAC (untreated and treated) with fiber



(c) Load–deflection curve for Treated RAC and fiber

Figure 15. Load versus deflection curve for all tested prisms

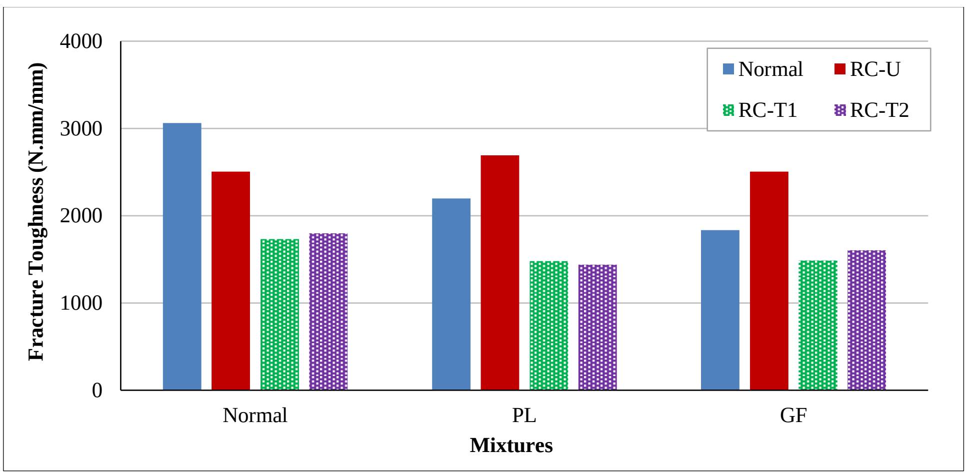


Figure 16. Fracture toughness versus mixtures

For treated RCA mixes, the presence of fiber sheet exhibits little effect. As shown in Figure 16, the fracture energy remained lower compared to normal and untreated aggregate. Several reasons may have led to this behavior, such as the denser and more rigid microstructure provided by the treated recycled aggregate. Also, the treatment method for recycled aggregate may increase the compressive strength, however, it reduces the capacity for energy dissipation. Further, the treatment technique produces an aggregate with a smoother surface that could reduce the bond efficiency and mechanical interlock with the fiber mesh.

As a result, treatment may improve some of the characteristics of RCA, but it can reduce its fracture toughness, especially with the presence of fiber mesh.

Figure 17 shows the crack and failure mode. All the specimens, including the specimens created with normal aggregate, untreated RCA, and treated RCA with and without fiber mesh, failed through a flexural crack initiated from the tip of the notch. The specimens made with normal aggregate exhibited ductile behavior, while the specimens made with treated recycled aggregate showed more brittle behavior.

Specimen with normal aggregate without fiber

Specimen with normal aggregate and fiber

Specimen with treated recycled aggregate and fiber

Figure 17. Crack and failure patterns of the tested specimens

4. Conclusion

This study examined the mechanical properties and fracture toughness of RAC with and without treatment, and with and without incorporating fiber mesh. It can be concluded that using recycled concrete aggregate (RCA) negatively affected the concrete workability, compressive strength, and fracture energy. This is mainly due to the weak nature and high porosity of recycled concrete aggregate (RCA). However, treating the recycled concrete aggregate, either by Method 1 or Method 2, significantly improved its behavior. The second treatment method, which uses silica, cement, sand, water, and superplasticizer, was more effective than the first. Treating recycled concrete aggregate using the second method provided good strength, even higher than the normal concrete, however, the concrete exhibited more brittle behavior. This brittle behavior negatively affected the fracture energy due to the faster and sharper formation of the cracks.

In contrast, untreated recycled concrete aggregate showed better crack resistance and fracture energy, especially with the inclusion of glass fiber mesh. Generally, the inclusion of fiber mesh, either glass or plastic, increased the crack resistance after cracking and helped slow down the crack growth. These findings show that while treating RCA can increase the concrete strength, untreated RCA with fiber mesh improves toughness and crack resistance. This behavior allows engineers to choose which behavior is more important: better durability against cracking or higher strength.

These findings show that when using RCA, it is important to make a balance between strength and toughness. Choosing a suitable treatment method and fiber type will help engineers modify their mix design based on project requirements. To get the best performance of RCA for different applications, more research is needed.

5. Declarations

5.1. Author Contributions

Conceptualization, M.M.A.H. and S.M.A.H.; methodology, S.Y.A.; software, M.M.A.H.; validation, S.M.A.H. and S.Y.A.; formal analysis, M.M.A.H.; investigation, S.M.A.H.; resources, S.Y.A.; data curation, S.Y.A.; writing—original draft preparation, M.M.A.H. and S.M.A.H.; writing—review and editing, S.Y.A.; visualization, S.M.A.H.; supervision, M.M.A.H.; project administration, M.M.A.H.; funding acquisition, M.M.A.H., S.M.A.H., and S.Y.A. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

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