

Research Article

Development of FRC Materials with Recycled Glass Fibers Recovered from Industrial GFRP-Acrylic Waste

Kishan Patel,¹ Rishi Gupta ,² Mohit Garg,² Boyu Wang,² and Urmil Dave¹

¹Department of Civil Engineering, Nirma University, Ahmedabad 382 481, India

²Department of Civil Engineering, University of Victoria, Victoria V8W 2Y2, Canada

Correspondence should be addressed to Rishi Gupta; guptar@uvic.ca

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Fiber-reinforced concrete (FRC) and engineered cementitious composite materials have demonstrated promising requisite in construction industry owing to its superior mechanical and durability properties. In this study, a sustainable approach was taken, i.e., to use industry waste as a reinforcement with improved interfacial bonding leading to enhanced mechanical performance of FRC. An efficient *in situ* recycling process allowed the authors to extract glass fibers from glass fiber-reinforced polymer acrylic waste. Concrete mixes with low fiber dosages including 0.1%, 0.2%, and 0.3% (by volume) of recycled as well as virgin glass fibers were prepared. The slump of concrete was maintained ~150 mm by using high water-reducing admixture (HWRA). Notably, lower amount of HWRA was required for raw glass fibers vis-à-vis recycled ones due to its hydrophobic nature. Overall, FRC enclosing 0.3% recycled glass fiber demonstrated >20% enhancement in compressive, split tensile, and flexural strength as compared to control (after 28 days of curing), also supported by morphological analysis.

1. Introduction

Cement-based composite materials demonstrate better performance under compression rather than in the tensile mode. Usually, ancient structures such as arches and masonry are not reinforced with steel bars. The sole purpose of steel bars in concrete is to act as the primary material that can sustain enormous tensile stresses, thus increasing the overall ductility of the structural member. With the advancement in technology, researchers started looking for other alternatives to provide structural reinforcement. Since corrosion of steel bars significantly affected the material properties, which ultimately led to structural failure, one of the possible solutions identified was to use either natural or synthetic fibers. Randomly distributed fiber reinforcement in matrices such as polymer/concrete has gained enormous appreciation and acceptability in commercial applications for more than two decades now, mostly in construction, automobile, marine, and aeronautical sectors [1–8].

Glass fiber-reinforced polymer (GFRP) material has properties such as high strength-to-weight ratio, high

corrosion resistance and low maintenance, and ease of fabrication. As a result, GFRP-based materials can handle high structural load, increase the durability, serve as an excellent cost-effective repair material, and thus is a great alternative to conventional materials [3–5, 8–12]. The commercially viable products manufactured using GFRP include mostly automotive parts, bathtubs, printed circuit boards, boats, and aerospace components. Researchers have also attempted to integrate fiber reinforcement in the concrete material, referred to as fiber-reinforced concrete (FRC) [1, 13–20]. FRC or GFRP fabricated sheets are retrofitted on beams, columns, and slabs to prevent the structure against corrosion as well as enhancing its longevity [21]. Fibers that have been successfully used in improving the strength and longevity of concrete infrastructures are glass [1, 7, 10, 11, 18, 22, 23], steel [1, 10, 11, 14, 15, 17, 24], carbon fibers [24–28], and polypropylene fibers [13, 15, 17, 29]. In particular, flexural and shrinkage properties have shown significant improvements with the addition of fibers in cement [16, 18, 22, 30]. Specifically, the work carried out by Banthia's group [16, 22, 30] has

demonstrated that the improved properties of FRC depend on parameters such as fiber orientation, water/cement ratio, fiber volume fraction, and intrinsic characteristics of the fiber itself. It is due to these factors and anisotropic behavior of monofilament fibers (in particular glass fibers) that researchers have reported diverse results. As a result, there has been a significant increase in synthesis of glass fiber and then using it as reinforcement for diverse applications around the globe.

For example, in the early 1900's, sanitary industry manufactured bathtubs with ceramic material, but with the advancements of technology, it got replaced with GFRP composites. GFRP composites are fabricated either using a thermosetting polymer (such as epoxy) or thermoplastic polymer (such as acrylic) along with glass fibers, and after curing, it results in a lightweight, high strength, and durable composite material. The 3D cross-linked structure of the material improves its performance and durability vis-à-vis ceramic one. Presently, most of the thermoset-based FRP waste is either being incinerated or landfilled, leading to negative environmental impacts and additional costs to FRP producers and suppliers [9, 31–36]. Furthermore, it has been observed by researchers that recycling of thermoset-based GFRP waste is a challenging task [9, 23, 31, 37–39] and also adds as a nonvalue cost to the owner for using it in the manufacturing process. Hence, an increased use of GFRP for commercial applications also results in an increase in the production of GFRP waste.

The sanitation industry took the benefit of this concept of constructing composites like GFRP. The waste produced from the sanitation industry (coming from discarded products and trims that are cut out) is posing a major challenge [40, 41]. In addition, this waste as compared to traditional GFRP is even more challenging to recycle as it not only constitutes resin reinforced with glass fibers but also a thin coating of acrylic, poly(methyl methacrylate) (PMMA) a thermoplastic resin as the finishing surface, from an environmental and economic perspective [41–43]. The authors define this waste as glass fiber-reinforced polymer acrylic (GFRPA) waste in this paper. The advanced thermochemical methods such as pyrolysis and fluidized bed techniques have shown positive results in terms of recycling of GFRPA waste and to reclaim glass fibers as well as resin [31, 41]. In particular, Esmizadeh et al. [41] described the benefits as well as disadvantages of different mechanisms to recycle PMMA such as thermal cracking, catalytic cracking, high heat application, and pyrolysis. An effort was made by the author to develop nanocomposites by reusing recycled PMMA waste. But on the contrary, the recycling process has resulted in a detrimental effect in terms of tensile strength of recycled glass fibers where the fiber strength was reduced to 50%–90% as compared to virgin fibers [23]. In addition to this, harmful gases such as CO and CO₂ are also released during this process, which leads to environmental contamination [35, 44]. Thus, recyclability of both the production waste and end-of-life (EOL) products has become an important and vital issue globally. The studies on GFRPA waste recycling and the reuse of sequent recyclates are limited [40, 45]. Cousins et al. [45] utilized the dissolution process to recover

the constituent materials from a thermoplastic composite waste part and further used the reclaimed glass fibers to fabricate the new material. It is interesting to note that the new material with recycled glass fibers reported higher stiffness and mechanical strength as compared to the virgin fibers, thus suggesting reusability of recycled glass fibers and possibility of selling the fibers and resin at a cheaper price to different industries. However, Correia et al. [23] reported worsened concrete performance (mechanical and durability related) by using thermoset-based GFRP waste in concrete mix and suggested to utilize low dosage of GFRP waste in nonstructural applications as a means to support waste management of FRP materials. However, with increased awareness of environmental matters, researchers identified and implemented few methods in the past to extract the glass fibers from the acrylic waste [41, 45], but still the results were not that promising. Also, the work reported so far in using GFRPA waste is very limited in terms of environmentally friendly extraction techniques and use as reinforcement in concrete.

Therefore, in this paper, the authors present an economical and ecofriendly technique to extract glass fibers as well as acrylic powder from an industrial waste. Till date, various chemical and mechanical processes have been reported in literature; however, they all seem to have an environmental impact as well as higher cost associated with the process [40, 41, 45].

Furthermore, the present study investigates the effect of using that recycled glass fibers from acrylic waste for various mechanical properties such as compressive and flexural strength and split tensile strength, when used as a reinforcement in concrete. Lastly, cost-effectiveness is more accurately assessed by comparing the mechanical test results obtained for analogous concrete mixes reinforced with virgin glass fibers and by observing the morphology of virgin and recycled glass fibers under an electron microscope.

2. Materials and Methods

One of the interesting methodologies reported in this study is the lab-scale separation of glass fibers and polymer resin from the GFRPA waste. The authors developed an *in situ* mechanical recycling process that is able to collect quantitative recycled glass fibers from GFRPA waste, thus providing an ecofriendly solution for the industry. Additionally, these recycled glass fibers also hold a strong potential in developing the ecofriendly concrete repair material. As a result, the recycled glass fibers were analysed for their morphological structure, using a scanning electron microscope (SEM), and for chemical composition, using EDX, and then is compared with virgin (raw) fibers.

Concrete cylinders of diameter 100 mm (4") and height 200 mm (8") were cast for investigating both the compressive and split tensile strength of concrete. On the contrary, prism specimens of dimension 100 mm × 100 mm × 350 mm were cast to assess the flexural strength of the concrete mix. For each of the tests mentioned above, three samples with and/or without fiber reinforcement were cast. The parameters of the study include control (no fiber) and 2 fiber types (recycled and

raw glass fiber), each with a dosage of fibers of 0.1%, 0.2%, and 0.3%. These results in a total of 105 test specimens (84 cylinder shaped and 21 prismatic shaped). The details on how to prepare these specimens has been discussed in Section 2.2.

2.1. Materials. General use, Type 10, Ordinary Portland cement (OPC) was used in the present study as it fulfils the requirement of Type I and Type II cement as per ASTM C150 standards [46]. Naturally, available aggregates found in the Sechelt pit in British Columbia (Canada) were used in the study as coarse aggregates. These aggregates had a maximum size of 25 mm and 0.69% absorption characteristics.

Furthermore, natural sand available in the same pit was used as fine aggregates in this experimental work. The sand collected from the pit was subjected to sieve shaker to identify the different particle size. The results have been summarized in Table 1. Notably, the fine aggregates had a fineness modulus of 2.61 and an absorption of 0.79%.

In addition, the authors used high-range water-reducing agent (HWRA) or superplasticizer, MasterGlenium® 3030. This superplasticizer has a polycarboxylate ether chemical, which acts as a catalyst to enhance the workability or slump value of concrete mix. A study by Asokan et al. [47] stated that the addition of 2 vol% of superplasticizer increases the compressive strength of concrete prepared with GFRP waste by 11%. Furthermore, the author reported a positive effect by including the waste from GFRP on drying shrinkage as well as compactness of concrete for potential use in structural and nonstructural applications.

As stated earlier, in the present study, two types of glass fibers were chosen, i.e., raw glass fibers (pristine) and recycled glass fibers. The properties of raw and recycled fibers are mentioned in Table 2. It can be seen that recycled glass fibers are about the same in diameter as virgin ones but have shorter length. This would be expected as process of manufacturing bathtubs does not change fiber diameter. Furthermore, the diameters of virgin and recycled glass fibers were supported by SEM analysis as well (for more details, refer Section 3.1). In general, the virgin E-glass fibers possess a tensile strength ranging from 3.1 to 3.8 GPa. In this paper, the innovative and cost-effective extraction and preparation of recycled fibers as a reinforcement in concrete has been discussed in detail in Section 2.4.

2.2. Mix Design. In the present study, ACI 211.1-91 [48] guidelines were followed for determining the mix design of normal concrete. The mix proportions for manufacturing of concrete specimens are discussed below.

In order to maintain a 150 mm slump, 25 mm of maximum aggregate size and non-air-entrained cement was used. Furthermore, water: cement ratio of 0.45 was chosen from Table A 1.5.3.4(a) of ACI 211.1 in order to prepare concrete samples with reasonable compressive strength. Additionally, according to the ACI standard, 0.67 m³ of dry rodded coarse aggregate was required for 1 m³ of concrete. Taking this into consideration the quantity of fine aggregates required was calculated. Table 3 summarizes the mix design

TABLE 1: Sieve analysis of fine aggregates.

Sieve size (mm)	% retained	% passing
10	0	100
5	0	100
2.5	10.3	89.7
1.25	17.7	72
0.63	21.9	50.2
0.315	28.6	21.5
0.16	16.2	5.3
0.08	4.1	1.2
PAN	1.2	0
Total	100	

used in the present study to develop FRC concrete with GFRPA waste.

Moreover, according to ACI 211.1-91, it is advisable to add 10% extra water for the lab trials to achieve the required slump. However, in this study, the authors considered adding 0.3% HWRA instead of adding extra water to maintain slump value close to 150 mm, compressive strength around 50 MPa for control concrete, and to aid in the dispersion of fibers in the concrete mix.

In the present study, the several parameters considered resulted in 7 different concrete mixes, where 6 of them were based on reclaimed and raw glass fibers (Table 3). The glass fibers were used as a partial substitute for fine aggregates at varying volume concentrations of the cement to cast FRC samples. As stated in Table 3, CV1, CV2, and CV3 acronyms refer to concrete mixes that contain 0.1, 0.2, and 0.3 vol% of virgin (raw or pristine) glass fibers, respectively. Similarly, CR1, CR2, and CR3 concrete were prepared using 0.1, 0.2, and 0.3 vol% of recycled glass fibers, respectively. The mix, CCON as stated in Table 3, was prepared to carry out a comparative analysis of the control mix with respect to FRC samples. The mix proportions along with per cubic meter weight (in kg/m³) of cement, sand, aggregates, water, superplasticizer, and fibers has also been reported in Table 3.

2.3. Mixing and Curing Procedure. All the ingredients of concrete such as cement, coarse and fine aggregates, water, glass fibers, and HWRA were weighed using a digital scale. During batching, first all coarse and fine aggregates along with glass fibers were mixed at moderate speed via a drum mixer for 1 minute to obtain a uniform dry mix. Following that cement was added into the dry mix through a continuous blending process while gradually pouring 70% of required water to transform into a paste. The remaining quantity of water was added into the cement paste to obtain a concrete with a reasonable workability, cross-verified by recording the slump value and then finally placing the paste into the moulds. Notably, a synthetic chemical was sprayed onto the sides of inner surface of moulds to prevent the adhesion of concrete onto the mould for easier fabrication. After the moulds were filled with concrete, they were subjected to compaction on the vibrating table for 1 minute to avoid honey combing.

Lastly, the fresh mix was left to cure at room temperature (15 ± 3 °C) for 24 hrs to harden. After 24 hrs, specimens were

TABLE 2: Raw and recycled glass fiber information.

	Length (mm)	Tensile strength (GPa)	Diameter of a single fiber, monofilament (μm)
Raw glass fiber	15	3.1–3.8	14
Recycled glass fiber	≤ 15	N/A	13.6

TABLE 3: Mix proportion of aggregates and water-cement ratio in developing FRC concrete with GFRPA waste.

Specimen type	Units (kg/m^3)						
	Cement	Water	Dry coarse aggregates	Dry fine aggregates	Virgin fibers	Recycled glass fibers	Plasticizer
Control (CCON)	448.89	202	1072	643.45	0	0	1.18
Virgin glass fiber-reinforced concrete (CV1), 0.1%	448.89	202	1072	643.45	2.5	0	2.37
CV2, 0.2%	448.89	202	1072	643.45	5	0	3.15
CV3, 0.3%	448.89	202	1072	643.45	7.5	0	3.95
Reclaimed glass fiber-reinforced concrete (CR1), 0.1%	448.89	202	1072	643.45	0	2.5	1.58
CR2, 0.2%	448.89	202	1072	643.45	0	5	2.37
CR3, 0.3%	448.89	202	1072	643.45	0	7.5	3.15

removed from the mould and placed into a water bath at $23 \pm 2^\circ\text{C}$ for 7 and 28 days of curing.

The next section details about the creative approach attempted by the authors in order to extract glass fibers from the industrial waste.

2.4. Extraction of Glass Fibers from Acrylic Waste. The manufacturing process includes preparing the bathtub using a blend of Aropol resin with a hardener as it wets the random glass fiber strands within a mould until it solidifies.

This process involved chopping a glass fiber tow using a chopper and inclusion of heated liquid resin. It should also be noted that this is done manually using a spray gun and the material received on the receiving mould is subject to human judgement. Upon solidification, a thin sheet of acrylic, PMMA, is thermomoulded onto the top surface of bathtubs to promote high scratch and impact resistance of the finished product. PMMA is considered an economical alternative to polycarbonate (PC) owing to its moderate properties, easier handling and processing, low cost, and transparency characteristics. The waste received from the industry reports a target fiber volume of about 10–15% in the polymer matrix, which results in a fiber volume of 6–9% when the total acrylic and resin is considered as the matrix. From here onwards, the authors would use the word “matrix” as a term to refer to combination of resin and PMMA in order to elucidate the readers. Overall, during the manufacturing process, leftovers (edges and small pieces) of acrylic are collected primarily during cutting and assembly processes of vacuum forming, referred to as GFRPA waste.

The authors were able to collect a quantitative GFRPA waste primarily from two areas in the industrial site: production line and quality inspection. The workers cut the extra edges hanging after bathtub manufacturing by using a cutter, which resulted in a sample, as shown in Figure 1. The authors identified that, at present, these acrylic wastes (from the industry) are being landfilled by the industry. However,



FIGURE 1: Sample of GFRPA waste.

they strongly believed from an engineering perspective that recycling of this waste could have dual benefits, i.e., environmental and economic.

2.4.1. Composition and Properties of GFRPA Waste. Firstly, the authors identified the physical and chemical properties of the waste, which are as follows:

- (i) Size: varies between 150 mm and 200 mm
- (ii) Thickness of waste: 4.70 mm to 5.00 mm
- (iii) Resin for glass fibers reinforcement: Aropol TM K 1866–18 C resin (45% styrene)
- (iv) Proportion of GFRPA waste (by volume): glass fibers 6–9%, resin 65–70%, and PMMA~25%

Aropol is categorized as an unsaturated polyester resin, which has the property that once its cured, i.e., cross-linked with styrene, liquid turns into a solid and maintains the shape of the mould. This resin illustrates exceptionally high strength and durability characteristics. Combination of the

resin with PMMA polymer and hardener results in a material that is lightweight, has high strength, shows resistance to chemicals, and provides excellent surface finish and water repellency and hence an excellent source for bathtub manufacturing.

As discussed earlier in Section 1, the recycling of GFRPA waste is a challenging task and poses a concern for a healthier community. The current practices tend to produce harmful gases such as CO and CO₂ during the process, which eventually leads to environmental contamination. Considering the above-stated facts and for developing a low-cost recycling process (in situ), the authors preferred mechanical (ecofriendly) methodology to extract glass fibers from the acrylic waste. In brief, mechanical recycling and shredding process have benefits such as (i) no atmospheric pollution by gas emission, (ii) much simpler equipment is required as compared to ovens necessary for the thermal process, and (iii) no need of chemical solvents with subsequent environmental impacts [9, 23, 49, 50]. Hedlund-Åström [50] considered life cycle assessment (LCA) and end-of-life (EOL) of polymer composite materials and proposed a recycling model that could be utilized for existing high volume of GFRP waste that is cost-effective and environmentally friendly. Similarly, Ribeiro et al. [49] and Meira Castro et al. [9] manufactured polyester polymer mortars that contained GFRP waste obtained by means of the shredding and milling process and reported improved mechanical properties with recycled reinforcement as a filler.

Taking into account the findings from the literature, the authors present in this paper the 3-stage ecofriendly mechanical recycling process carried out on a commercial “Crushing and Milling System,” as illustrated in Figure 2, with a power of 45 kW, procured from Zhangjiagang City Yili Machinery Co. Ltd., China, to obtain recycled GFRPA waste. The process is summarized below:

2.4.2. Mechanical Shredding. The equipment was operated by a trained technician, who would feed large rectangular pieces of leftover acrylic composite waste (either 150 × 150 mm or 200 × 200 mm in dimension) for shredding. The shredder broke down those large GFRPA sheets into small granular (10–50 mm) size, as illustrated in Figure 3, in approximately 3–5 minutes (depending upon the volume). The simultaneous water-cooling system in the grinding machine would allow it to run continuously and effectively until all the required volume was shredded. At the end of this process, small GFRPA waste was collected in a pan at the bottom of the shredder, which was a mixture of glass fibers with PMMA coating on the top. The next step was to separate the GFRP reinforcement from the PMMA layer.

2.4.3. Reclamation of Glass Fibers. At Step 2, the shredded GFRPA waste from Step 1 served as an input, which helped in the separation of the PMMA sheet and some resin from GFRP reinforcement with the help of a high speed, commercially available fan. As the shredded waste freely fell in front of the fan, due to the winnowing effect of a fan, the lower density fibers landed farther away resulting in

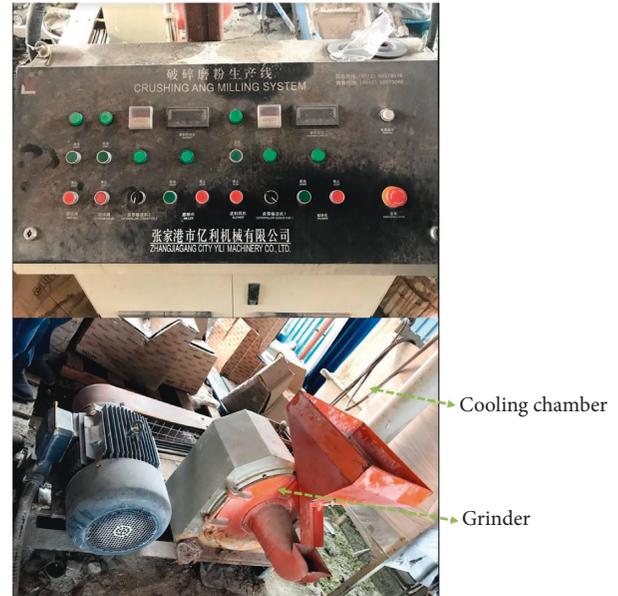


FIGURE 2: Crushing and milling system.

separation of the main layer of PMMA (and some resin) from GFRP samples. As shown in Figure 4, the reclaimed glass fibers may contain some bonded resin. Likewise, the separate acrylic chunks include resin and some fraction of fibers that are embedded in the PMMA chunks.

The authors observed this process to be repeatable, having an efficiency of 80–90% to reclaim glass fibers. Following that, a 600 μm sieve was used to separate the fine dust from the glass fibers obtained.

2.4.4. Grinding of Polymer Waste. Lastly, in Step 3, the objective was to prepare a fine powder of the polymer waste by using a grinding machine. As a result, the authors passed big chunks of acrylic waste and small granulates of acrylic collected in the previous two steps through an industrial crusher. At the end, the authors obtained a very fine powder, as shown in Figure 5. This fine powder holds the potential to be used as a reinforcing filler material in developing polymer composite and cement composite materials. The integration of the powder as a partial replacement for cement in concrete has been kept as a future scope of this study. On the contrary, the recycled fibers collected illustrated strong bonding with each other, probably due to the resin attached to its surface. Hence, from these observations, the authors hypothesize that this bonding may affect fiber dispersion in cement.

2.5. Characterization

2.5.1. Workability. Workability of GFRC and normal concrete samples was measured using ASTM C143.

2.5.2. Compressive Strength of Concrete. Compressive strength of GFRC and normal concrete samples was obtained using ASTM C39 [51]. All the compression tests were

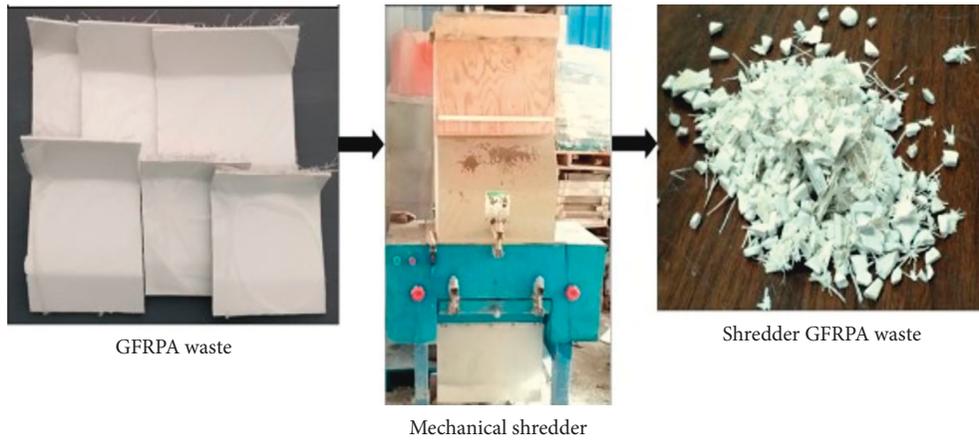


FIGURE 3: Step 1 for GFRPA waste—mechanical shredding.

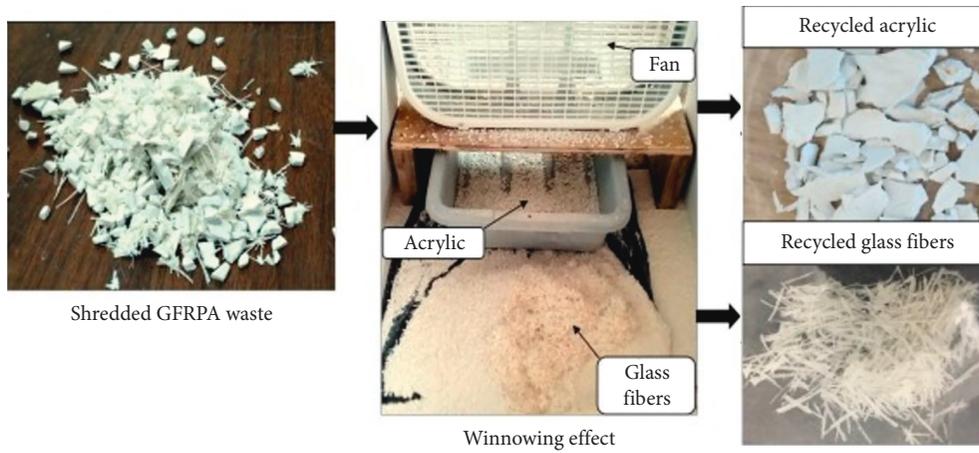


FIGURE 4: Step 2 for GFRPA waste—reclamation of glass fibers from acrylic waste.

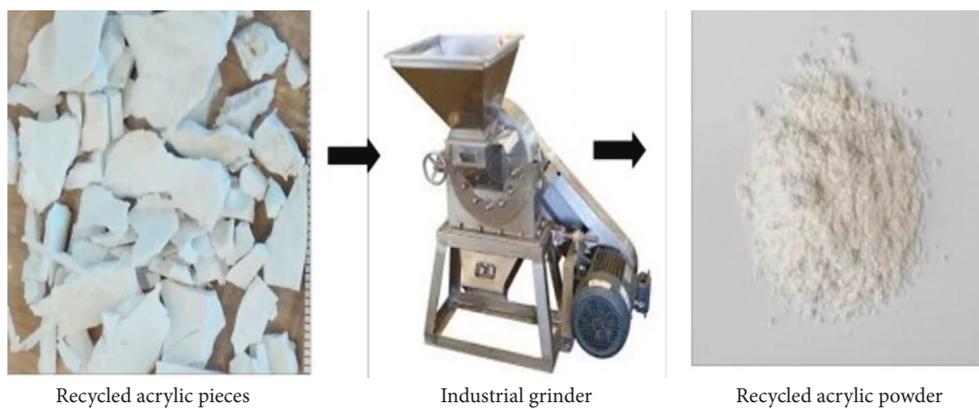


FIGURE 5: Step 3 for GFRPA waste—grinding of polymer waste using a crusher.

performed using a 650 kip capacity Forney test pilot. The cylinder-shaped samples, 100 mm (4") diameter and 200 mm (8") in length, with control concrete and FRC were tested after 7 and 28 days of curing to determine the compressive strength. The sample preparation involved concrete cylinders being ground to remove the rough

surface. Later, compressive axial load was applied gradually to the cylinders until the failure occurred, and then the peak load was noted. Subsequently, this information was used to calculate the compressive strength of the material. For each mix, 3 samples were tested, and an average value has been reported in this paper.

2.5.3. *Split Tensile Strength.* ASTM C496 was used to measure the split tensile strength of concrete [52]. The split tensile tests were carried out on all concrete mixes and three samples of each mix, and the average value has been reported in this paper. Cylindrical concrete specimens of diameter 100 mm (2") and length of 200 mm (4") were tested using 65000 lb capacity Forney test pilot. Diametric compressive force along the length of a cylinder was applied until the failure occurred, and the peak load was recorded. As a result, splitting tensile strength was calculated by using the following formula:

$$\text{split tensile strength} = \frac{2 \times P}{\pi \times l \times d}, \quad (1)$$

where P = peak load in Newton's, l = length of cylinder in mm, and d = diameter of the cylinder in mm.

2.5.4. *Flexural Properties of Concrete Samples Using a Closed-Loop System.* To evaluate the flexural performance of GFRC, ASTM C1609 [53] was used in the present study. Four-point bending using the closed-loop and servo-controlled testing system, MTS 250 K, having a capacity of 250 kN was used in order to obtain the load-deflection curve. The flexural performance of the prism/beam samples (having dimensions: 100 mm (4") \times 100 mm (4") \times 350 mm (14")) was then calculated using the parameters derived from the load-deflection curves.

The closed-loop system was used for loading; the deflection at centre of the prism was measured and used to control the rate of the deflection. The span of the prism was kept constant at 300 mm (12"), and distance between the loading roller was held at 100 mm (4"). In order to achieve the closed-loop mode, the authors ensured that the jig assembly remained attached to the beam to hold the LVDT (linear variable differential transformer) properly. Two LVDTs, as shown in Figure 6, effectively maintained deflection at a rate of 0.025 mm/min up to $L/900$ deflection and 0.05 mm/min beyond $L/900$. The flexural performance of GFRC up to the cracking stage was determined from the first peak strength. However, for a particular deflection, the residual strength characterized the residual capacity after the cracking. The first peak strength was calculated using the following formula. The same formula can be used to calculate the modulus of rupture at a particular deflection:

$$\text{strength, } f = \frac{P \times L}{b \times d^2}, \quad (2)$$

where P = load in Newton's, L = span length in mm, b = width of specimen in mm, and d = depth of specimen in mm.

2.5.5. *Morphological and Chemical Analysis.* HITACHI S-4800 scanning electron microscope was used for analysing the surface morphology of concrete samples, while EDX provided the chemical composition of recycled glass fibers and raw glass fibers. Also, the specimens were coated with a 10 nm carbon layer in order to make the sample surface

conductive and for higher production rate of secondary electrons.

3. Results and Discussion

3.1. Properties of Glass Fibers

3.1.1. *Raw Glass Fibers.* Chopped virgin glass fibers from the bathtub manufacturing industry were collected for this study, as shown in Figure 7(a). A chopping gun was used to shorten their length to 15 mm from the roving. Furthermore, SEM and EDX characterization of these raw glass fibers were carried out to record the physical and chemical properties. From the morphological analysis, it was observed that fibers had a diameter of 14 μm (Figure 7(b)), while the EDX analysis in Figure 7(c) reveals the absence of zirconium (Zr). It is observed that glass fibers are sensitive to alkalis in Portland cement paste, but fibers with Zr demonstrated resistance to alkali degradation [54, 55].

3.1.2. *Recycled Glass Fibers.* Furthermore, to compare the reclaimed glass fibers with raw ones, the authors conducted the morphological and chemical analysis of the samples collected after the extraction process was complete (Section 2.4). During the SEM analysis, the authors observed that the diameter of an individual recycled glass fiber was similar to the virgin glass fibers, i.e., $\sim 14 \mu\text{m}$ (Figure 8(a)). Additionally, thicker bundles of recycled fibers were observed under the microscope owing to the polymer resin holding several fiber strands together (Figure 8(b)). Lastly, the chemical composition (Figure 8(c)) of resin-doped recycled glass fiber demonstrates a maximum concentration of ions such as Ca, S, and O, which highlights the abundant calcium sulphate presence. The extra calcium sulphate would undergo the hydration reaction and act as a catalyst in improving the compressive strength of concrete.

3.2. *Workability of Concrete.* In preparing fiber-reinforced concrete samples, it is important to maintain the workability which is generally done by recording the slump value. It has been observed that, with the addition of fibers in concrete, it tends to affect its workability. As a result, researchers overcame this challenge by mixing the high-water reducing agent (HWRA), also known as superplasticizer, into the cement. Researchers have recommended a maximum of 2% concentration (of cement content) for FRC samples to maintain the concrete slump value above 150 mm. Taking into consideration this phenomenon, the authors conducted a series of experiments, and each time, the slump of concrete was measured using the cone, as described earlier. The slump values obtained for various concrete mixes are mentioned in Table 4.

The values in Table 4 reveal that the concentration of HWRA varied with the type of fiber as well as with the fiber dosage in cement. Virgin glass fiber (CV) samples required higher concentration vis-à-vis recycled glass fiber (CR) samples. Interestingly, CV3 mix, having 0.3% raw glass fibers, had the minimum slump, i.e., 130 mm, but highest HWRA

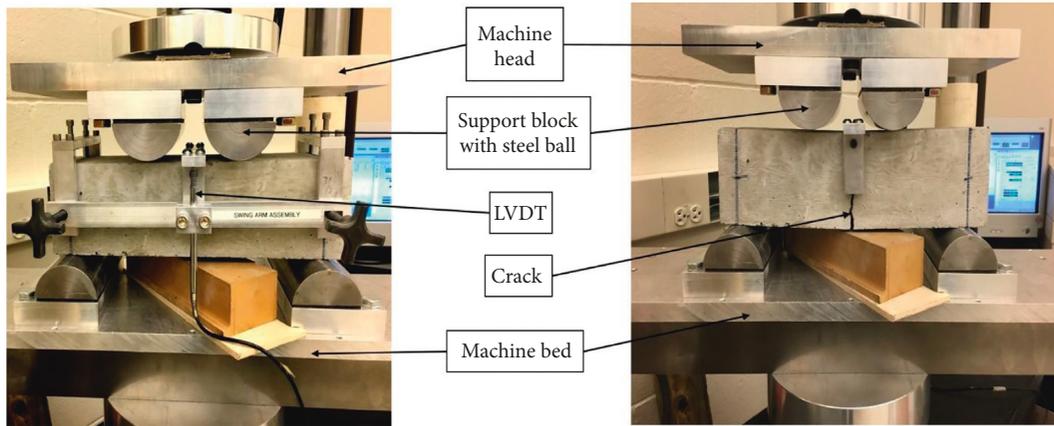
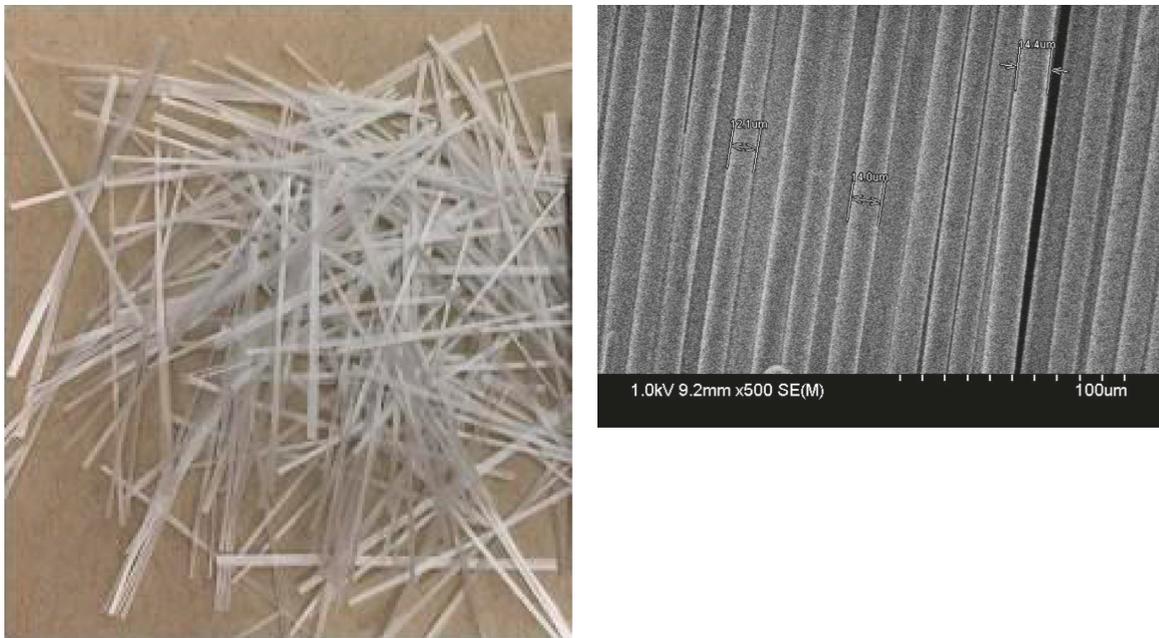
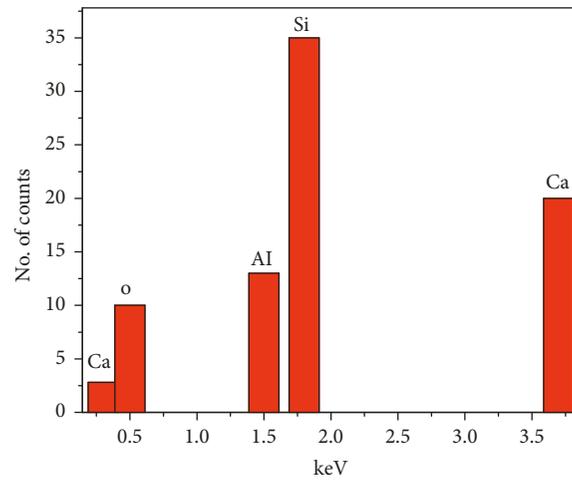


FIGURE 6: Flexural setup.



(a)

(b)



(c)

FIGURE 7: Virgin glass fibers: (a) sample; (b) SEM image; (c) EDX analysis.

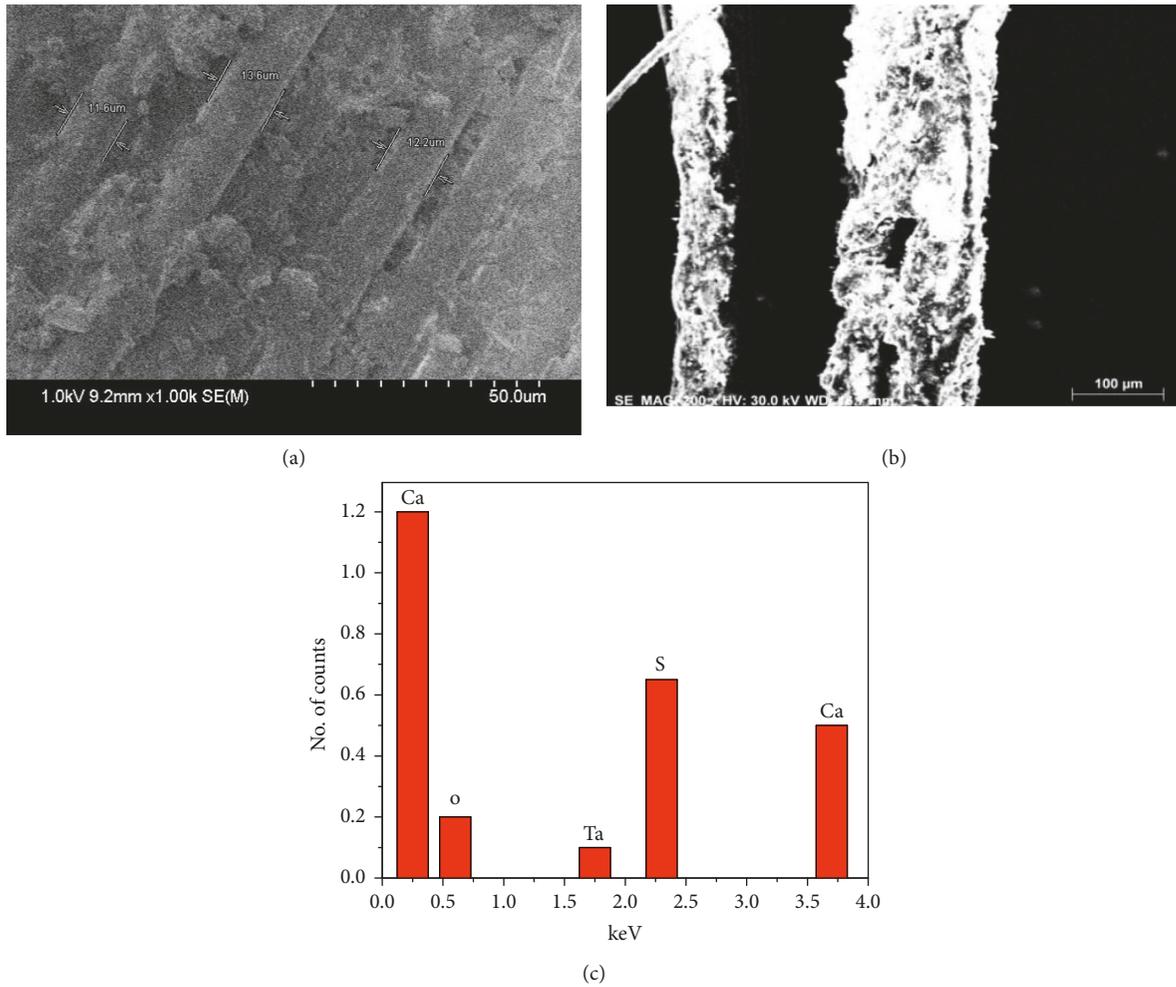


FIGURE 8: Recycled glass fibers: (a) SEM image; (b) fibers doped with resin; (c) EDX analysis.

TABLE 4: Workability of different concrete mixes.

Type of concrete mix	Slump value (mm)	Dosage of glass fiber (%)	HWRA content (%)
CCON	165	0.0	0.3
CV1	152	0.1	0.6
CV2	143	0.2	0.8
CV3	130	0.3	1
CR1	162	0.1	0.4
CR2	160	0.2	0.6
CR3	155	0.3	0.8

content of 1%. The use of 1% superplasticizer in FRC's is considered to be a higher dosage according to Aruntas et al. [56]. Also, the experimental results demonstrate that as the percentage of glass fiber increases, a higher dosage of HWRA is required to maintain the slump close to 150 mm and combat the stiffening effect of reinforcing fibers. Also, higher quantity of HWRA in concrete acted as a catalyst to overcome the hydrophilic behavior of glass fibers. Notably, less amount of HWRA was required for concrete prepared with recycled glass fibers as compared to raw glass fibers. It is possibly due to the fact that recycled glass fibers existed in bundle form and there was also a coating of resin on its surface. The coating possibly reduced

the water adsorption by the fibers, and thus, less amount of HWRA was required for that concrete mix. Thus, it can be stated that the addition of fibers affects the workability of concrete, and it is further dependent on the type and quantity of fibers. In particular, the recycled glass fibers have shown better performance than raw ones in concrete. It is interesting to observe the consequences of workability on different mechanical properties, which has been discussed in the following sections of the paper.

3.3. *Compressive Strength.* Figure 9 illustrates the absolute values of average compressive strength after 7 and 28 days of

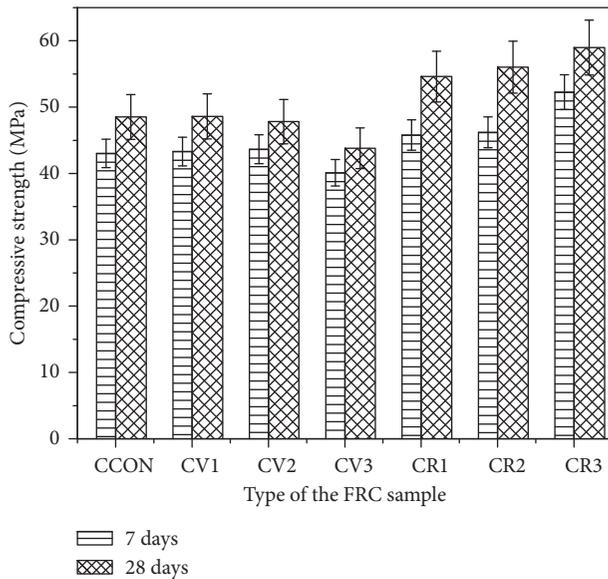


FIGURE 9: Effect of fiber reinforcement in concrete on compressive strength after 7 and 28 days of curing.

curing regime for both recycled and raw glass fibers with varying fiber concentrations as compared to the control one.

The FRC prepared using 0.3% recycled glass fibers revealed the maximum increase, 21.46% (from 43.02 to 52.25 MPa), as compared to the control samples. Notably, an increasing trend in strength was witnessed for an increasing dosage of recycled glass fibers. A possible reason to explain this explicit behavior can be credited to an increase in calcium sulphate content in the matrix, contributed by recycled glass fibers present in the sample. On the contrary, no significant change was observed when concrete samples were reinforced with virgin glass fibers. Even by increasing the fiber dosage to 0.2%, the strength increased only by 1.47%. The strength dropped significantly (to 40.11 MPa), when the fiber dosage was increased to 0.3%, as shown in Figure 9. A possible explanation for the low strength of CV3 mix vis-à-vis control mix owes to its low workability, which led to a less dense microstructure as compared to other mixes.

Furthermore, 28 days curing of the samples and testing thereafter demonstrated a similar behavior as can be seen in Figure 9. The authors made an important observation that the compressive strength of FRC samples, prepared with recycled glass fibers increased by approximately 20%, specifically for 0.1 and 0.2% fiber dosage as compared to similar samples when cured for 7 days. This illustrates that concrete had gained 90% of its strength within the first 7 days, thus demonstrating reliability of the experimental study. Furthermore, the average compressive strength recorded for the 0.3% recycled glass fiber sample was still maximum, 59 MPa, as compared to 48 MPa for the control. On the contrary, concrete samples prepared using virgin glass fibers continued to demonstrate deterioration with curing time as well as with increments of fiber dosage when tested at 28 days.

Hence, from this test, it can be inferred that the recycled glass fibers have outperformed in terms of compressive

strength as compared to both control and virgin glass fiber concrete samples.

3.4. Split Tensile Strength. The tensile strength is considered as one of the basic and important properties of concrete. In general, concrete is very weak in tension due to its brittle behavior and is thus not expected to resist the tension forces acting on it, resulting in crack formation. It is due to these reasons that the authors were interested in identifying the peak load at which the fiber-reinforced concrete members may crack and also if there was any change in the failure mechanism such as brittle to ductile.

Figure 10 illustrates the split tensile strength obtained for two types of fiber along with 3 different dosages vis-à-vis control sample after the 7 day curing regime. From Figure 10, it can be observed that the control sample had a split tensile strength of 2.45 MPa, and with the incorporation of fibers, as a reinforcing material, there is an increase in strength for different fiber dosages.

Interestingly, FRC prepared with 0.3% recycled glass fiber dosage revealed a maximum increase of 22%, 2.45 to 2.99 MPa, vis-à-vis control sample. The stronger bonding between the fiber surface and cementitious matrix is possibly resisting the external forces being applied during the testing and thus resulting in enhanced compressive and tensile strength. On the contrary, the tensile strength of FRC prepared with raw glass fibers (CV1, CV2, and CV3) has also shown improvement as compared to the control mix. However, in this case, the strength of 2.86 MPa was recorded for 0.2% raw fiber dosage, while it slightly dropped to 2.83 MPa for 0.3% dosage. This illustrates once again that increasing the fiber dosage possibly resulted in poor workability and agglomeration of fibers in the matrix which tends to affect the properties of the concrete mix.

Further curing of the samples up to 28 days showed an improvement in split tensile strength, as shown in Figure 11, and as observed earlier for compressive strength results (Figure 9). When compared to 7-day curing regime samples, a similar pattern in tensile strength is visualized for the FRC samples, i.e., a maximum of 3.46 MPa is recorded for 0.3% recycled glass fiber concrete sample. The split tensile strength of the CR3 sample increased by 24% and 11% as compared to control and CV3, respectively. Also, as the percentage of recycled glass fiber increases, the split tensile strength increases. A glimpse of Figure 11 shows that the increase in split tensile strength at 28 days for CV1 and CV2 mix is higher as compared to CR1 and CR2 mix. Hence, from this test, it can be stated that the reinforcement of raw glass fibers with 0.1% content also has a significant positive effect on the split tensile strength of concrete. Similar improvement in tensile strength was also reported by Gupta and Banthia [16] upon reinforcing concrete with various virgin fiber types.

Thus, it can be stated that the recycled glass fibers have shown better performance than raw glass fibers and control concrete in terms of both compressive and split tensile strength, in particular at 0.3% fiber dosage. The authors believe that better performance with higher dosage of

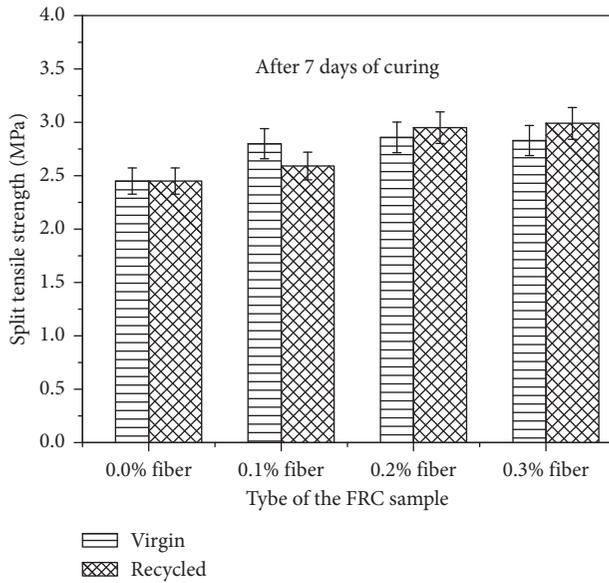


FIGURE 10: Effect of fiber reinforcement in concrete on split tensile strength after 7 days of curing.

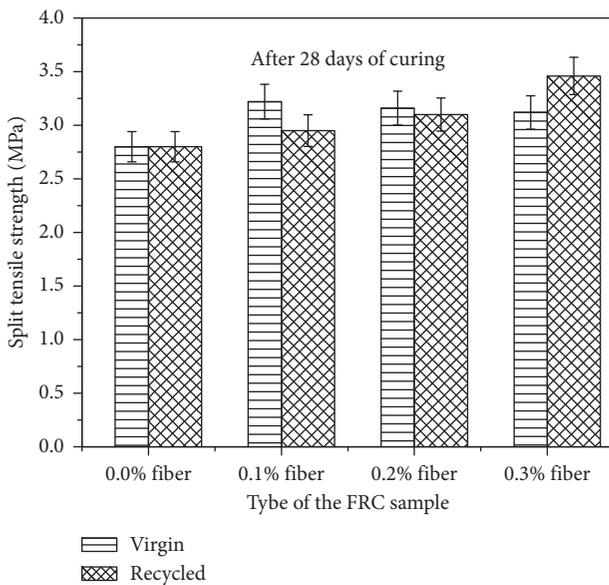


FIGURE 11: Effect of fiber reinforcement in concrete on split tensile strength after 28 days of curing.

recycled glass fibers in FRC supports the waste management of FRP materials.

3.5. Flexural Strength. After investigating the behavior of FRC in both compressive and tensile loading conditions, it became interesting to observe the effect of fibers under flexural loading conditions too. For that purpose, the authors carried out four-point bending test using a closed-loop system as described earlier in the paper for all mixes. The absolute values of average flexural strength obtained from the experimental study after 28 days of curing have been presented in Figure 12.

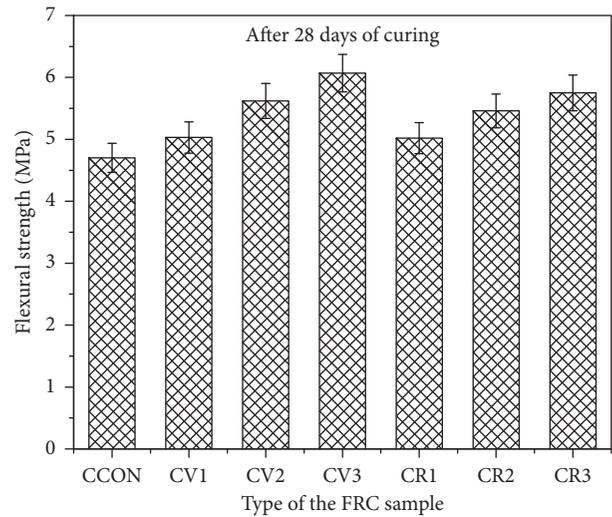


FIGURE 12: Effect of fiber reinforcement in concrete on flexural strength after 28 days of curing.

The control concrete sample had an average flexural strength of 4.70 MPa. By analysing Figure 12, it is evident that an increase in fiber dosage results in improving the strength of the material. Interestingly, at 0.1% dosage, both raw and recycled glass fiber concrete samples illustrate a similar increase in strength, at about 7%. On the contrary, the flexural strength of CV2 and CV3 mixes was comparatively higher than CR2 and CR3 mix, respectively. Furthermore, net deflection at cracking was also found to be higher for CV3 mix as compared to CV1 mix. A possible reason for this behavior is credited to the higher compressive strength obtained for CV1 mix vis-à-vis CV3 mix. Similar behavior was also observed by the authors for CR1 than CR3 mix. The analysis of this test reveals that the addition of 0.3% of raw glass fibers increases flexural strength by 28.93%, while the addition of recycled glass fibers with the same concentration increased the strength by 22.16%. Similar improvement in flexural strength with the incorporation of GFRP waste [33] and proper orientation of fibers in the cementitious matrix [22] have been reported previously.

Hence, it can be stated that raw glass fibers performed better specifically for flexural strength, but overall, recycled glass fibers have shown better improvement in other mechanical properties. Therefore, the positive experimental results obtained with utilizing recycled glass fibers still support the authors' belief about recycled glass fibers as it holds the potential to provide a better sustainable, eco-friendly, and cost-effective solution for the future structural developments by the construction industry at large.

So far, the authors have reported the mechanical effect, but it is also important to analyse the effect of the fibers and different fiber concentrations on the fiber-matrix interface, which has been carried out by analysing the morphology of the fractured samples.

3.6. Morphological Analysis. The fractured surfaces of two samples, i.e., concrete reinforced with raw and recycled glass

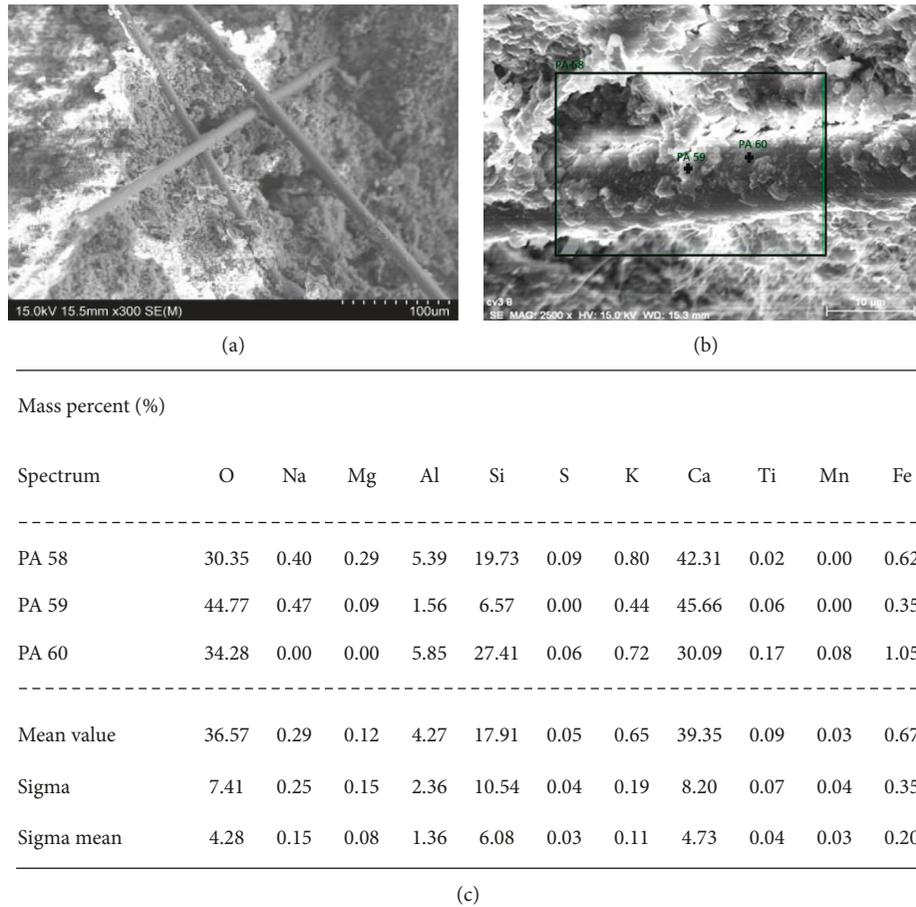


FIGURE 13: CV3 (virgin glass fiber) sample: (a) SEM image; (b) location for EDX analysis; (c) EDX analysis.

fibers with 0.3% dosage, were analysed to study the fiber-matrix interface and chemical composition. In view of this, the samples were made moisture-free by placing in a vacuum chamber for couple of hours prior to SEM analysis. Following that, the samples were coated with the 15 nm thick carbon layer. The morphology of CV3 (raw fibers) and CR3 (recycled fibers) samples differed as illustrated in Figures 13(a)–13(c) and 14(a)–14(c), respectively.

Figure 13(a) depicts the SEM image captured at magnification of 300x, clearly illustrating that raw glass fibers were randomly oriented in concrete in the form of agglomerates while fiber pull-outs were also visible. The presence of fiber pull-out highlights the poor interfacial bonding of fibers with the concrete mixture, which in turn justifies the lower compressive strength and split tensile strength reported earlier in this paper. Additionally, at a higher magnification (Figure 13(b)), chemical composition of a particular section on the sample surface was investigated, and the results have been tabulated, as shown in Figure 13(c). From the table (represented in Figure 13(c)), it can be interpreted that, at 3 different locations, in particular PA 60 which refers to raw glass fiber, the main concentration is silicon, which is the basic constituent in a glass fiber. However, PA 58 and 59 report the presence of silica, aluminium, and calcium ions, which is possibly due to some

covalent bonding between glass fibers and C-S-H as well as C-A-H gel inside the interface.

On the contrary, the microscopic analysis of recycled glass fiber-reinforced concrete (as shown in Figure 14) is quite different than those prepared with raw glass fibers. In Figure 14(a), the glass fibers seem to be oriented in the longitudinal direction, surrounded by the thick matrix layer and present in small bundles. It highlights the fact that there was better interfacial bonding between the cementitious materials and the glass fibers, due to which the samples demonstrated significantly better performance during various mechanical tests. Carefully analysing Figures 14(c) and 13(c), it can be noted that there is higher combined concentration of calcium, silicon, sulfur, and aluminium in recycled glass fiber concrete vis-à-vis raw glass fiber. The slightly higher concentration of calcium silicate hydrate in the interface explains the positive affect observed earlier on the compressive strength of concrete. Hence, the mechanical performance of FRC seems to be justified after analysing the fractured surfaces.

The authors believe that this research can be extended by increasing the dosage of recycled glass fiber in cement to investigate the effect on shrinkage properties. Also, the residual fine powder collected by sieving of glass fibers can act as one of the fillers in preparing the concrete material,

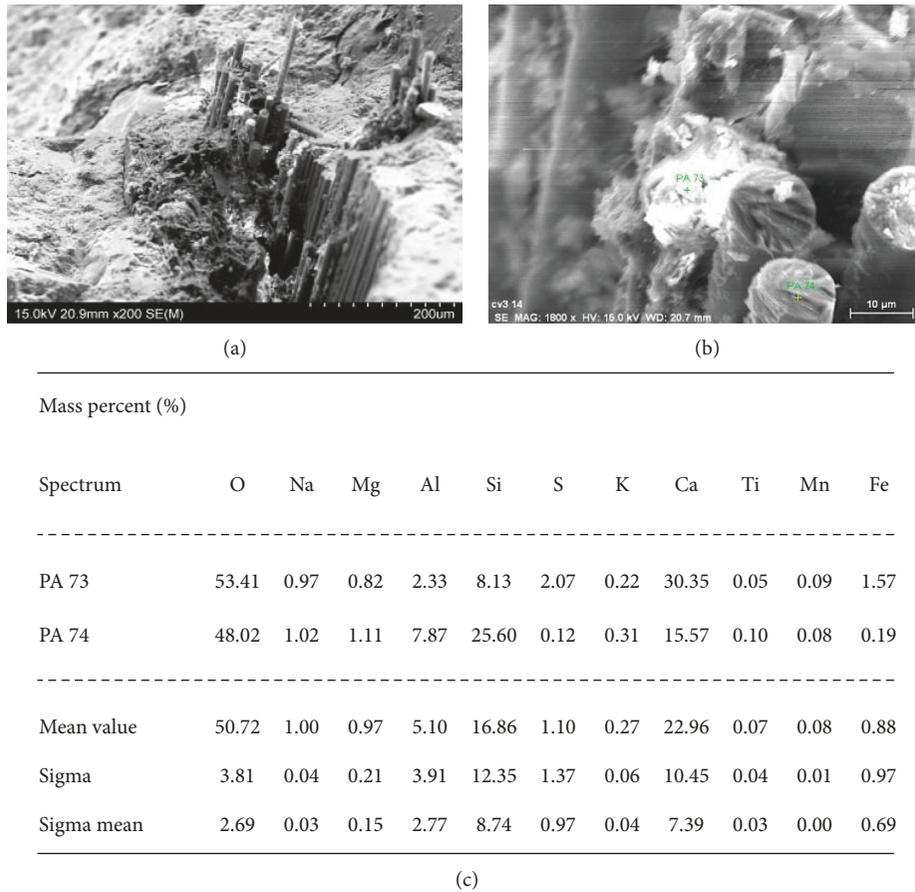


FIGURE 14: CR3 (recycled glass fiber) sample: (a) SEM image; (b) location for EDX analysis; (c) EDX.

which can lead to an ecofriendly and cost-effective alternative to use of Portland cement. Following that, the mechanical properties of the concrete can be investigated.

4. Conclusions

Based on the results of this experimental investigation, the following conclusions are drawn:

- (1) *In situ* mechanical method of recycling demonstrated quantitative reclamation of glass fibers and PMMA powder from GFRPA waste. The winnowing technique was efficient in separating the GFRPs from the shredded waste. Following that, a fine sieve assisted in removing the fine polymer powder from the recycled glass fibers.
- (2) The recycled glass fibers appeared to have a resin coating which promoted their existence in bundles, as visualized under SEM. Calcium silicate (gypsum) ions were identified in the fiber-matrix interface using EDX analysis, which assisted in improving the mechanical performance in concrete. The sharp fractured edges of glass fibers confirmed the brittle failure of the concrete material during mechanical tests.
- (3) The compressive strength of concrete mix increased as the percentage of recycled glass fibers increased for both 7 and 28 days of curing schedule. In the case of FRC mixes reinforced with virgin fibers, compressive strength decreased for 0.2% (28 days of curing) and 0.3% (7 and 28 days of curing) fiber dosages, vis-à-vis the control mix. On the contrary, maximum enhancement of 22% was achieved for 0.3% volume fraction of recycled glass fibers as compared to control the concrete sample for both 7 and 28 days of curing regime.
- (4) Incorporation of both types of glass fibers demonstrated a positive impact on the split tensile strength of concrete. Furthermore, an increase in dosage of fibers in the mix showed an increase in strength for both 7 and 28 days of curing cycle. Interestingly, once again 0.3% recycled glass fibers had a maximum tensile strength of 3.46 MPa vs 2.48 MPa (control). Also, lower concentration of raw glass fiber concrete samples showed slightly better strength than the other fibers. The authors believe that the results of split tensile strength were partially influenced by the compressive strength of the concrete for that mix.
- (5) Lastly, the reinforcement of virgin and recycled glass fibers (with an increasing concentration) also

enhanced the flexural strength of concrete. As compared to the control sample, average flexural strength was enhanced by 29% and 22% for virgin and recycled glass fiber samples, respectively, after 28 days of curing at 0.3% volume fraction of the mix. However, all concrete mixes had a brittle failure, and no postcrack deflection was observed.

Data Availability

The experimental data used to support the findings of this study will be made available upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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