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Enhancing mortar performance using recycled plastic fibers: A sustainable solution for solid waste management

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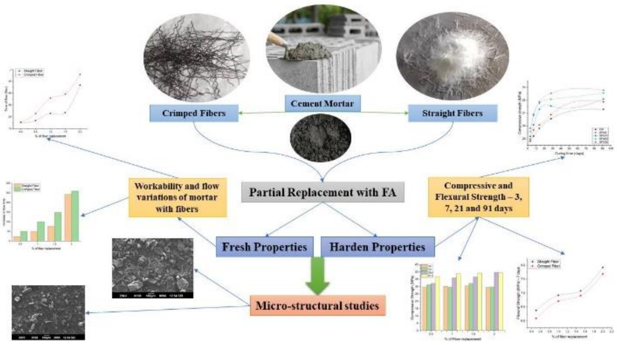
Graphical abstract



Abstract

The primary goal of the research was to determine how recycled plastic fiber's shape affected the functionality of mortar made from naturally occurring limestone residue. The identical length (20 ± 2 mm) and diameter (0.45 ± 0.07 mm) of two types of recycled fibers, straight and crimped, were employed. The fibers used for this study were taken in four different ratios 0.5%, 1%, 1,5%, and 2%. Compared to the crimped fibers, the straight fibers with concrete mix have high compressive and flexural strengths. i.e., 37.52 Mpa and 9.78 Mpa of compressive and flexural strength were observed for crumped fibers lower than the straight fibers (39.73 MPa and 10.48 Mpa) mixed with concrete mix. The results reveal that the geometry of the recycled plastic fibers is a key factor affecting the performance of the limestone residue mortar. The findings show that a restricted dose of 1% and 0.5% of the recycled plastic fiber is required to produce a workable mortar for both straight and crimped fibers. Incorporating recycled plastic fibers has been demonstrated to enhance the flexural and compressive properties of limestone residue mortar; nevertheless, the strength values of straight fiber mortar (SFM) are greater than those of crimped fiber mortar (CFM). The microstructure investigation validates the fiber mortar's excellent performance.

Keywords: Plastic fibers, limestone mortar, fiber geometry, strength analysis, microstructure

1. Introduction

The use of recycled plastic fibers in mortar has gained attention due to growing concerns over plastic waste management and the push for sustainable construction materials. Enhancing mortar performance using recycled plastic fibers involves an experimental approach to assess the influence of these fibers on the properties of the mortar. In certain nations, the significant requirement for natural aggregates in the manufacturing of concrete poses a considerable challenge. When it comes to supplies, builders need to look elsewhere for things like leftovers, garbage, and repurposed materials. The vast amount of waste left behind from this crushing process is abundant in nature and is not used for building or road construction. One of the primary factors preventing this waste from being used more often in the production of concrete is its high fine content, which requires more water during mixing and can thus adversely alter the characteristics of the concrete. But with river sand being overfished, which causes a lot of ecological issues, using limestone residue as substitution sand becomes a good attempt to carry out construction projects as well as a suitable answer for environmental and economic problems. It is noteworthy to mention that several writers (Cepuritis *et al.*, 2016) believe that crushed sand with fines has a financial benefit because it does not require filler when used to make concrete. The beneficial impact of crushed sand on mortar strength and durability has been linked to its fine content, as indicated by other researchers, including Ma *et al.* (2022). Additionally, the increasing prevalence of plastic in various human and industrial applications is leading to a daily rise in plastic waste, which is recognized as one of the most critical solid waste concerns on a global scale. This poses a danger to both the environment and public health. Plastic waste is a major source of environmental issues because of its low biodegradability. However, recycling it in construction projects can help combat global warming, fight ecological issues, and create

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cementitious products that have great potential for specific uses. By addressing these issues, recycled plastic fibers can become a viable and sustainable alternative to conventional reinforcements in mortar, contributing to both environmental and construction industry advancements.

Plastic waste fibers have several advantages for the environment. Still, they may also increase the mechanical properties of mortar and concrete and make them more ductile by lowering the likelihood of breaking. Numerous instances found in the literature attested to these advantages. For example, the study by Islam *et al*. (2023) indicated that PVC fiber reinforcing concrete increases its compressive, flexural, and split tensile strengths. According to Suraweera *et al*. (2023), recycled PET fiber improves concrete performance in a way that is comparable to that of virgin fibers. Additionally, recycled plastic waste fibers greatly decreased the overall crack areas, average crack widths, and plastic shrinkage cracking of mortar slab surfaces, as revealed by Folorunsho *et al*. (2024) prior experimental testing. According to Pešić *et al*. (2016), the recycling of high-density polyethylene plastic fibers has resulted in diminished plastic shrinkage, cracking, drying shrinkage, and water permeability. Furthermore, Hernández *et al*., (2024) suggest that utilizing longer fiber lengths and increased fiber doses can enhance load transfer between the fiber and the matrix. Based on existing literature, recycling various waste resources is typically necessary to produce environmentally acceptable building materials. This is the scenario in which the study was carried out, using abundant limestone residue in place of the overused alluvial sand to create an inexpensive mortar. Recycled plastic waste derived from the manufacturing of household brooms was employed as fiber reinforcement to enhance the quality of the mortar. Implementing straight and crimped fibers in construction presents several challenges, including practical considerations and limitations. The addition of fibers, particularly crimped fibers, can reduce the workability of the mortar. This may necessitate the use of additional water or chemical admixtures, potentially affecting the mix's overall performance. Although recycled fibers are cost-effective compared to virgin materials, their availability and consistent quality can be a concern, particularly in regions with limited recycling infrastructure. While incorporating straight and crimped fibers into construction materials has the potential to improve sustainability and mechanical properties, several challenges need to be addressed. These include optimizing workability, ensuring durability, managing costs, and meeting regulatory standards. Overcoming these limitations requires continued research, innovative solutions, and the development of standardized guidelines to facilitate widespread adoption in the construction industry. This experiment is unique in that it assesses how the shape of the waste affects the qualities of the mortar both while it is fresh and when it has hardened. The resulting mortar can be used in various buildings depending on its qualities. It is commonly recognized that the type, geometry, mechanical attributes, and dose of fibers appear to influence how effective they are at improving the quality of the material. Therefore, the goal of the current study is to assess how these factors impact the mechanical strength, microstructure, and workability of the material. Two fiber geometries straight and crimped were evaluated in this work at different doses of 0.5%, 1%, 1.5%, and 2% weight percentage.

2. Materials used and methods

The primary objective of this study is to evaluate the influence of recycled plastic fibers on the mechanical strength, microstructure, and workability of mortar. The study specifically compares two fiber geometries, straight and crimped, incorporated at varying dosage levels of 0.5%, 1.0%, 1.5%, and 2.0% by weight of cement. This methodology ensures a comprehensive evaluation of the potential of recycled plastic fibers to enhance mortar performance while promoting sustainability. The mortar utilized for testing was prepared using a 0.2mm limestone residue, Portland cement CEM II/A rated at a strength class of 42.5 MPa, and recycled plastic fibers. The sand used was obtained as a byproduct from limestone rock crushing. This material exhibits the following properties: density of 2.41 g/cm^3, an adsorption rate of 4.2%, a modulus of fineness of 1.72, and 55% compactness. Approximately 27% of the residue comprises particles smaller than 0.16mm, while 6% consists of particles less than 0.063mm. The presence of clay minerals in this residue did not negatively impact the material's durability, as indicated by a Methylene Blue value of 0.13 mL/g. **Figure 1** displays the particle size distribution of the utilized residue, while **Table 1** presents the chemical composition of cement and limestone residue. The fibers used in this study were sourced from discarded plastic, specifically polypropylene (PP) fibers obtained as a byproduct of the manufacturing process for domestic cleaning tools. Two types of fibers with identical dimensions (20 ± 2 mm in length and 0.45 ± 0.07 mm in diameter) were utilized. **Figure 2** represents the fibers used in this study along with their microscopic view. **Table 2** provides a detailed characterization of the employed fibers. Four different dosages were tested: 0.5%, 1%, 1.5%, and 2% by weight for each type of fiber. The mortar mixtures were prepared following a systematic approach to ensure homogeneity and repeatability. The freshly prepared mortar was cast into molds to produce prismatic specimens. The samples were compacted using vibration to eliminate air voids and ensure consistency. The specimens were then covered with plastic sheets and stored in a controlled environment at 23±2°C and 95% relative humidity for 24 hours before demolding. To evaluate the workability of the mortar, the flow time for each mix was recorded using a workability meter B, following the guidelines set forth by French Standards NF P18-452. The measurements were repeated three times per mixture to ensure accuracy, and the mean values were reported. Mechanical strength assessments were conducted at different curing ages (3, 7, 14, 28, and 91 days) using a Universal Testing Machine (UTM – 2000 kN).

The compressive strength tests were performed on half-prisms measuring 40x40x80 mm, derived from the initial prismatic specimens. Flexural strength was assessed using prismatic samples measuring 40x40x160 mm, in compliance with European Standards EN 196-1. Each strength value reported represents the mean of three specimens tested, with a standard deviation of approximately 6%. A microstructural analysis of the mortar matrix was conducted using Scanning Electron Microscopy (SEM). This analysis focused on evaluating the fiber-matrix interaction, the distribution, and anchoring of fibers within the cementitious matrix, and the presence of potential voids or defects that could impact mechanical performance. The SEM images provided insights into the bonding mechanisms between the recycled fibers and the cementitious matrix, highlighting any morphological changes due to fiber incorporation. This methodological framework ensures a systematic and reproducible approach for assessing the effects of recycled plastic fibers on mortar performance. The combination of workability, mechanical, and microstructural analyses provides comprehensive insights into the feasibility of using such fibers in sustainable construction applications.

Table 1. Properties of cement, plastic fibers, and limestone residue

Properties of cement		**Plastic fibers and their properties**		**Limestone residue composition**	
Type of property	**Distribution in %**	**Type of property**	**Distribution in %**	**Type of property**	**Distribution in %**
CaO	64.59	Specific density (g/cm^3)	0.98	$CaCO_3$	89.28
SiO_2	20.41	Tensile strength (N/mm^2)	210 – 250	SO_3^{2-}	0.41
Al_2O_3	4.51	Elasticity Modulus (GPa)	4 – 5	Insoluble Materials	6.26
Fe_2O_3	3.88	Water absorption (%)	Nil		
MgO	1.54				
SiO_3	0.92				
K_2O	0.58				
Na_2O	0.09				

Table 2. Mix the proportion of mortars and their details (w/c ratio 0.45) as per IS 456: 2000

S. No.	**Type of mix**	**Cement (g)**	**Sand (g)**	**Water (mL)**	**Super-plasticizer (g)**	**Fiber Straight (g)**	**Fiber Crimped (g)**
1.	SFM5	300	900	135	10	6.7	-
2.	SFM10	300	900	135	10	13.3	
3.	SFM15	300	900	135	10	20.02	-
4.	SFM20	300	900	135	10	26.70	-
5.	CFM5	300	900	135	10	-	6.7
6.	CFM10	300	900	135	10	-	13.3
7.	CFM15	300	900	135	10	-	20.02
8.	CFM20	300	900	135	10	-	26.70

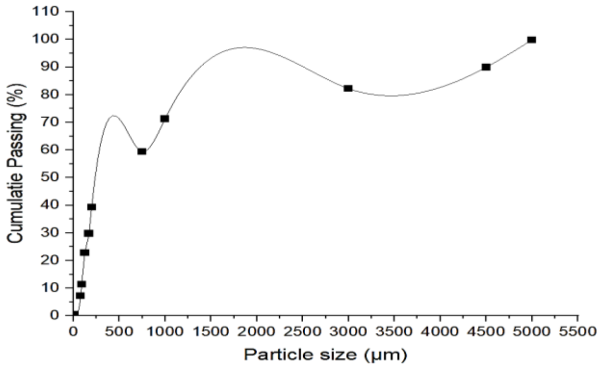

Figure 1. Limestone residue size distribution

3. Results and discussion

3.1. Fresh mortar properties

Figure 4 (a) illustrates how adding recycled plastic fibers to mortar affects its workability. With an increase in fiber content, mortar flow time is seen to rise. The significant impact of fiber dosage on workability is evident in **Figure 4 (b)**, which displays the percentage increase in flow time of various mortars in comparison to the control mortar. The detrimental impact on workability probably arises from the physical characteristics of the fibers used within the mortar, as they act as inclusions possessing a high specific surface area. This finding is supported by the great majority of literature studies (Ahmad *et al.*, 2023; Mohamed *et al.*, 2024; Ahmad *et al.*, 2022; Ahmad *et al.*, 2021; Seddiqi *et al.*, 2021).

Crimped fibers, characterized by their irregular structure that enhances the bonding between the fiber and the matrix while also retaining greater amounts of water, yield less plastic mortar than straight fibers (**Figure 5**). When examining fiber doses of 0.5%, 1%, and 1.5%, it is observed that the flow time for crimped fibers is more than 40% greater than that for straight fibers. However, this percentage decreases to 10% when 2% of fibers is administered. Establishing the optimal composition that yields both efficient and durable materials is essential, as workability represents the primary characteristic of cementitious materials in their fresh state and also influences their properties once hardened. Experimental results and visual assessments suggest that to guarantee the workability of mortar, the fiber content by weight should be kept at 1% for straight fibers and 0.5% for crimped fibers.

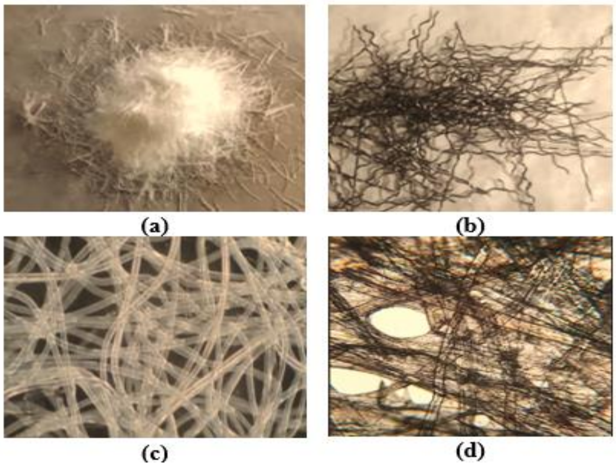

Figure 2. (a) Straight, (b) Crimped fibers, Microscope view of (c) Straight and (d) Crimped fiber

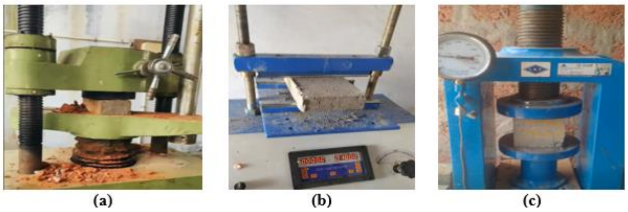

Figure 3. (a) UTM, (b) Flexural strength, and (c) Compressive strength testing machines

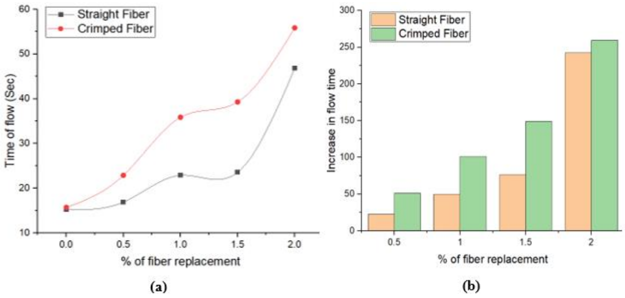

Figure 4 (a) Flow time variations for plastic fibers in mortar, (b) Increase in flow time

Figure 5. Crimped fiber mixed with the fresh mortar mix

3.2. Characteristics of hardened mortar

3.2.1. Flexural strength

The flexural strength progression for mortar with straight fibers and mortar with crimped fibers is depicted in **Figures 6 and 7**, respectively. Every mortar that has been tested, regardless of the fiber's shape, has shown a consistent rise in strength with age. The increase in strength is undoubtedly a result of the ideal curing circumstances for the continuance of the hydration reaction, a favorable humidity of 80 ± 5% where the samples were preserved. Additionally, this preservation enhances the matrix-fiber transition zone's quality, which has a favorable impact on the fiber mortar's mechanical strength. It was demonstrated by Jackson *et al*. (2017) that although the matrix strength requires a longer curing period, the interface fiber matrix reaches its full strength after just two days. For both kinds of mortars, an improvement in strength is also shown with increased fiber dose. As seen in **Figure 8**, straight fiber mortar (SFM) has superior flexural strength values across all age groups. As opposed to straight fiber mortar, crimped fiber mortar is less workable, which might account for this outcome. A more compact material with improved mechanical strengths cannot be obtained because of the limited workability, which causes certain challenges during installation and moulding operations. Comparing recycled plastic fiber mortars to control mortars, In **Table 3**, the flexural augmentation percentage of the prior data is displayed. In mortar SFM20, for instance, the flexural strength increases by around 34% and 25% after 28 days, respectively, whereas in mortar CFM20, it increases by about 24% and 38% after 90 days. The mechanical advantages of adding 2% recycled plastic fibers to mortar made of limestone residue were validated by these findings. According to Camille *et al*. (2021), the high energy absorption capacity of synthetic fibers is undoubtedly the reason behind their positive effect on flexural behavior, which multiple studies have proved (Zhang *et al*., 2024; Azevedo *et al*., 2024; Khalighi *et al*., 2023; Ng LF *et al*., 2024).

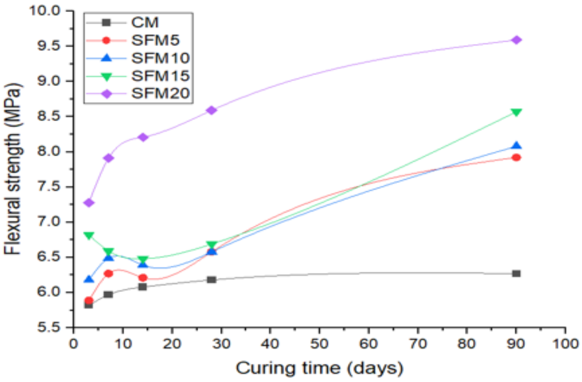

Figure 6. Flexural strength of the straight fiber mortar

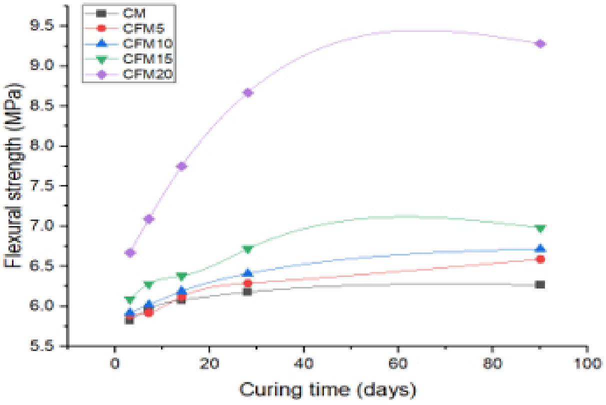

Figure 7. Flexural strength of the crimped fiber mortar

3.2.2. Compressive strength

The compressive strength differences between mortars with straight fibers and those with crimped fibers are presented in **Figures 9 and 10**, respectively. These mortars have been kept covered with plastic film to ensure a controlled environment at a temperature of 25 ± 5°C. This method has enabled the hydration process to advance, enhancing the maturity of the mortars and leading to an increase in their compressive strength over time. While both forms of recycled plastic fibers typically have a positive impact on the compressive behavior of mortar, straight fibers have a marginally greater impact (**Figure 11**). These results align with a few literature research (Nicolás *et al*., 2024; Fraternali *et al*., 2014). Nonetheless, several published studies have claimed that while fibers may decrease a material's compressive strength, they do not influence it (Yang *et al*., 2021; Islam *et al*., 2022; Zhao *et al*., 2022; Qian *et al*., 2023; Hossein *et al*., 2023). However, their little impact on compressive strength is meaningless because the addition of fibers to concrete is intended to enhance its tension behavior and decrease cracking. According to this, the kind, dose, geometric factors, and orientation of fibers appear to determine how they affect compressive behavior. The significant degree of flexibility exhibited by the recycled plastic fibers utilized in this study, when compared to other types of fibers, facilitates their easy arrangement into the mortar's mass without compromising its density and subsequently contributes to its effective improvement of compressive behavior. **Table 4** compares the improved compressive strength to the control mortar and displays the result as a percentage (%). A mechanical analysis indicates that incorporating 2% recycled plastic fibers into mortar is the optimal dosage. This addition leads to an increase in compressive strength of about 20% for mortar containing straight fibers and 14% for mortar with crimped fibers at 28 days relative to the control mortar. At 90 days, the enhancements are recorded at 15% and 13%, respectively.

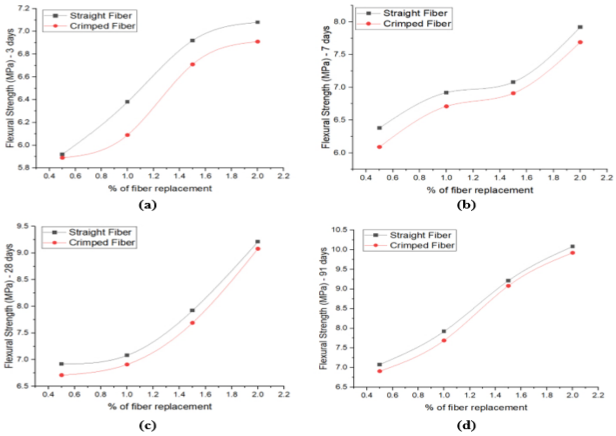

Figure 8. Changes in Flexural strength at different days (a) 3, (b) 7, (c) 28, (d) 91

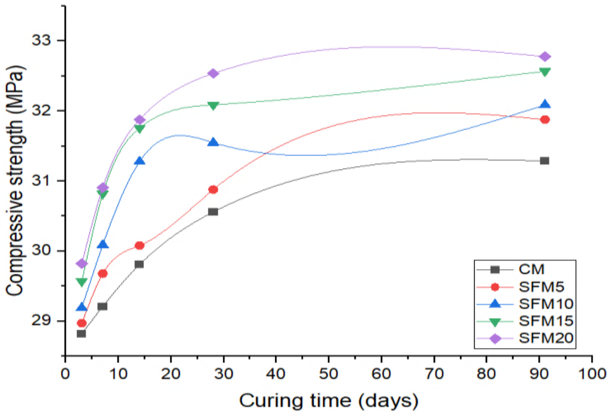

Figure 9. Compressive strength of the straight fiber mortar

Table 3. Flexural strength of mortar mixes and its augmentation in different ages

S. No.	Type of mortar mix	Ages (days)				
		3	7	14	28	91
1.	SFM5	2	14	9	7	23
2.	SFM10	20	14	9	10	26
3.	SFM15	26	15	11	17	31
4.	SFM20	37	33	35	34	38
5.	CFM5	2	3	1	3	3
6.	CFM10	12	6	6	5	9
7.	CFM15	13	8	3	8	10
8.	CFM20	28	27	30	25	24

Table 4. Compressive strength of mortar mixes and their augmentation in different ages

S. No.	Type of mortar mix	Ages (days)				
		3	7	14	28	91
1.	SFM5	5	3	6	2	7
2.	SFM10	7	6	7	5	13
3.	SFM15	7	10	9	5	19
4.	SFM20	9	10	12	20	15
5.	CFM5	-18	-10	-5	-8	3
6.	CFM10	-2	-7	-7	-3	10
7.	CFM15	3	1	3	3	13
8.	CFM20	5	6	11	14	13

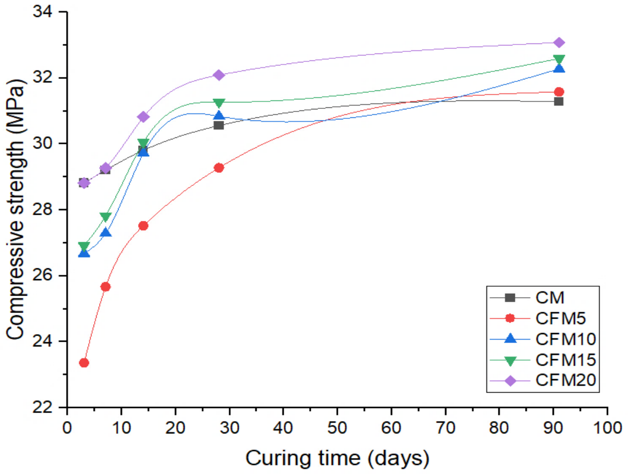

Figure 10. Compressive strength of the crimped fiber mortar

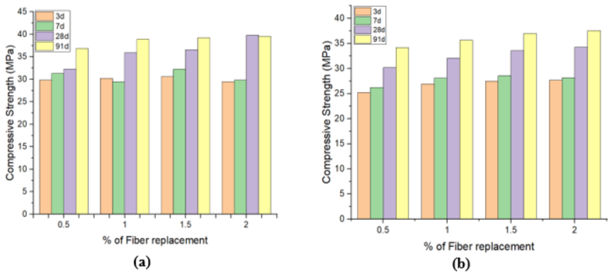

Figure 11. Changes in Compressive strength at different days (a) Straight Fibers and (b) Crimped Fibers

3.3. *Examination of mortar microstructures*

A highly effective approach to elucidating the mechanical properties of fiber materials, such as flexural strength, toughness, and fracture energy, involves the analysis of their microstructure. This investigation offers a clear method for evaluating the quality of the fiber surface, the characteristics of the transition zone between the matrix and the fiber, as well as the distribution of fibers within the matrix. After mortar samples have undergone mechanical testing, an SEM examination is carried out. In this research, the polypropylene plastic fibers, which are available in both straight and crimped forms, exhibit a smooth surface that contributes to a reduced quantity of paste being present on them, as shown in **Figure 12 (a)**. Moreover, a slight porosity of approximately 5µm can be observed between the fibers and the matrix (demonstrated in **Figure 12 (b)**). When fibers have insufficient anchoring in the fracture zone, this porosity contributes to their pulling out of the matrix (**Figure 12 (c)**). The absorptivity of the material is increased when pores are present in the transition zone between polypropylene fiber and mortar, as described by Wang *et al*., 2023. Some fibers are pulled out of the matrix during the microstructure inspection; this is likely because the fibers are orientated randomly into the mortar, and the efficiency of the length that is being used increases the likelihood that more fibers will be orientated in the direction of failure load. The successful mechanical behavior of fiber mortars in the preceding sections already supports all of these findings. After its pull-out, the contact surface fiber matrix shows no signs of damage, as seen in **Figure 12 (d)**. Because of their shape, recycled polypropylene plastic fibers have a high capacity for absorbing energy. They begin to fail before the load is transferred to the matrix, confirming once more how effective they are at enhancing the material's flexural behavior both during peak loading and after (**Figure 12 (d)**). The dense microstructure of the mortars under test is evident in **Figures 12 (e, f)**. This is likely attributed to the way the hydration process progressed and the fact that the sand made from limestone waste, which comprises 27% tiny particles smaller than 0.16 mm, was utilized. The purpose of these particles is to enhance the mortar's compactness by filling up its pores. The high strength values in all mortars at 28 days of engaging, which surpasses 6.7 MPa for flexure and 31 MPa for compression, may be explained by observation.

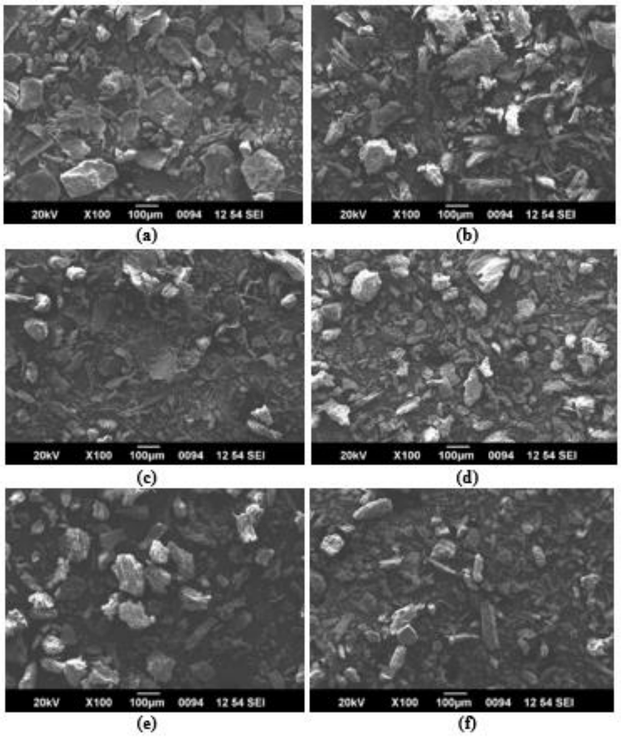

Figure 12. Microstructure studies of (a, b) CM, (c, d) SFM, and (e, f) CFM mixes

Future research could focus on optimizing fiber content and surface treatment methods to enhance bonding strength within the matrix. Additionally, long-term durability studies under different environmental conditions, such as freeze-thaw cycles and chemical exposure, could further validate the viability of these fibers in real-world applications. Investigating alternative waste-derived fibers and their hybridization with other reinforcements may also provide innovative solutions for sustainable construction materials.

4. Conclusion

The fine aggregate used in this study's mortar preparation was sourced from plastic waste, with fibers also derived from recycled materials. Various fiber shapes and weight dosages were evaluated to assess the workability and mechanical properties of cementitious materials, both of which are critical characteristics. For optimal workability, the recycled plastic fiber content in the mortar should not exceed 1% by weight for straight fibers and 0.5% for crimped fibers. The CFM 20 mix exhibited significantly higher flexural and compressive strength compared to the standard mix. Additionally, incorporating straight and crimped fibers in varying ratios individually further enhanced the mechanical strength of the mortar mix. Straight fibers positively influenced the mortar's mechanical properties, improving setting times and workability at the same dosage. Increasing recycled plastic fiber content in limestone residue mortar also contributed to enhanced mechanical strength. Microstructural analysis revealed a robust material with effective fiber lengths and well-organized fiber orientations, further validating the high performance of the fiber-reinforced mortar.

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