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Study on the Effects of Cellulosic Fiber Reinforcements on Tensile and Flexural Properties of Fiber-reinforced Mortar

Tahreem Beg[1], Sarah Jaweed[1], Muhammad Ali[2]
[1]Department of Textile Engineering, NED University of Engineering & Technology, Karachi, Pakistan

[2]Royal College of Art, Kensington Gore, London, United Kingdom

ABSRACT

Responsible disposal and recycling of textile waste has become one of the most pressing subjects, which is continuing to increase with the growing population and correspondingly expanding demand for clothing. The utilization of cellulosic fibrous waste, which is currently dominating the textile market in terms of production and consumption, is one of the most significant issues to be addressed. Recycling cellulosic fibres as reinforcement materials in mortars is a technique that has long been used and studied. This study aims to sequentially prepare reinforced mortar specimens incorporating different forms of spinning waste, for example, fresh cotton fibres, spinning fly, comber noil, viscose waste, and tencel fly, by initially treating them with 2, 4, 6, 8, and 10% caustic soda. A set of experiments was then sequentially performed to assess the mechanical performance of the resulting mortar samples. It was finally concluded that viscose fibers exhibited superior properties as compared to the rest of the samples. Overall, findings from the study suggest that waste cellulose fibers have a good prospect of being utilized in the reinforcement of cement mortars.

Keywords: Cellulosic fibers, Mortar, Recycling, Sustainable Infrastructure, Fiber Reinforcement

1. Introduction

Construction sector alone contributes about 40% greenhouse gas emissions and 50% water consumption in the industrial sector globally [1] [2]. Thus, both academia and industry have been making efforts to reduce the environmental impact of this sector by developing new materials, processes and techniques. One area that has gained considerable attention from researchers is cement-based mortars. Cement-based mortar is widely used because of its many beneficial properties, including good compressive strength, high fire resistance, ease of application, and low cost [3]. It is well-known that cement-based mortar possesses very low tensile strength, low flexural strength, limited ductility, and thus little resistance to cracking. The primary reason for such weakness of cement mortar is its inability to resist the initiation and growth of cracks when tensile stress is applied onto it [4]. This inherent deficiency can be overcome by adding fibers as a reinforcement material to arrest the cracks and allow much larger deformation beyond the peak stress prior to failure. The superior properties of Fiber-reinforced Mortar (FRM) over cement-based materials in terms of tensile and flexural strength are well documented in the literature [5] [6] [7] [8] [9]. To achieve the aforementioned advantages, natural fibers can be used as an alternative to synthetic fibers to further alleviate the environmental impact of traditional construction materials [8]. A number of researchers examined the effect of using different amounts and types of natural fibers (cotton, flax, lignin, hemicellulose, and cellulose fibers) on the behavior and characteristics of FRMs [10] [11] [12] [13] [14].

Chemical treatments such as alkaline pretreatment, silane, Maleic and Succinic anhydride grafting, Peroxides, acylation, enzyme treatment , acidic treatment and coating have also been proven to improve the physio-mechanical properties of fibers in order to improve the binding with matrix [15] [16] [17] [18] [19] [20] [21] [22] [23] [24] [25] [26] [27] [28] [29]. In the present study, the chemical modification technique used is alkaline treatment which is expected to enhance the fiber-matrix bond and consequently, improve the mechanical properties of FRM [30]. The use of cellulose fibers in cement-based composites is promising due to several other reasons such as sustainability, low cost, renewability, biodegradability, low density, ease of availability and production [31] [32] [33] [34].

2. Materials and Methods

2.1 Materials

The materials used in this research for reinforcement include different cellulosic fibers such as cotton (in the form of comber noil and spinning fly), viscose and tencel. All of the fibers were obtained from a local spinning mill in Karachi, Pakistan (Figure 1). It is noteworthy that these fibers were declared wastes of the spinning department, and a large proportion is usually dumped as solid waste in landfills.

Figure 1. Cellulose waste

Various properties of the selected fibers were assessed, such as tensile strength (ASTM D1445) [35], elongation (ASTM D1445), fiber length (ASTM D1447) [36] and moisture regain (ASTM D2495) [37]. The results of these characterization tests are provided in table 1.

Table 1. Properties of cellulosic fibers used in the study

Fiber type	Tensile strength (g/tex)	Elongation (%)	Length (in)	Moisture regain (%)
cotton fibers	18.3	8.172	1.13	9
spinning fly	18.3	8.172	0.916	7
comber noil	18.22	7.9	0.54	7
viscose	18.34	10.1	1.2	11
tencel fly	18.36	7.1	1.15	9

For preparing cement mortar, river sand of particle size <2.36 mm and Ordinary Portland Cement (OPC) conforming to 53 grade (IS 12269) were used. Properties of OPC, as provided by the manufacturer, are provided in table 2. In this study, sand was used as the Aggregate. The specific gravity of the sand used was 2.65 and water absorption of 0.50%. The size of sieve that was used for fine aggregate is #200. The percentage retained and passed is specified in Table 3.

Table 2. Properties of Ordinary Portland cement

Properties	Value
Average compressive strength, (28 days setting time)	33 MPa
Fineness	225 m^2/kg.min
Soundness (by Le Chatelier's method)	10
Soundness by autoclave method	0.8
Initial setting time	60 min
Final setting time	500 min
Specific gravity	3.15 g/cm^3

Table 3. Sieve size designation for aggregates

Aggregates	Sieve designation	% Weight retained	% Weight passed
Fine Aggregate	#200	99.3	0.1

2.2 Methodology

2.2.1 Caustic Treatment and its optimization

The primary focus of the present study was to compare and contrast the performance of different cellulosic fibers as reinforcement in FRM in their as-supplied form and after NaOH treatment. Thus, the first step was to optimize the NaOH treatment process. For this purpose, the cotton fibers were treated with different concentrations of NaOH solution w/v%, i.e., 2%, 4%, 6%, 8%, and 10%, and the resulting properties were evaluated. The fiber mass to be treated was added to the desired NaOH solution and kept at 90 ºC for five minutes with constant agitation. For 25.68 g of fiber, the volumes of NaOH solution at 2, 4, 6, 8, and 10% were 0.57 ml, 1.12 ml, 1.66 ml, 2.24 ml, and 2.75 ml, respectively. The fiber mass was then extracted from the solution, washed in boiling water, rinsed, and then neutralized in a 1% acetic acid solution. In the end, the fibers were again hot washed, rinsed, and dried in the oven for 2 hours. Subsequently, tensile strength, moisture regain, and elongation were evaluated according to the test methods mentioned in Section 2.1, and the results are tabulated in Table 4.

The results presented in table 4 clearly show that the optimum concentration of caustic treatment was 6%, as it was found to result in maximum increase in tensile strength and reduction in fiber elongation. Thus, all the selected fibers were then treated with 6% NaOH using the treatment method described in the aforementioned text.

Table 4. Properties of NaOH-treated cotton fibers

NaOH %	Moisture regain (%)			Tensile strength (gm/tex)			% Elongation		
	Before treatment	**After treatment**	**% change**	**Before treatment**	**After treatment**	**% change**	**Before treatment**	**After treatment**	**% change**
2	9.60	6	-37.5	17.6	19.48	10.6818	7.52	5.54	-26.329
4	9.60	6	-37.5	17.6	18.34	4.20454	7.52	7.68	2.127
6	9.60	12	25	17.6	25	42.045	7.52	6.08	-19.148
8	9.60	8	-16.77	17.6	19.31	11.9	7.52	7.52	0
10	9.60	11	14.5	17.6	19.7	9.7	7.52	6.40	-14.6

2.2.2 Manufacturing and testing of FRM samples

FRM samples containing 2 wt% fibers were manufactured. The fiber mass was hand-mixed in the mortar. The mix was then poured into a mold and vibrated using a vibration table to avoid voids. The top surface of the samples was smoothed using cement mortar. After 28 hours, the molds were removed, and test samples were kept at room temperature for curing. The properties of the test samples (both with treated and untreated fibers) were compared with those of the control sample of mortar. Mortar briquettes (Figure 2) were made for tensile strength testing using the standard ASTM C307 [38], and beams (Figure 3) were made for flexural testing using the standard ASTM C348 [39]. All the samples, as listed in Table 5, were conditioned in a standard testing atmosphere for 12 hours before testing. The compositions of beams and briquettes were calculated and presented in Table 6. The cement-sand ratio for all the samples was 1:2.75, and all of them were cured 28 days before evaluation.

Table 5. Mixture symbols for beams and briquettes

Sample Form: Briquettes (3x1.75x1 in^3)						
Fiber	Nil	Cotton	Spinning fly	Comber noil	Viscose	Tencel
Mixture Symbol	M0	M1	M2	M3	M4	M5
Sample Form: Beams (4x4x16 in^3)						
Fiber	Nil	Cotton	Spinning fly	Comber noil	Viscose	Tencel
Mixture Symbol	B0	B1	B2	B3	B4	B5

Figure 2. Tensile strength testing of mortar samples

Figure 3. Flexural strength testing of mortar samples

Table 6. Composition of beams and briquettes

Mixture	Cement (g)	Fine aggregate (g)	Fibers (g)	Water (ml)
Beam	799.8	2199.8	60	387.9
Briquette	123.33	339.15	9	59.8

3. Results and discussions

3.1 Caustic treatment of fibers

For the determination of optimal parameters of caustic treatment, the cotton fibers were subjected to treatment with caustic solution of different strength, as described in Section 2.2.1. The results pertaining to the change in various properties of the cotton fibers are tabulated in Table 4 in the methodology section.

The results presented in Table 6 clearly show that the optimum concentration of caustic treatment was 6%, as it was found to result in a maximum increase in tensile strength and a reduction in fiber elongation. Thus, all the selected fibers were then treated with 6% NaOH using the treatment method described in the methodology section. The results of tensile strength obtained after the selected fibers were treated indicate that the tensile strength of all the fibers increased considerably. A noticeable increment was observed in viscose fiber of about 33%, followed by raw cotton fiber showing an increase of 22.9%, comber noil 7%, tencel fly 2.1%, and spinning fly 1.1%. The caustic treatment of fibers has also minimized the inherent variations of diameters within the fibers by swelling if fibers' primary cell wall, thereby giving more even and better results.

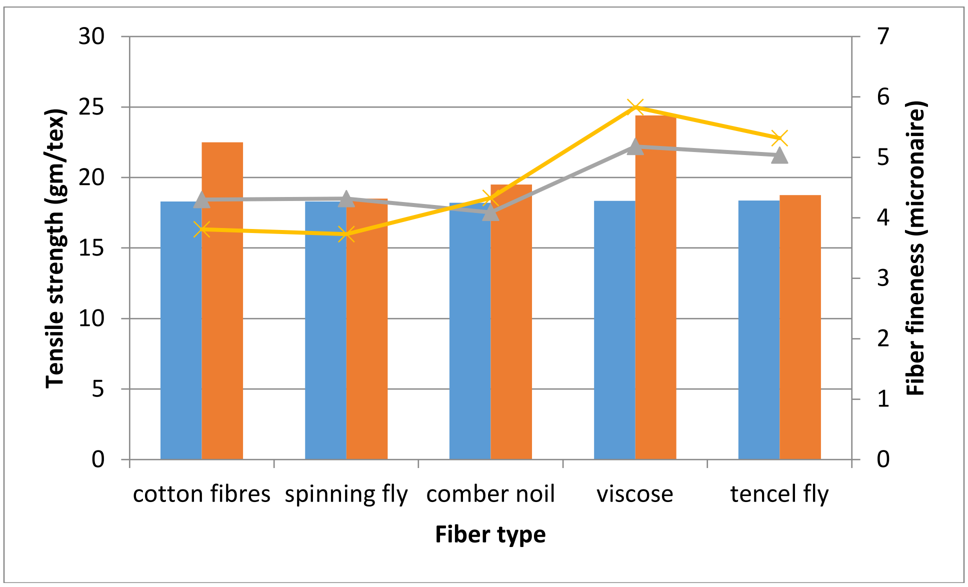
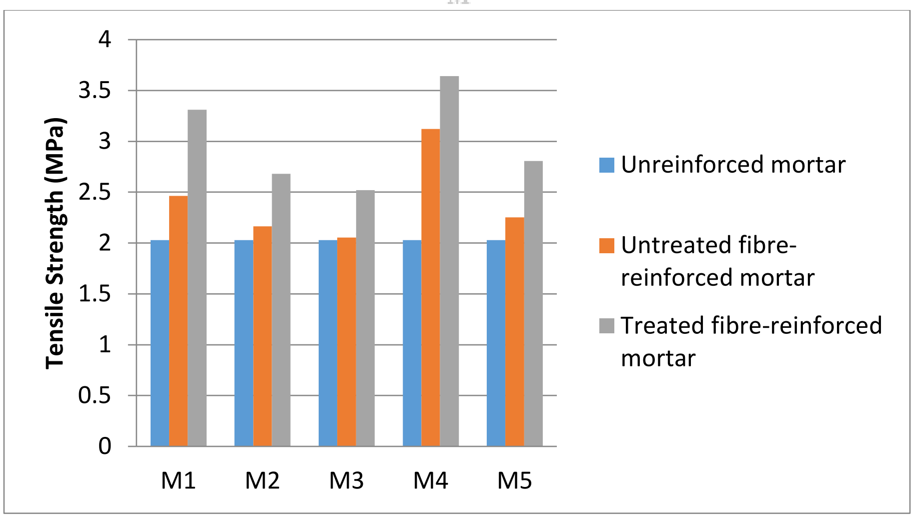


Figure 4. Comparison of tensile strength and fineness of treated and untreated fibers

Fiber fineness of the treated fibers was also observed to be increased in the case of viscose with an increment of 12.5%, comber noil at 5.87%, and tencel fly at 5.6%. This indicates that the fibers have swollen as a result of caustic treatment. Raw cotton and spinning fly contained a huge amount of foreign matter, dust, ash, and other particulate contaminants, due to which their micronaire value decreased after caustic treatment. The results are summarized in Figure 4.

3.2 Tensile strength of treated and untreated fiber-reinforced briquettes

Three samples of each type, as mentioned in Table 4, were prepared, and the tensile strength was subsequently determined according to ASTM D1445. The relevant results are presented in Figure 5. It is evident that the inclusion of fibers, whether treated or untreated with caustic soda, exhibited an increase in the tensile strength of mortar. More importantly, the tensile strength of mortar samples containing the treated fibers was noticeably higher. The effect was most pronounced in viscose-reinforced mortar, showing a difference (increase) of 33%, followed by cotton fibers at 22.95%. The variations in tensile strength of different fiber reinforced samples after they have been incorporated in mortar samples is because of the difference in interactions between these fibers and cement. The highest strength is exhibited by viscose due to strong bonding between viscose fiber and cement attributing to surface roughness of viscose. Viscose fibers exhibit the highest fiber length of 1.2 inch as compared to all the other fibers, which has resulted in the highest degree of tensile strength of viscose-reinforced mortar samples. The increased micronaire value of comber noil, viscose and tencel fly, and reduced impurities after the alkaline treatment have resulted in the improved contact area of fiber with the cement mix, therefore resulting in an increased mechanical property as compared to the unreinforced mortar samples. The addition of fibers to the cementitious matrix kept the structure aggregated, even with the formation of small faults, as shown in 2. The fibrous material supports cracks by fiber pullout and sliding against the matrix, preventing the propagation of cracks by stabilizing and applying traction to close the crack surface. Thus, it prevents premature breakage of the structure by the increasing strength and deformation levels of the composite. It is also worth noting that even though the strength and fineness of tencel fly was smaller in the fibrous form as compared to comber noil, the reinforced mortar of tencel exhibits higher value of tensile strength. This is related to the fact that comber noil in its fibrous form has numerous physical and mechanical variations as they are purely natural sources of cellulose fiber. Tencel, however, is semi-synthetic fiber and less prone to inherent variations. Tencel has less flexural rigidity than cotton and can easily be bent and deformed during composite manufacturing, thereby producing an FRC exhibiting better and uniform mechanical and physical properties.



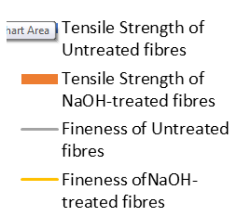


Figure 5. Tensile strength of unreinforced and fiber-reinforced mortar (NaOH treated and untreated)

3.3 Flexural strength of treated and untreated fiber-reinforced beams

Flexural strength of beams was calculated using Equation 1.

$\sigma_f = 0.0028P$ Equation 1

Where σ_f= flexural strength (MPa) and P= maximum load (Newton).

This test also revealed that the flexural strength of reinforced mortar tends to increase in all cases. It is further increased when these fibers are treated with caustic soda, with a 42.8% increase in the case of viscose fiber-reinforced mortar and 34.5% in the case of cotton fibers. Complete data pertaining to the results of this test is provided in Figure 6.

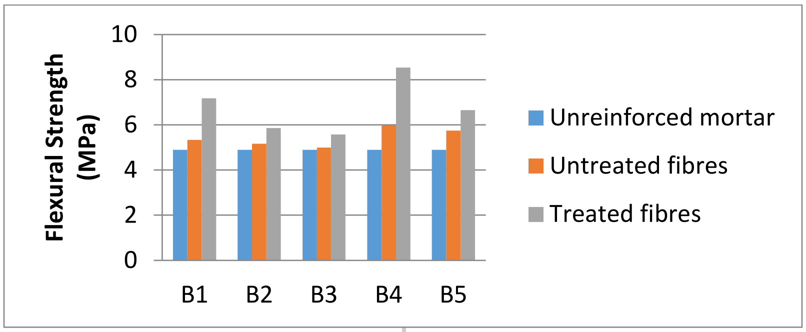


Figure 6. Flexural strength of unreinforced and fiber-reinforced mortar (NaOH treated and untreated)

A substantial increase in tensile and flexural strength of mortar samples as a result of the incorporation of fibers is known to occur because of the improvement in fiber-matrix bonding, the mechanisms of which are well known in the literature and discussed in the Introduction section. Specifically, the morphological structure of the fiber that is used as a reinforcement material plays a crucial role. Irregular cross-section, as in the case of viscose fibers, provides more surface area for fiber-matrix mechanical interlocking and thus results in effective transfer of the applied stresses from the matrix to the fibers. Alkali treatment further improves the surface roughness of cellulosic fibers by removing the hydroxyl coating materials and wax. The interplay of these factors manifests itself as improved bonding between fiber and matrix at the macro level.

4. Conclusion

The results obtained in the present study indicate that the inclusion of textile fibers results in an increase in the tensile strength and flexural strength of FRM. Furthermore, chemical treatment with caustic soda increases the strength of fibers and brings about changes in the morphology of cellulosic fibers that result in a significant increase in the strength of FRM. Our investigation shows that among the selected cellulosic fibers, viscose fiber is the most beneficial option, as it results in considerably higher tensile and flexural strength than any other fiber. Regarding crack resistance, it was observed that the inclusion of fibers makes the FRM more resistant to crack initiation and progression. The capacity of the modified mortar to support strain without fragmentation increased compared with the brittle behavior of the control mortar. Furthermore, higher fiber content was found to be more beneficial in terms of the properties of FRM being considered in the present study. The effect of fiber length on the mechanical properties of mortar needs to be further investigated. Nonetheless, the study shows that there is considerable potential for the use of waste fibers as a reinforcement material in mortars.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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