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Studies on the durability of natural fibres and the effect of corroded fibres on the strength of mortar

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Abstract

This paper presents the results of the variation in chemical composition and tensile strength of coir, sisal, jute and *Hibiscus cannabinus* fibres, when they are subjected to alternate wetting and drying and continuous immersion for 60 days in three mediums (water, saturated lime and sodium hydroxide). Compressive and flexural strengths of cement mortar (1:3) specimens reinforced with dry and corroded fibres were determined after 28 days of normal curing. From the results it is observed that there is substantial reduction in the salient chemical composition of all the four fibres, after exposure in the various mediums. Coir fibres are found to retain higher percentages of their initial strength than all other fibres, after the specified period of exposure in the various mediums. The compressive and flexural strengths of all natural fibre reinforced mortar specimens using corroded fibres are less than the strength of the reference mortar (i.e. without fibres) and fibre reinforced mortar specimens reinforced with dry natural fibres.

Keywords: Natural fibres; Durability; Chemical composition; Compressive and flexural strengths; Cement mortar

1. Introduction

In the last two decades, considerable effort has been directed towards using various vegetable fibres, which are available in abundance in tropical and sub-tropical countries, as reinforcement in cement composites for producing cost-effective building materials with a view to have a sustainable development. However, the long-term durability of natural fibres in cement composites has been the single concern, which has come in the way of widespread application and acceptance of the above materials. In order to overcome the durability problem associated with natural fibres in cement-based composites, a proper understanding of the 'deterioration mechanisms' of the fibres in the matrix is required.

Several investigators have studied the durability of natural fibres, such as, sisal, coir, jute, etc., in various mediums and exposure conditions (Table 1) and the durability of natural fibre cement composites exposed to various environments, based on the changes in a chosen strength criterion (Table 2) [1–21]. However, the effect of various mediums on the chemical composition of natural fibres, which will be different for various fibres, due to their widely varying composition, have not been quantified and reported. Moreover, the durability of natural fibres has been ascertained by the various investigators based on the durability of the composites, evaluated based on a chosen strength criterion (Table 2), which in reality cannot be attributed to the deterioration characteristics of the natural fibre alone. For example, fibre debonding, the effect of corroded fibres and the effect of the exposure conditions would have a cumulative effect in reducing the strength of the composite, which is sought to be used to explain/understand the durability of the natural fibres. Possibly, investigations on the

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Table 1
Overview of durability of natural fibres investigated

Sl. no.	Fibre type	Aging/exposure conditions											Reference
		1	2	3	4	5	6	7	8	9	10	11	
1	Agava (Lechuguiva and Maguey pulquero)	•	•							•	•	•	[15]
2	Akwara		•										[6]
3	Bamboo	•	•										[7]
4	Coir	•	•	•	•	•	•	•	•				[1,2,4,7,9,11]
5	Date palm		•										[17]
6	Elephant grass	•	•										[5]
7	Hemp	•											[4]
8	Jute	•	•	•									[1,4,7,16]
9	Musamba	•	•										[5]
10	Remie		•										[16]
11	Sisal	•			•								[1,2,4,10]
12	Plantain	•	•										[4,5]
13	Water reed	•	•										[3,5]

Note: (i) Description of codes in aging/exposure conditions are as follows:
1—Alkaline medium (continuous/alternate wetting and drying under room/elevated temperature); 2—Alternate wetting and drying; 3—Tap water (over varying periods); 4—Cement saturated water; 5—Seawater; 6—H_2SO_4 solution (1%); 7—One year old mortar and water cured; 8—One year old mortar (air-cured); 9—Na_2SO_4 solution (10%); 10—Alternate freezer and water curing; 11—Alternate elevated and normal water temperature.
(ii) Criterion to evaluate the durability of fibres after exposure in the various test conditions can be summarized as: Tensile strength; Changes in length/diameter/weight.

Table 2
Overview of durability of natural fibre composites investigated

Sl. no.	Fibre type	Composite type	Criterion for evaluating durability					Aging/exposure conditions											Reference
			F	T	L	S	I	1	2	3	4	5	6	7	8	9	10	11	
1	Agava (Lechuguilla and Maguey pulquero)	Mortar	✓						•	•		•	•	•	•				[15]
2	Banana	Mortar	✓							•	•								[14]
3	Cellulose fibre	Cement sheet				✓										•	•		[18]
		Cement sheet	✓	✓														•	[19]
		Cement sheet	✓					•											[20]
4	Coir	Mortar	✓	✓	✓			•	•	•	•								[1]
		Concrete	✓					•		•									[2]
		Mortar	✓							•									[8]
		Concrete		✓															[12]
		Mortar	✓							•	•								[13]
5	Date palm	Mortar	✓					•											[17]
6	Jute	Mortar	✓							•	•								[13]
		Mortar	✓								•								[16]
7	Ramie	Mortar	✓							•	•								[13]
		Mortar	✓								•								[16]
8	Sisal	Mortar	✓	✓	✓			•	•	•	•								[1]
		Concrete	✓					•		•	•								[2]
		Mortar	✓							•	•								[13]
		Mortar	✓							•									[14]
9	Wood fibre	Cement sheet	✓	✓			✓	•		•									[21]

Note: (i) F—Flexural strength; T—Toughness; L—French and Belgian load ratios; S—(Compression) Shear; I—Impact strength
(ii) Description of codes for aging/exposure conditions are as under: 1—Tap water; 2—Alkaline medium; 3—Outdoor environment; 4—Alternate wetting and drying; 5—Na_2SO_4 solution (10%); 6—Alternate elevated and near zero temperature; 7—Alternate elevated and curing in normal water temperature; 8—Alternate freezer and curing in normal water temperature; 9—Cyclic freeze—thaw; 10—Accelerator carbonation; 11—Hot water soak test (ASTM C 1185).

changes in the strength characteristics of cement composites using natural fibres in dry condition and after exposing them in alkaline and other environments may offer better insight into the actual deterioration process and help to understand the deterioration mechanism of natural fibres in alkaline environments.

Hence, an attempt is made in this paper to study the effect of alkaline mediums (calcium hydroxide and sodium hydroxide) and fresh water on the durability of coir, sisal, jute and *Hibiscus cannabinus*. The effect of the above mediums on some of the salient chemical compositions of fibres, which are susceptible for dissolution, have also been studied. Compressive and flexural strengths of cement mortar specimens reinforced with the above fibres in their natural (dry) condition and with the 'corroded fibres' (i.e. the fibres subjected to continuous immersion/alternate wetting and drying in the above mediums) are determined and compared with the strengths of 'control mix' specimens.

2. Materials and methods

2.1. Materials used

Four types of fibres, namely, sisal, coir, jute and *Hibiscus cannabinus* fibres were collected in locally available form, cut into pieces manually and used. The various physical characteristics of the above fibres are presented in Table 3. Chemical analysis on clean and well-dried samples of fibres, were carried out for determining the hemi-cellulose, cellulose and lignin contents of each type of fibre and the test results are presented in Table 4. Ordinary Portland cement (OPC), good quality locally available river sand and potable water were used. A commercially available superplasticizer (ROFF SUPER PLAST 320) was selected and used for improving the workability of the natural fibre reinforced mortar.

Table 3
Physical properties of natural fibres

Sl. no.	Fibre type	Fibre length (mm)	Fibre diameter (mm)	Tensile strength (N/mm^2)	Elongation (%)
1	Coir	60–250	0.40–0.10	15–327	75.0
2	Sisal	180–600	0.10–0.50	31–221	14.8
3	Jute	128–1525	0.04–0.35	29–312	19.0
4	*Hibiscus cannabinus*	163–1527	0.04–0.16	18–180	12.4

Table 4
Salient chemical composition of natural fibres

Sl. no.	Fibre type	Hemi-cellulose (%)	Cellulose (%)	Lignin (%)
1	Coir	31.1	33.2	20.5
2	Sisal	26	38.2	26.0
3	Jute	22.7	33.4	28.0
4	Hibiscus	25	28	22.7

Note: (i) The compositions are % by wt. of dry and powdered fibre sample.
(ii) Only the salient chemical compositions are indicated.

2.2. Durability studies

Durability studies on fibres were carried out by immersing the fibres in three different mediums, namely, (i) in clean and fresh water (pH = 7.5); (ii) saturated lime solution [$Ca(OH)_2$] and (iii) in a deci-normal (0.1 N) solution of sodium hydroxide (NaOH) and determining the changes in the chemical composition of each type of fibre after a specified period. During the period of exposure, the pH of the calcium hydroxide was maintained at 14 and that of the sodium hydroxide solution at 13. Fibres of 15–20 cm in length were kept immersed in airtight containers containing the above mediums. At 24 h time intervals, the fibres were taken out, washed with plenty of water and dried at room temperature (28 ± 3°) and then replaced in the same bottle. This alternate wetting and drying operation were repeated for 30 cycles (i.e. for a total of 60 days). The concentration of alkaline mediums and the duration of exposure were fixed based on the reported work of Singh [4]. In order to evaluate the performance of natural fibres subjected to alternate wetting and drying cycles, separate set of fibres were kept continuously immersed up to 60 days in airtight containers. At the end of the above exposure period, the fibres were taken out and their salient chemical compositions and tensile strength were determined.

2.3. Preparation and testing of specimens

First, a reference cement mortar (1:3), with water cement (w/c) ratio of 0.65 and a flow value of 112 (based on flow table test as per I.S: 2250-1981) [22], was prepared. Natural fibres conditioned in the various mediums were directly used for casting the fibre reinforced mortar beams (size: 40 mm × 40 mm × 160 mm; fibre content 1%-by weight of cement). Mortar beams were also cast using natural dry fibres (i.e uncorroded fibres), to serve as control specimens. In order to determine the 'desirable dosage' of the superplasticizer so as to achieve comparable workability (i.e., flow value) with that of the 'reference mortar', the dosage of the superplasticizer was varied gradually within the range recommended by the manufacturer. The desired dosages thus obtained are: (i) 0.15% (by wt. of cement) for coir fibres and (ii) 0.2% (by wt. of cement) for sisal, jute and *Hibiscus cannabinus* fibres. The above dosages were maintained constant for all the workability and strength studies.

3. Results and discussion

3.1. Effect of exposure conditions on the chemical composition

The chemical composition and the percentage reduction in their composition for the fibres after 60 days of

Table 5
Chemical composition of natural fibres after 60 days of alternate wetting and drying

Sl. no.	Fibre type	Sodium hydroxide			Saturated lime			Fresh water		
		Chemical composition (%)								
		H	C	L	H	C	L	H	C	L
1	Coir	18.2 (41.5)	13.7 (58.7)	10.0 (8.1)	21.2 (31.8)	10.8 (67.5)	9.7 (52.8)	19.2 (38.3)	19.2 (42.2)	11.6 (43.4)
2	Sisal	17.4 (33.0)	9.5 (75.1)	16.3 (37.3)	23.1 (11.1)	14.9 (61.0)	16.9 (26.1)	11.8 (54.6)	14.0 (63.4)	19.2 (26.2)
3	Jute	8.4 (63.0)	18.2 (45.5)	11.2 (60.0)	18.3 (19.4)	5.1 (84.7)	9.1 (67.5)	18.2 (19.8)	13.4 (59.9)	15.6 (44.3)
4	Hibiscus	10.4 (58.4)	14.4 (48.6)	11.1 (48.5)	15.0 (40.0)	9.2 (67.1)	14.2 (37.4)	0.1 (100.0)	4.3 (84.9)	2.5 (89.0)

Note: (i) H—Hemi-cellulose; C—Cellulose; L—Lignin.
(ii) Figures within brackets indicate the loss in the respective chemical composition after 60 days of alternate wetting and drying cycles in the respective mediums.

Table 6
Chemical composition of fibres after 60 days of continuous immersion

Sl. no.	Fibre type	Sodium hydroxide			Saturated lime			Fresh water		
		Chemical composition (%)								
		H	C	L	H	C	L	H	C	L
1	Coir	9.7 (68.8)	23.8 (28.3)	15.1 (47.0)	24.0 (22.8)	8.8 (73.5)	18.9 (33.7)	13.4 (56.9)	10.4 (68.7)	10.8 (62.1)
2	Sisal	13.0 (50.0)	12.9 (66.2)	18.0 (44.2)	17.4 (33.0)	10.6 (72.3)	18.8 (27.7)	18.7 (28.1)	19.9 (47.9)	14.5 (44.2)
3	Jute	9.1 (59.9)	19.9 (40.4)	14.5 (48.2)	16.8 (26.0)	19.9 (40.4)	15.2 (45.7)	12.5 (44.9)	18.7 (44.0)	18.2 (35.0)
4	*Hibiscus cannabinus*	12.4 (50.4)	8.8 (68.6)	14.1 (37.9)	18.2 (27.2)	13.3 (52.5)	14.9 (34.3)	14.2 (43.2)	16.2 (42.1)	17.1 (24.7)

Note: (i) H—Hemi-cellulose; C—Cellulose; L—Lignin.
(ii) Figures within brackets indicate the loss in the respective chemical composition after 60 days of continuous immersion in the respective mediums.

alternate wetting and drying and after 60 days of continuous immersion in the chosen three mediums are presented in Tables 5 and 6. From a critical analysis of the above results following salient observations/inferences, are drawn:

- Reduction in hemi-cellulose and cellulose contents of coir fibres exposed to alkaline environments are in the range of about 32–68% and 38–73% respectively, which are closer to the values for fresh water. However, a wide variation in the reduction of lignin content of the above fibre is observed, in alkaline environments (i.e. 8–53%) than in fresh water (43–62%). Sodium hydroxide for hemi-cellulose, saturated lime for cellulose and fresh water for lignin seem to be highly aggressive in causing maximum reduction in the respective contents, irrespective of the type of conditioning of coir fibres (i.e. alternate wetting and drying/continuous immersion).
- Reduction in hemi-cellulose and cellulose contents of sisal fibres are in the range of 11–50% and 61–75% respectively in alkaline environments. The effect of fresh water is found to be within the above ranges. However, the maximum percentage reduction in hemi-cellulose content of sisal fibres is less than coir fibres, whereas, the maximum percentage reduction in cellulose content is almost the same as that of coir fibres. However, a lesser range in the percentage reduction of cellulose content is observed than coir fibres. Moreover, reduction in the lignin content of sisal fibres (i.e. 26–44%) found to be less than the range for coir fibres. Alkalis, especially, sodium hydroxide seems to have the same effect in sisal fibres, as that of coir fibres. On the other hand, lignin content is severely affected by sodium hydroxide and water, especially due to continuous immersion.
- The range of reduction in hemi-cellulose and cellulose contents of jute fibres are comparable to that of coir fibres. However, the effect of alkalis on jute fibres due to alternate wetting and drying seem to be higher than coir fibres. Lignin content in jute fibres has been severely reduced, when compared to coir and sisal fibres. Sodium hydroxide for hemi-cellulose; sodium

hydroxide and fresh water for cellulose and alkalis, (in general), for lignin, seem to be very aggressive, in causing maximum reduction in the above chemical composition of jute fibres, irrespective of the type of immersion.
- More than the alkalis, fresh water seems to be aggressive in the case of *Hibiscus cannabinus*, causing the maximum reduction in the chemical composition, due to alternate wetting and drying of the fibres. However, the effect of alkalis on the hemi-cellulose and cellulose contents is severe, than in fresh water, due to continuous immersion of the above fibres. The effect of alternate wetting and drying is about 2–3 times severe than continuous immersion in fresh water, for all the chemical composition of the fibres.

3.2. Effect of exposure conditions on the tensile strength characteristics

The tensile strength of various fibres after exposure in the three mediums, were determined by testing fibres in an universal tension testing machine (5 kN capacity) at low strain rates and the results are presented in Tables 7 and 8. The decomposition of fibres have an effect on the tensile strength of various fibres. The tensile strength of the fibres in dry condition were compared with that of the tensile strength of the fibres after exposure in various mediums and the following are the observations/inferences were drawn:

- There is a substantial reduction in tensile strength of natural fibres in all the mediums, irrespective of the type of exposure. This may be attributed to the chemical dissolution of lignin, especially in alkaline mediums, which acts as the binder for the cellulose and hemi-cellulose present in the fibre. The above chemical dissolution is responsible for the loss in strength of the fibres and their efficiency as reinforcement.
- Maximum reduction in tensile strength was observed due to the effect of saturated lime on sisal, jute and *Hibiscus cannabinus* fibres. After 60 days of alternate wetting and drying in saturated lime, sisal and *Hibiscus cannabinus* fibres were completely destroyed, whereas, coir fibres were able to retain about 20–40% of its original strength. This may be attributed to the absorption of the alkaline solution into the higher pores present in the above fibres, than in coir fibres [1,4,9]. The alkaline water thus absorbed gets crystallized and thereby make the fibres brittle. Jute fibres could retain about 10–20% of the original tensile strength, which is marginally better than sisal and *Hibiscus cannabinus*.
- In sodium hydroxide, coir fibres retain about 40–60% of its original strength, sisal, jute, *Hibiscus cannabinus* on the otherhand, could retain only 10–20% of their tensile strength, irrespective of the type of immersion.
- Coir and sisal fibres were able to retain about 50–60% and 60–70% of their corresponding initial tensile strength, whereas, the other fibres (i.e. jute and

Table 7
Tensile strength of fibres after 60 days of alternate wetting and drying

Sl. no.	Fibre type	Tensile strength (N/mm^2)			
		Natural dry condition	Alternate wetting and drying in		
			Sodium hydroxide	Saturated lime	Fresh water
1	Coir	15–327	7.6–150.5	3–143.7	3–178.9
2	Sisal	31–221	5–55	(*)	1–164
3	Jute	29–312	2.7–34	3.5–16.3	7.5–58.5
4	*Hibiscus cannabinus*	18–180	10	(*)	3–37

Note: (i) (*)—indicates that the fibres failed to take any load.
(ii) The range of values indicated correspond to the lowest and the highest tensile strength of each type of fibre after the durability studies.

Table 8
Tensile strength of fibres after 60 days of continuous immersion

Sl. no.	Fibre type	Tensile strength (N/mm^2)			
		Natural dry condition	Alternate wetting and drying in		
			Sodium hydroxide	Saturated lime	Fresh water
1	Coir	15–327	40–109	22.6–64	46.4–144.4
2	Sisal	31–221	23–38	4.5–18	16–90
3	Jute	29–312	5–22	2–12	15–45
4	*Hibiscus cannabinus*	18–180	1–22	7–18	10–74

Note: The range of values indicated correspond to lowest and the highest tensile strength of each type of fibre after the durability studies.

Hibiscus cannabinus) were able to retain a maximum of about 20% of their strength, considering both types of immersion in fresh water.

3.3. Mortar strength characteristics

Compressive and flexural strength of fibre reinforced mortar under natural dry condition and with fibres after exposing them in the various mediums and under two different types of immersion, are presented in Tables 9 and 10. The maximum-loss in strength of various fibre reinforced mortars, (considering all the three mediums and two types of immersion) are presented in Table 11. Comparing the above strength with that of the reference mortar strength, following inferences are drawn:

- Compressive and flexural strengths of all types of fibre reinforced mortars are less than the reference mortar strength (i.e. without using fibres), when fibres were used in their natural dry condition.
- Both the above strengths of fibre reinforced mortars reinforced with corroded fibres (i.e. fibres after exposed in the various mediums) are also less than the reference mortar strength and that of mortars reinforced with fibres in their natural dry condition. The above phenomena are true for all types of fibres and for the two types of immersion, considered in this study. This may be due to the embrittlement of the various fibres consequent to their exposure in the various mediums.
- The loss in strength is generally found to be more severe in the mortar specimens, wherein, fibres subjected to alternate wetting and drying in the various mediums were used. Considering the strength variation of various fibres and the strength-loss of fibre reinforced mortars, it can be inferred that certain types of fibres are susceptible for deterioration even in water, apart from alkaline mediums.
- Reduction in the strength of cement composites reinforced with corroded fibres (Table 11) indicate that it may be due to the cumulative effect of the matrix and that of corroded fibres on the strength and bond.

Table 9
Compressive strength of fibre reinforced mortar (1:3)

Sl. no.	Fibre type	Compressive strength (N/mm^2)						
		Water		$Ca(OH)_2$		NaOH		Natural dry condition
		1	2	1	2	1	2	
1	Coir	15.6	16.9	7.5	11.8	14.8	16.6	17.3
2	Sisal	9.4	12.8	10.8	7.8	10.8	10.0	13.8
3	Jute	5.5	10.2	6.8	6.7	9.0	10.0	11.3
4	*Hibiscus cannabinus*	8.8	7.5	7.5	4.5	8.9	5.0	8.8

Note: (i) Compressive strength of control mix (1:3), without fibres = 27.0 N/mm^2.
(ii) (1)—indicates alternate wetting and drying and (2)—indicates continuous immersion in the respective mediums.

Table 10
Flexural strength of fibre reinforced mortar (1:3)

Sl. no.	Fibre type	Flexural strength (N/mm^2)						
		Water		$Ca(OH)_2$		NaOH		Natural dry condition
		1	2	1	2	1	2	
1	Coir	1.1	3.9	1.0	1.9	2.5	2.1	4.7
2	Sisal	1.7	4.1	1.1	2.9	1.2	3.2	5.8
3	Jute	1.4	3.3	1.1	3.0	1.7	4.0	4.3
4	*Hibiscus cannabinus*	1.4	3.4	1.8	1.8	1.8	2.0	3.5

Note: (i) Flexural strength of control mix (1:3), without fibres = 6.9 N/mm^2.
(ii) (1)—indicates alternate wetting and drying and (2)—indicates continuous immersion in the respective mediums.

Table 11
Comparison of strength-loss of fibre reinforced mortar (1:3)

Sl. no.	Fibre type	Maximum reduction in	
		Compressive strength (%)	Flexural strength (%)
1	Coir	56.7 [$Ca(OH)_2$]	75.8 (H_2O)
2	Sisal	32.2 (H_2O)	80.0 (NaOH)
3	Jute	51.4 (H_2O)	75.2 [$Ca(OH)_2$]
4	*Hibiscus cannabinus*	14.2 [$Ca(OH)_2$]	60.4 (H_2O)

Note: The strength loss are based on the strengths of corresponding fibre under natural dry condition.

4. Conclusions

- In general, there is substantial reduction in the salient chemical composition of all the four natural fibres (i.e. 20–85% of celluloses and 30–70% of lignin) considering their exposure in all the three mediums and the two types of immersion. It is observed that in most of the cases, continuous immersion is found to be critical, affecting the fibre characteristics.
- However, the effect of fresh water on *Hibiscus cannabinus* is very severe than in the other three fibres (i.e. the reduction in the chemical compositions is about 25% higher).
- Coir fibres retain about 40–60% and 20–40% of their original tensile strength, considering all the three mediums and when subjected to alternate wetting and drying and continuous immersion, respectively.
- All other fibres, in general, lost their entire initial tensile strength after exposure in the three mediums, except, sisal fibres which retain 60–70% of their initial tensile strength after exposure in fresh water. This shows that the fibres also lose strength after exposure in fresh water, which may be due to microbiological action.
- Compressive and flexural strength of all natural fibre reinforced mortars using corroded fibres (i.e. using fibres after exposing them in the various mediums), are less than the strength of reference mortar (i.e. without fibres) and fibre reinforced mortars using fibres in dry condition. The strength reduction is high when the fibres exposed to alkaline mediums are used in mortar, which clearly indicate the exclusive effect of alkalinity on the fibres and their consequent strength-loss when natural fibres are used in cement composites.
- Compressive strength of mortar reinforced with corroded natural fibres is 30–60% to less than the compressive strength of mortar reinforced with fibres in dry condition, irrespective of the type of fibre and medium of exposure.
- Further studies are required to correlate the fibre strength and durability in alkaline mediums with that of the composite exposed to laboratory/field conditions.

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