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Impact strength of a few natural fibre reinforced cement mortar slabs: a comparative study

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Abstract

This paper presents the experimental investigations of the resistance to impact loading of cement mortar slabs (1:3, size: 300 mm × 300 mm × 20 mm) reinforced with four natural fibres, coir, sisal, jute, hibiscus cannebinus and subjected to impact loading using a simple projectile test. Four different fibre contents (0.5%, 1.0%, 1.5% and 2.5%—by weight of cement) and three fibre lengths (20 mm, 30 mm and 40 mm) were considered. The results obtained have shown that the addition of the above natural fibres has increased the impact resistance by 3–18 times than that of the reference (i.e. plain) mortar slab. Of the four fibres, coir fibre reinforced mortar slab specimens have shown the best performance based on the set of chosen indicators, i.e. the impact resistance (R_u), residual impact strength ratio (I_{rs}), impact crack-resistance ratio (C_r) and the condition of fibre at ultimate failure.

Keywords: Natural fibres; Impact strength; Projectile test; Residual impact strength ratio; Impact crack-resistance ratio

1. Introduction

Natural fibres have the potential to be used as reinforcement to overcome the inherent deficiencies in cementitious materials. In recent years, there has been sustained interest in utilizing natural fibres in cement composites and in manufacturing products based on them with a view to have alternate building materials, which are energy-efficient, economical and eco-friendly. If the function of natural fibres in a relatively brittle cement matrix is to achieve and maintain toughness and ductility of the composite, then, the durability of such fibres in a highly alkaline cement matrix must be taken into consideration and ensured by effective modifications made either to the fibre surface or to the matrix composition to overcome the inherent problem i.e. 'embrittlement' of natural fibres, as evident from the pioneering work of Gram [1] and the subsequent studies so far carried out by various researchers [2–6].

The capability to absorb energy, often called 'toughness', is of importance in actual service conditions of fibre reinforced composites, when they may be subjected to static, dynamic and fatigue loads. Toughness evaluated under impact loads, is the impact strength. Apart from ensuring durability of natural fibres in the cement matrix, it is necessary to study the impact strength characteristics of natural fibre reinforced cement composites to understand their behaviour and assess their performance for various potential uses.

Impact resistance of fibre reinforced composite can be measured by using a number of different test methods, which can be broadly grouped into the following categories: (i) drop weight single or repeated impact test, (ii) weighted pendulum charpy type impact test, (iii) projectile impact test (iv) explosion – impact test, (v) constant strain rate test, (vi) split Hopkinson bar test and (vii) instrumented pendulum impact test [7]. The resistance of the material is measured using one of the

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criteria, such as, (i) energy needed to fracture the specimen; (ii) number of blows to achieve a specified distress level (in a repeated impact test) and (iii) the size of the damage (i.e. crater size, perforation) or the size and velocity of spall after the specimen is subjected to a surface blast loading [8].

The measured performance can be used to compare different material compositions or to design a structural system that should withstand certain kinds of impact loads. However, the results from these tests should be interpreted very carefully as they depend on a number of factors including specimen geometry, loading configurations, loading rate, test systems compliance and the prescribed failure criteria [9].

Several investigators (Table 1) have evaluated the impact strength characteristics of fibre reinforced composites and that the repeated impact (drop weight) test has been extensively used to evaluate the impact strength, which may be due to its simple technique [7–41]. However, the above method cannot be used to determine the basic properties of composites. Rather, the method is designed to obtain the relative performance of plain cement matrix and fibre reinforced composites containing different types and volume fractions of fibres [8]. From the above review of literature, it can be seen that studies on the impact strength characteristics of natural fibre reinforced composites, in general, have been rare and are not exhaustive.

The main objective of this paper, is therefore, to study the behaviour of cement mortar slab specimens (1:3) reinforced with four types of natural fibres (coir, sisal, jute and hibiscus cannebinus) at four different fibre contents (0.5%, 1.0%, 1.5% and 2.0%—by wt. of cement) and using three fibre lengths (20 mm, 30 mm, 40 mm) under a repeated projectile test (devised for the present study and manually operated). The results obtained have been compared with that of reference mortar slab specimens,and their relative performance have been evaluated based on the set of chosen indicators, namely, the ultimate impact resistance (R_u), residual impact strength ratio (I_{rs}), crack-resistance ratio (C_r) and the condition of fibre at ultimate failure.

Table 1
Overview of impact resistance measurement for fibre reinforced composites

Sl. no.	Test method	Type of fibre	References
1	Drop weight	Steel	[10–15,30–36]
		Polypropylene	[19,37]
		Elephant grass	[21]
		Jute	[22,23,26]
		Coir	[23,26,36,38,39]
		Sisal	[39,41]
		Palm-kernel	[27]
		Malva	[40]
2	Instrumented impact	Steel	[9]
		Polypropylene	[16–18]
3	Explosive impact	Polypropylene	[20]
4	Projectile impact (low/high velocity)	Steel	[26,36]
5	(a) Pendulum (Charpy/Izod) impact	Akwara	[24]
		Steel	[28]
	(b) Modified pendulum impact (instrumented charpy)	Steel	[29]

2. Experimental investigations

2.1. Materials used

Ordinary Portland cement (OPC) was used as the binder. Good quality river sand free from silt and other impurities was used as the fine aggregate. Four types of natural fibres, namely, coir, sisal (*agava sisalana*), jute and hibiscus cannebinus (*Indian hemp*), which are locally available in processed form, are used in this study. The specific gravity was determined based on the method specified in IS: 2386 (part III) [42]. Five gram of each sample of fibres was accurately weighed in an electronic balance and the water absorbed after 24 h of continuous immersion was determined. The ultimate tensile strength of the fibres was determined by the tension test on a 5 kN universal tensile testing machine at a pre-set loading rate, which was maintained constant for all fibres. A gauge length of 100 mm was chosen to measure the maximum elongation (at failure) and the fibres were held securely in position using a special gripping device available for testing of wires and ensuring 'no slip' during loading and testing. As a single strand of jute and hibiscus cannebinus was difficult to obtain, coir and sisal fibres were bundled to match the available maximum diameter of the other two fibres (i.e. 1.8 mm) and their tensile strength determined by tension test. Salient results of the physical properties of the four natural fibres are given in Table 2. Potable water was used for casting and curing mortar specimens.

2.2. Preparation and testing of specimens

The required quantity of water for the mortar mix (1:3—cement:sand) was assessed to maintain a flow value of 110%, as prescribed in I.S.2250–1981 [43]. The water cement ratio corresponding to the above flow value is 0.47, which was maintained constant for casting all slab specimens (plain and with various combinations of fibre content and fibre length). Altogether 147 mortar slab specimens (144 mortar slab specimens with fibres and three specimens without fibres) were cast and moist cured for 28 days. At the end of the above curing period,

Table 2
Physical properties of fibres (in natural dry condition)

Sl. no.	Properties	Sisal	Coir	Jute	Hibiscus Cannebinus
1	Specific gravity	1.17	1.00	1.00	0.71
2	Water absorption in 24 h (%)	200	180	281	285
3	Max. tensile strength (MPa)	58.16	50.89	60.14	76.04
4	Max. elongation (mm)	6.00	17.6	13.10	6.70

Note: The values of max. tensile strength and max. elongation do not agree with the generally accepted values which may be due to the test conditions adopted.

the specimens were tested in a projectile impact test set-up specially fabricated for the present study with the specimen mounted on a M.S. frame (Fig. 1). For each slab specimen, the number of blows required for the appearance of the first crack, the crack width and crack length at failure, were noted. The height of fall (i.e. 200 mm) and the weight of the metallic ball (weighing 0.475 kg) were maintained constant for testing all the specimens. The test set-up was so adjusted, such that the metallic ball will fall exactly at the center of the specimen and it was also ensured that the four edges of the specimens were freely supported.

3. Theoretical background

When a concrete slab is subjected to a load released from a defined height thereby constituting an impact loading, in general, there is a loss of potential energy which is absorbed and dissipated as strain energy, causing cracks due to stresses developed in the element. The width of crack thus developed is related to the intensity of the energy, the amount of energy absorbed and the properties of the concrete. The energy absorbed is dissipated in the form of crack patterns produced from the impact loading and that the crack pattern is also dependent on the properties of the concrete [27]. A relationship for the potential energy (PE) of an impact loading due to a falling body and the strain energy dissipated in cracks that develop in a target may be expressed based on fundamentals of strength of materials approach as

$$Ne = R_u l_c d_c w_c \tag{1}$$

where, N = no. of blows; e = energy (in Joules)/blow; l_c = total length of all cracks; d_c = maximum crack depth and w_c = maximum crack width. The above relationship was based on the equation proposed by Kankam [27]. Using Eq. (1), the ultimate crack resistance (R_u) of the mortar slab specimens were calculated. A dimensionless factor 'impact crack resistance ratio' was also defined (Eq. (2)) and evaluated.

$$C_r = R_u f_{cu} \tag{2}$$

where, C_r = impact crack resistance ratio; f_{cu} = cube compressive strength of the reference mortar in MPa (1:3, 70.7 × 70.7 × 70.7 mm). Kankam [27] used the above approach for studying the resistance to impact loading of concrete slabs reinforced with palm-kernel fibres, by loading it as a pavement slab (i.e. placing the slab over sand bed). He has assumed that the total computed energy imparted to the slab specimen is fully absorbed by it alone, even though the actual experimental condition was not close to the theoretical approach. However in this study, the experimental set-up closely simulates the theoretical approach. Hence, Eq. (1) can

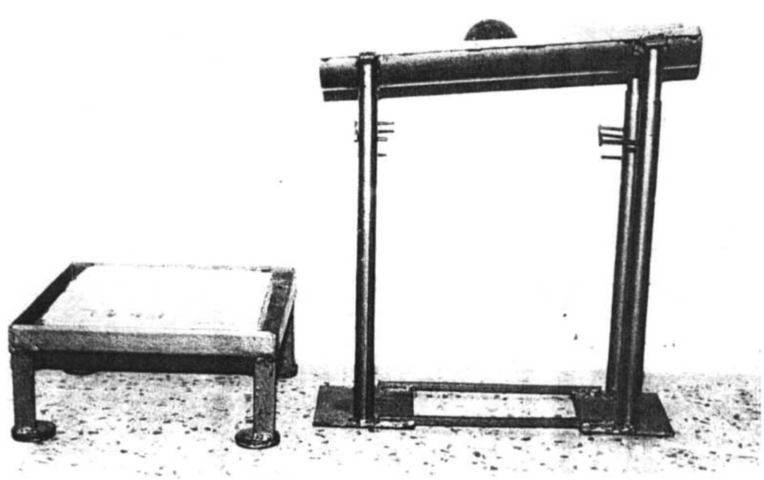

Fig. 1. Projectile impact test set-up.

be used with confidence to study the behaviour of specimens subjected to impact loading.

4. Results and discussion

4.1. Impact energy

From the projectile impact test, the number of blows required for the initiation of first crack was based on visual observation and the ultimate failure was determined based on the number of blows required to open the crack in the specimen sufficiently and for the propagation of the crack through the entire depth of the specimen. It was observed during testing that the crack propagates and also widens simultaneously. As only the relative performance of impact resistance can be evaluated by any type of drop-weight method, it is essential to determine the maximum energy absorbed under impact load. Hence, the test was conducted till the crack propagated to the entire depth of slab. It was also observed that there is not much variation in the maximum crack width of slab specimens with fibre content and types of fibres. Hence, the maximum crack width and the crack depth (i.e. entire depth of the specimen) was used to compute the energy absorbed by the specimen. The impact energy per blow was computed for the (chosen) weight of the ball and its velocity at the instant it strikes the mortar slab specimen. The impact energy absorbed by the mortar slab specimens were computed based on the number of blows required to cause ultimate failure and the impact energy per blow (i.e. 0.94 J). The impact energy absorbed by the fibre reinforced mortar specimens were compared with that of the reference mortar specimens (Table 3). It was observed that the fibre reinforced mortar slab specimens do not break into distinct pieces, where as, plain mortar slab specimens were broken into separate (distinct) pieces. From the above results, it is seen that due to incorporation of fibres in mortar the impact resistance of the slabs has increased 2–18-fold (in terms of impact energy absorbed), depending on the type of natural fibre and fibre content. Moreover, the ultimate crack resistance generally increases with increase in fibre content, but, irrespective of the fibre length, for all the four types of fibre reinforced slabs. Of the four types of fibres considered, coir fibre reinforced slab specimens have absorbed higher energy, when compared to the other three types and that the highest impact energy absorbed was 253.5 J (fibre content = 2% and fibre length = 40 mm). This may be due to the higher ductility and lesser susceptibility to embrittlement of coir fibres. The impact resistance of natural fibre reinforced slab specimens also increase with increase in the fibre length, which may be due to the interlocking of the fibres in the cement matrix. Slab specimens which appear to possess relatively a low impact resistance at the appearance of first crack were found to improve and obtain higher impact resistance at failure. For example, slabs reinforced with coir fibres (fibre content = 2% and fibre length = 40 mm) needs only 64.31 J for the initiation of first crack, whereas, 253.5 J is

Table 3
Impact energy absorbed by slab specimens (reference and natural fibre-reinforced)

Sl. no.	Type of fibre	Fibre content (% by wt. of cement)	Impact energy absorbed by natural fibre reinforced slab specimens (in Joules)					
			A		B		C	
			Initial	Final	Initial	Final	Initial	Final
1	Reference	0.0	10.25	13.98	–	–	–	–
2	Sisal	2.0	55.92	81.08	62.44	91.34	58.73	121.16
		1.5	45.67	71.76	44.74	81.08	50.33	88.54
		1.0	31.69	52.19	37.28	60.58	44.74	82.95
		0.5	28.89	41.94	35.42	42.87	29.82	44.74
3	Coir	2.0	49.4	210.63	51.26	231.14	64.31	253.5
		1.5	39.14	132.34	40.08	148.19	41.09	164.03
		1.0	35.42	54.06	39.14	52.19	41.94	73.63
		0.5	32.62	45.67	38.21	47.53	39.14	67.10
4	Jute	2.0	25.16	44.74	26.10	49.4	34.48	68.02
		1.5	18.64	35.42	25.16	41.09	27.03	54.02
		1.0	17.71	31.69	22.37	36.35	27.03	41.01
		0.5	17.71	30.76	19.57	36.35	25.16	37.28
5	Hibiscus	2.0	21.44	49.4	26.10	53.12	34.48	64.31
	Cannebinus	1.5	21.44	46.60	23.30	48.46	27.03	58.75
		1.0	16.78	26.10	22.37	41.01	26.10	54.99
		0.5	16.78	25.16	22.37	31.69	25.16	32.62

Note: A, B, and C corresponds to the fibre length of 20 mm, 30 mm and 40 mm, respectively, used to reinforce slabs.

required to cause ultimate failure. Hence, the residual impact strength ratio (I_{rs}), defined as in Eq. 3, for the above fibre reinforced slab specimen is about 3.91.

Residual impact strength ratio (I_{rs})

$$= \left[\frac{\text{Energy absorbed at ultimate failure}}{\text{Energy absorbed at initiation of first crack}}\right] \quad (3)$$

The same phenomenon i.e. substantial improvement in the impact resistance characteristic in the form of large amount of absorption of energy after the initiation of first crack and up to the ultimate failure was observed for all the other three types of fibre reinforced slab specimens at higher fibre contents (i.e. >1.0%). However, only the residual impact strength ratio (I_{rs}) was found to be different, which varied from 2.06 to 1.87 for sisal to hibiscus, which may be attributed to the reduction in the tensile strength of fibres due to the alkaline medium present in the composite.

4.2. Crack resistance and crack resistance ratio

Based on the energy absorbed, the maximum crack width (w_c), crack length (l_c) at failure, the ultimate crack resistance (R_u) and the crack resistance ratio (C_{rs}) were evaluated and presented in Table 4. From the above results, it is seen that the maximum crack width and the maximum crack length do not exhibit appreciable variation with respect to the fibre content, fibre length and the type of fibre. On the other hand, the ultimate crack resistance follows the same trend as that of the ultimate impact resistance, irrespective of the type of fibre. Coir fibre reinforced slabs have the maximum ultimate crack resistance, followed by sisal, jute and hibiscus, taken in that order. Maximum ultimate crack resistance has been offered by coir fibre reinforced slab specimens at 2.0% fibre content and reinforced with 40 mm length of fibres. The crack resistance ratio generally shows an increasing trend with increase in the fibre content and length of fibre. However, the average increase in the crack resistance ratio, considering the lower and upper bounds of fibre content used in this study, is the highest for coir fibre reinforced slab specimens (i.e. 3.14) and it is about twice that of the other three fibre reinforced slab specimens, which ranges between 1.3% and 1.5% only.

4.3. Failure pattern

Considering the nature of failure, it was observed that the plain mortar slab specimens broke into pieces, whereas, the fibre reinforced mortar slab specimens, had a number of multiple cracks (Fig. 2(a) and (b)). Moreover, in the case of coir fibre reinforced mortar slabs, fibre pull-out was observed at ultimate failure, whereas, 'fracture of fibres' were observed in all the other slab specimens. The above failure mechanism is typical of natural fibre reinforced composites, as observed by other investigators [6,44].

Table 4
Ultimate crack resistance and crack resistance ratio

Sl. no.	Type of fibre	Fibre content (% by wt. of cement)	Maximum crack width (w_l) (mm)			Maximum crack length (l_c) (mm)			Ultimate crack resistance (N/mm^2) (R_u)			Crack resistance ratio (C_r)		
			A	B	C	A	B	C	A	B	C	A	B	C
1	Reference	0.0	0.2	–	–	605	–	–	5.77	–	–	0.15	–	–
2	Sisal	2.0	0.23	0.21	0.20	603	620	611	29.2	35.0	49.7	0.77	0.92	1.31
		1.5	0.19	0.18	0.17	601	607	615	31.4	37.1	42.3	0.82	0.98	1.11
		1.0	0.16	0.19	0.17	608	601	600	26.8	26.5	40.6	0.70	0.70	1.07
		0.5	0.17	0.16	0.12	610	595	593	20.2	22.5	31.4	0.53	0.60	0.82
3	Coir	2.0	0.19	0.20	0.19	601	592	579	92.2	97.6	115	2.42	2.56	3.03
		1.5	0.18	0.17	0.18	609	592	565	60.3	73.6	80.6	1.58	1.93	2.12
		1.0	0.17	0.17	0.16	600	589	582	26.5	26.0	39.5	0.69	0.68	1.04
		0.5	0.15	0.13	0.13	602	585	597	25.3	31.2	43.2	0.66	0.82	1.13
4	Jute	2.0	0.22	0.17	0.18	595	589	578	17.0	24.6	32.7	0.45	0.65	0.86
		1.5	0.18	0.21	0.17	602	610	592	16.3	16.0	26.8	0.43	0.42	0.70
		1.0	0.17	0.15	0.15	583	600	591	15.9	20.1	23.1	0.42	0.53	0.60
		0.5	0.16	0.19	0.13	599	569	600	16.0	16.8	23.9	0.42	0.44	0.62
5	Hibiscus	2.0	0.22	0.19	0.18	599	595	600	18.7	23.5	29.8	0.49	0.61	0.78
		1.5	0.20	0.19	0.13	592	563	576	19.7	22.6	39.2	0.51	0.59	1.03
		1.0	0.18	0.17	0.16	589	594	610	12.3	20.3	28.2	0.32	0.53	0.74
		0.5	0.17	0.15	0.17	600	592	610	12.3	17.8	15.7	0.32	0.47	0.41

Note: A, B, and C corresponds to the fibre length of 20 mm, 30 mm and 40 mm, respectively, used to reinforce slabs.

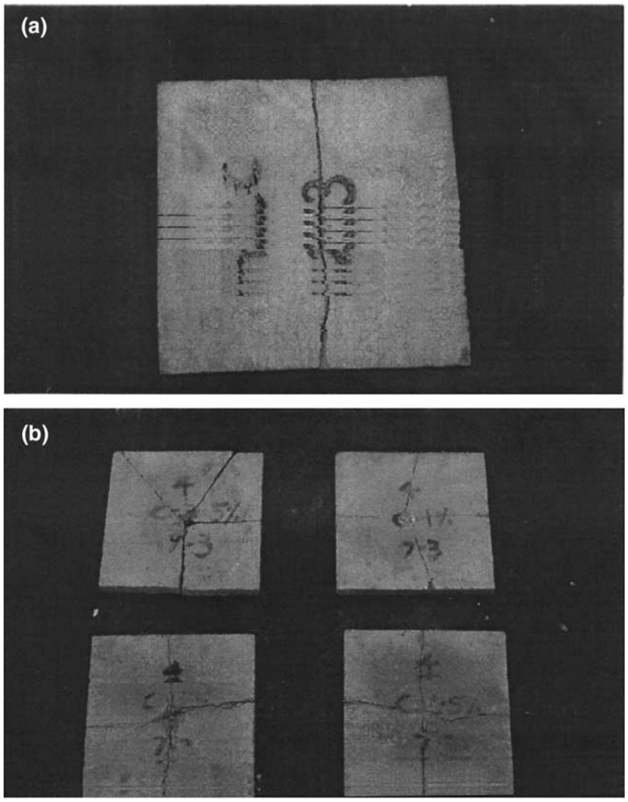

Fig. 2. (a) Typical crack pattern of plain Mortar slab Specimen (assembled after impact). (b) Typical crack pattern of coir Reinforced slabes (assembled).

5. Conclusions

Following are the salient conclusions based on the experimental investigations reported in this study:

- The impact resistance of the four natural fibre reinforced cement mortar slabs considered in this study, are found to be 3–18 times higher than that of plain cement mortar slabs.
- Coir fibre reinforced mortar slab specimens have absorbed the highest impact energy (i.e. 253.5 J, at 2% fibre content and fibre length = 40 mm).
- Residual impact strength ratio (I_{rs}) of all natural fibre reinforced slab specimens ranges from 1.87 to 3.91 and that coir fibre reinforced slab specimens have the highest residual impact strength ratio (I_{rs}) among the various types of natural fibres.
- The maximum crack width and length are not sensitive to the type and content of fibre, whereas, the ultimate crack resistance exhibits the same trend as that of the ultimate impact resistance, irrespective of the type of fibre.
- The average increase in the crack resistance ratio (C_{rs}), considering the lower and upper bounds of fibre content used, is the highest for coir fibre reinforced slab specimens (i.e. 3.14) and it is about twice than that of specimens reinforced with the other three types of natural fibres.
- Coir fibre reinforced slab specimens exhibit 'fibre pull out' failure, whereas, all other type of fibre reinforced specimens, exhibit 'fibre fracture', at ultimate failure.
- The projectile test set-up (manually operated) has proved to an economical, simple, portable and reliable one, to evaluate the impact resistance of natural fibre reinforced mortar slab specimens.

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