STRENGTH AND IMPACT BEHAVIOR OF PAVING CONCRETE INCORPORATING DISCARDED COCONUT COIR FIBERS

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Abstract

With the aim to explore the potential contributions of discarded coconut fibers (DCF) as reinforcement in concrete the hardened properties of coir concrete of similar slump, with different fiber lengths and dosages are analysed in this paper, including compressive strength and stiffness, flexural response, and mainly the resistance to impact loading using two tests, that proposed by the ACI Committee 544 and a new method based on the application of Growing Impact Loads. It was found that DCF yields similar effects as synthetic microfibers in fresh and hardened properties of concrete but the incorporation of longer DCF shows improvement in terms of impact resistance.

Keywords: Bleeding; Coconut coir; Concrete pavements; Impact; Residual capacity; Strength.

1. INTRODUCTION

The construction industry is using natural fibers more due to increased environmental awareness. Such fibers used in civil engineering applications include coir, jute, and sisal; amongst them, coir from the coconut tree *(cocos nucifera)* is promising due to its extensive availability, higher toughness, and durability properties [1-3]. Coir fiber is used in tropical countries of Africa, Asia, and America, with the worldwide coconut coir market estimated to be worth roughly USD 304.8 million in 2020 [4].

Natural fibers, especially coir, are extensively explored for various applications in the construction industry, including roof tiles, corrugated slabs (asbestos), bricks, plywood, and hollow blocks. Coir fibers longer than 50 mm are preferred in common applications (such as mattresses, mats, ropes etc.), whereas shorter fibers are usually discarded [5] or incinerated. Many studies have been performed on incorporating such fibers as reinforcement for cement pastes or mortars. Some studies on coir concrete have highlighted drastic reduction of workability [6-10], mainly when high fiber volumes are incorporated. There are discrepancies among the studies where some reports showed enhancement in the mechanical parameters of mortars and concretes [3, 11-14], whereas others indicated lower performance due to fiber incorporation [7, 12-14]. However, most reports confirmed that coir fibers would not impair the hardened concrete properties when used in small dosages [3, 7, 11-16]. In addition, Hwang *et al.* [17] concluded that there is a reduction in plastic cracking and an improvement in flexural strength, toughness indices, and impact resistance of cementitious sheets due to coir fiber reinforcement.

Concrete pavements are especially susceptible to early-age cracking in hot weather conditions where high wind rates and low humidity are critical factors promoting plastic shrinkage cracks. Appropriate curing is the key in hot weather situations but may not always be practical in many cases due to logistics, non-availability of water, or human errors. The consequent surface cracks could promote further defects and it is crucial to avoid them at a minimum cost to ensure durable pavements. It has been shown that plastic shrinkage cracking can be mitigated by adding fibers, with polypropylene and other synthetic fibers being the most used in practice [18-22]. The main limitations of synthetic fibers are the high cost and embodied carbon emissions, which could be reduced by employing suitable natural fibers [23-24]. It has also been found that short coir fibers could eliminate plastic shrinkage cracks even if used in small proportions [21-22]. The effectiveness of using DCF in concrete has been demonstrated, and it has been stated that conventional methods can also be employed to mix DCF and achieve good fiber dispersion in the concrete [25]. In rural areas with low traffic volumes, the potential application of DCF proves advantageous due to the challenges of ensuring adequate curing and quality control measures. Replacing polypropylene microfibers with discarded coir can significantly reduce the embodied greenhouse gas emissions, which are estimated to be in the range of 2-3 kg CO_2-eq. (cradle-to-gate system) for the microfibers.

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This paper presents the results of the assessment of concrete mixes with the aim of analysing the effects of the incorporation of different dosages of coir fibers on the hardened properties of paving concrete. Special attention was paid to evaluating FRC impact behavior, where information is more limited. The study was performed in La Plata, Buenos Aires, Argentina, as part of the cooperation within an extensive research program ongoing at the Indian Institute of Technology Madras, Chennai.

2. MATERIALS AND CONCRETE MIXES

The coir fibers were the same used in a previous study [25]; they were extracted from tender coconuts discarded after removal of water from them. Two fiber lengths were used, 10 and 50 mm, and their water absorption was nearly 100 %.

The study used concrete mixes commonly used in pavement construction in Buenos Aires province, Argentina. Blended CP40 portland cement (350 kg/m^3), natural siliceous sand (700 kg/m^3), crushed sand (175 kg/m^3), and crushed granitic coarse aggregates of 20 mm maximum size (1000 kg/m^3) were used. The specific gravity and the coefficient of water absorption of the coarse aggregate, crushed and natural sand were 2.77, 2.75 and 2.63, and 0.5, 0.7 and 0.8 %, respectively. The water/cement ratio was kept constant at 0.50 in all the mixes. A constant dosage of water-reducing chemical admixture was used in all concrete mixes. In addition, an adequate dosage of naphthene-based superplasticiser was incorporated into each batch to obtain a slump of 140 ± 40 mm in all concrete mixes.

Six concrete mixes were studied, a plain concrete as control mix, four fiber reinforced concretes (FRCs) incorporating DCF at two dosages (1 and 4 kg/m^3, near 0.1 and 0.4 % in volume) of fiber lengths (10 and 50 mm), and a FRC incorporating polymer microfibers at a typical dosage of 0.6 kg/m^3.

DCF can be incorporated by mixing them with the aggregates before adding the water or by introducing them after preparing the fresh mixture; the latter procedure was used in this study. However, it must be noted that coir fibers had to be dispersed carefully to avoid balling, mainly in the case of fibers of 50 mm in length.

The slump test, the number of drops in the Powers Remoulding test, the unit weight, the air content (Washington apparatus), and the bleeding of concrete as per ASTM C 232 Standard [26] were determined in fresh concrete.

Cylinders of 100 × 200 mm, discs of 150 × 60 mm and prisms of 75 × 105 × 430 mm were cast; they were compacted using a vibration table, demoulded after 24 hours, and cured in a moist room for 28 days. Then, all specimens remained for 7 days in the laboratory environment to avoid variations in their moisture content during testing. Both static and impact tests were performed in the period between 35 to 42 days.

3. TESTING METHODS FOR HARDENED CONCRETE

Compression tests were carried out on 100 × 200 mm cylinders in accordance with ASTM C39 standard [27]. Bending tests were performed to evaluate the flexural strength, residual strength capacity and toughness as per the general guidelines of the EN14651 standard [28]. As usual the beams were rotated 90° for testing being the height 105 mm and the width 75 mm; a span of 350 mm and a sawn notch of 17 mm, located in the centre of the tensile face, were adopted to maintain the same height/span ratio and notch/height ratio used in EN14651 standard [29]; loads were applied in a closed loop system using a clip gage as a control signal.

Two test procedures were implemented for the evaluation of the impact behavior, the method proposed by ACI Committee 544 [30] and a new method based on the application of Growing Impact Loads (GIL) [31]. In the ACI-544 impact test (see Figure 1), weight drops through a Proctor compaction hammer (4.54 kg mass and 457 mm height of fall are applied on a steel sphere (63.5 mm in diameter) placed on the moulding face of a cylinder of 150 mm (diameter) by 63 mm (height) centred on a stiff steel plate with four lugs. The test consists of applying successive impacts, lifting and dropping the hammer freely on the sphere. Once the first crack appears, the number of impacts applied is recorded (N_1). Then, additional impacts are applied until the specimen touches three of the four lugs of the base. The number of impacts at this stage is also recorded (N_2). The energy absorbed by the specimen can be estimated from N_1 and N_2.

Figure 2 shows the machine used for the GIL test. The device has two main parts: the projectile displacement system, which consists of two rails that guide the vertical movement and allow the height of fall to vary; and support system with one fixed and another mobile support, which makes it possible to place the specimens simply supported. A 5 kg projectile impacts the

Figure 1: View of the used equipment for the ACI-544 impact test [30]

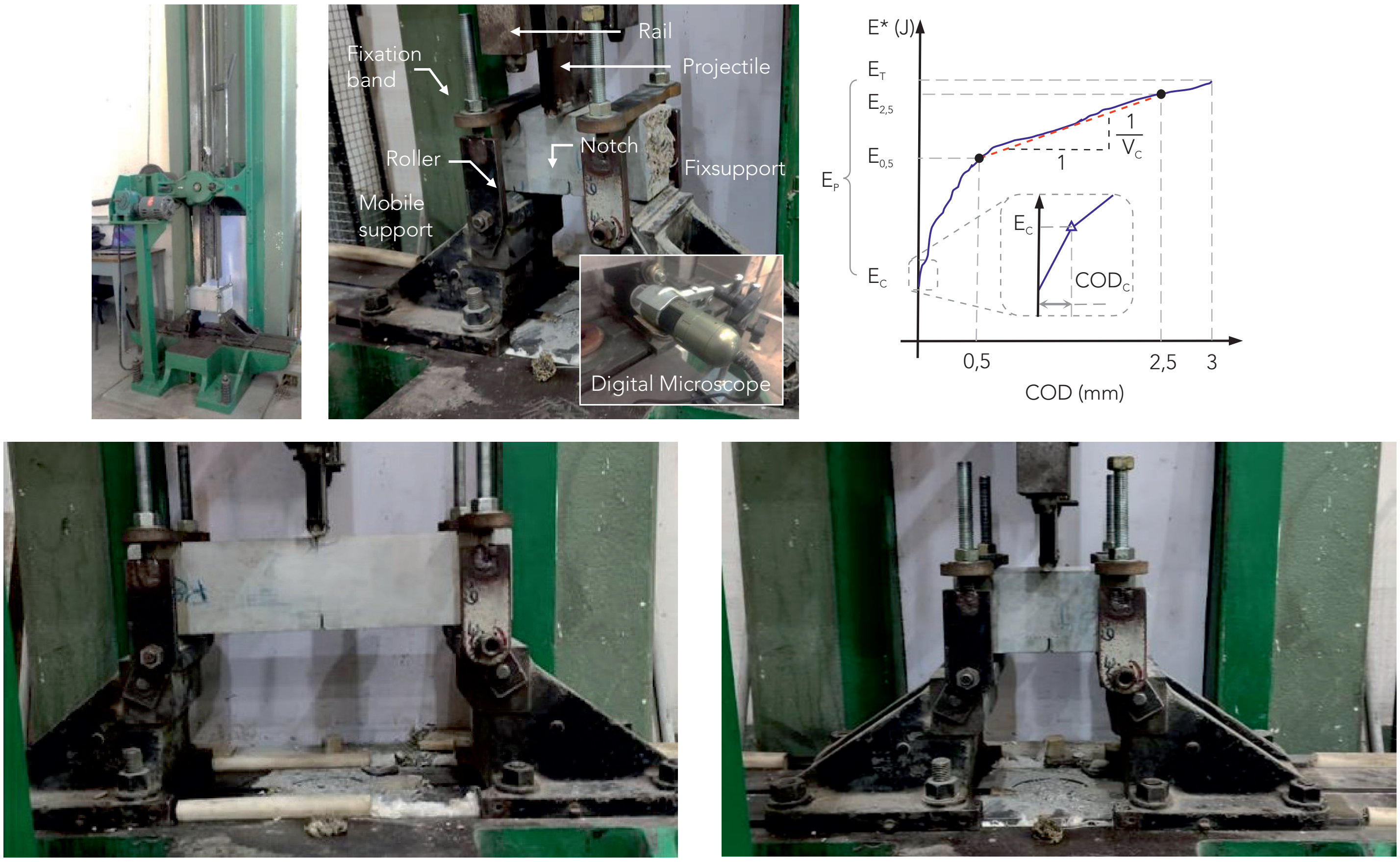

Figure 2: Machine and devices used for the GIL test and evolution of cumulated energy with COD.
Bottom: setup for GIL with span length to (left) 350 mm and (right) 160 mm

specimen uniformly over its width. Prisms with dimensions of 75 mm width and 105 mm height were used, the same used for static bending tests. As the size of the specimens was smaller than those used in previous studies [31-33], the impact pattern was modified to achieve a sensitivity capable of detecting differences in the performance of the different concrete mixes. Tests were performed using two span lengths: 350 and 160 mm, with a sawn notch located in the centre of the tensile face (depth of 17 mm). The first emulated the supporting conditions of the static test, and the second adopted a slenderness ratio as in the original test proposal [31]. In the GIL test, impacts are applied in two phases. In Phase 1, the initial height of the fall (h_0) is 25 mm, and the subsequent impacts are applied by increasing the height (Dh) of 25 mm after each time; Phase 1 ends when the specimen cracks. Then Phase 2 starts, in which three impacts are applied at each height level, unlike the previous one. In Phase 2, h_0 is again equal to 25 mm, and the increment between successive height levels (Dh) is 25 mm. Phase 2 ends when the crack opening displacement (COD) measured as explained below, is greater than 3 mm. All heights of fall are measured with respect to the upper specimen face. After each impact, the COD is measured at 80 mm below upper face of the specimen. A digital microscope (Dino-lite Premier AM4113T) was used in this study, placed on a magnetic base with a separation of 80 mm from the front face of the prism (inset Figure 2). With this setup and an image increment between 10X and 20X, it was possible to measure the COD with a precision of 0.0001 mm.

From the measurements during the GIL test, an Impact Curve was obtained by plotting the accumulated energy (E*) (vertical axis) versus the COD values (horizontal axis). The energy (E) of each impact is calculated as m $\times \cdot g \times$ h, where g is the acceleration of gravity, and E* is defined as the sum of E values from the impacts provided until a specific test moment. The resulting parameters from Phase 1 are the Cracking Energy (E_c), which means the cumulative energy until the appearance of the first crack, and the width of the initial crack denoted as COD_C. From Phase 2 arises E_P, which is the cumulative energy after cracking and until the end of the test, and V_C or the crack growth rate, is calculated as shown in Equation 1, where $E_{0.5}$ and $E_{2.5}$ are, respectively, the cumulative energy at COD of 0.5 and 2.5 mm.

$$V_C = \frac{2000}{(E_{0.5} - E_{2.5})}\ (\mu m/J) \qquad (1)$$

The global parameter of the test is the total energy (E_T), which is obtained by summing E_c and E_p E_P. More details about the machine, devices employed, and test procedure can be found in previous papers [31-33].

4. ANALYSIS OF RESULTS

Table 1 shows the mixture identification, the fiber content, and the properties of fresh concrete mixes. For a similar slump, there was a slight reduction in the remoulding energy (number of drops in the Powers test) for lower fiber content (0.1 % in volume). The remoulding energy increases slightly as the coir fiber content increases without affecting the compaction processes. No significant influence was found in the air content but there was a slight reduction in the unit weight in the case of micro synthetic and coconut fiber concretes, as expected. More importantly, coir and polymer microfibers lead to a clear reduction in the bleeding capacity and, in most cases, the rate and duration of bleeding, which could be an advantage in the case of pavement concrete slabs. Bleeding could be critical in pavements and slabs, where high bleeding could reduce the abrasion resistance due to the weaker top surface [34-35]. Nevertheless, some bleeding can reduce plastic shrinkage cracking of the pavement [36]. Figure 3 shows the evolution of the cumulative volume of water during the bleeding tests, and the calculated bleeding parameters are included in Table 1; similar results have been observed in a previous study at IIT Madras [25] that showed an inverse relationship between the coir dosage, and the bleed capacity and rate of bleeding. The bleeding duration was also reduced, which could be attributed to the water retention capacity of the coir fibers, leading to higher stability and consequently lower plastic settlement in pavement slabs. In the previous study, no plastic shrinkage cracks were seen for 0.4 %, both with 10 and 50 mm DCF [25].

The obtained results indicate that the use of DCF enhances the cohesiveness of fresh concrete, similar to synthetic microfibers. Both types of fibers reduce the risk of plastic shrinkage cracking and segregation, and at the same time, prevent excessive bleeding and improve the surface quality of the pavement. The water retention capacity of the coir fibers can also contribute to enhancing the homogenous distribution of moisture along the height of the slabs reducing curling.

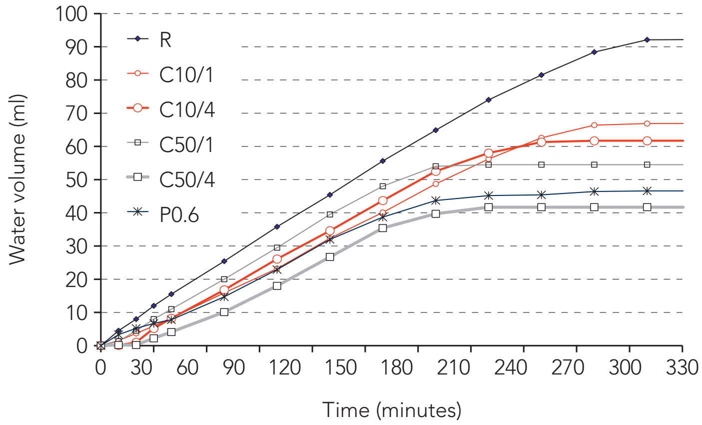

Figure 3: Evolution of cumulative volume of water during bleeding tests

The compressive and bending test results are summarised in Table 2, where f'_c is the compressive strength, E is the modulus of elasticity, f_L is the first crack stress, and f_{R1} and f_{R3} are the residual stresses at crack mouth opening displacements (CMOD) of 500 and 2500 microns, respectively. The coefficients of variation (COV) are also written within brackets.

Comparing the results obtained in all concrete mixes, no significant adverse effects were found in compressive behavior. However, some reduction in compressive strength and elastic modulus was observed in C50/4 concrete, which had the highest

Table 2: Mean values of compressive and bending test results *

MIX	f'_c (MPa)	E (GPa)	f_L (MPa)	f_{R1} (MPa)	f_{R3} (MPa)
R	38.4 (5)	38.0 (4)	5.13 (7)	-	-
C10/1	39.6 (2)	36.2 (5)	5.20 (9)	1.03 (17)	0.08 (42)
C10/4	41.2 (3)	37.3 (3)	5.31 (9)	1.26 (18)	0.29 (25)
C50/1	38.4 (4)	38.0 (4)	5.31 (8)	1.18 (44)	0.06 (25)
C50/4	36.8 (7)	37.5 (8)	5.36 (8)	1.44 (16)	0.42 (25)
P/0.6	40.1 (2)	38.4 (2)	5.31 (5)	1.57 (20)	0.18 (16)

*COV mentioned within brackets

Table 1: Fibers mixture proportions and the properties of fresh concrete

MIX	FIBER		SLUMP	POWERS TEST	UNIT WEIGHT	AIR CONTENT CAPACITY	BLEEDING PARAMETERS		
							RATE	DURATION	
	TYPE	(kg/m³)	(mm)	(DROPS)	(kg/m³)	(%)	(%)	(m/s 10⁻⁸)	(min)
R	None	-	160	16	2390	2.1	4.8	11	310
C10/1	Coir, 10 mm	1	170	10	2380	1.9	3.5	9	310
C10/4	Coir, 10 mm	4	145	19	2370	1.9	3.2	10	280
C50/1	Coir, 50 mm	1	155	12	2370	2.1	2.9	12	190
C50/4	Coir, 50 mm	4	135	19	2380	1.9	2.2	9	220
P/0.6	Polymer	0.6	150	13	2380	2.3	2.4	9	280

dosage of the longest coir fibers, mainly due to the lower ease of compaction.

In the case of the bending tests performed on notched prisms, no significant differences were found in the stress-CMOD curves; only a marginal contribution of DCF on flexural strength was observed and the same in the case of synthetic microfibers. This was expected, as it is known that the synthetic microfibers do not contribute to the residual capacity of FRC. However, Table 2 shows slight increase in residual stresses at the greatest CMOD with the DCF; for 4 kg/m^3 of coir fibers (C10/4, C50/4), the f_{R3} were higher than those observed in the FRC incorporating polymer microfibers.

Regarding impact behavior, the results obtained with the ACI 544 Committee method are given in Table 3, while Figure 4 shows some images of specimens of different concrete mixes after testing. These results indicate that all concrete containing fiber mixes yielded better performance when compared to plain concrete, even in the case of concretes incorporating 10 mm length fibers. Although the COV is high, as is usual in ACI 544 test, the general trend is clear. It is found that higher dosages of DCF can also improve the impact response, which was mainly observed when 50 mm fibers (concrete C50/4) were used, with the increase in total energy being more than 300 %. Comparing pre-cracking and post-cracking energies (E_1, E_2), contrary to that observed with polymer microfibers, coconut fibers improve impact response in the cracked state, with $E_2 > E_1$ always. This can be justified by considering that, after matrix cracking, coconut fibers do not break or pull out as quickly, as observed in the case of concrete containing synthetic microfibers.

Better insight on the impact response can be found in the GIL tests. Figure 5 shows the mean cumulative energy-COD curves

Table 3: Mean values of ACI-544 committee impact tests*

MIX	N_1	E_1 (J)	N_2	E_2 (J)	N_{1+2}	E_{1+2} (J)
R	9 (65)	190 (65)	6 (58)	112 (58)	15 (51)	302 (51)
C10/1	10 (64)	200 (64)	10 (38)	193 (38)	19 (25)	394 (25)
C10/4	7 (43)	136 (43)	16 (34)	326 (34)	23 (31)	461 (31)
C50/1	11 (51)	220 (51)	14 (34)	288 (34)	25 (27)	509 (27)
C50/4	18 (82)	356 (82)	32 (27)	655 (27)	50 (36)	1011 (36)
P/0.6	14 (73)	285 (73)	7 (53)	142 (53)	21 (55)	427 (55)

* COV mentioned within brackets

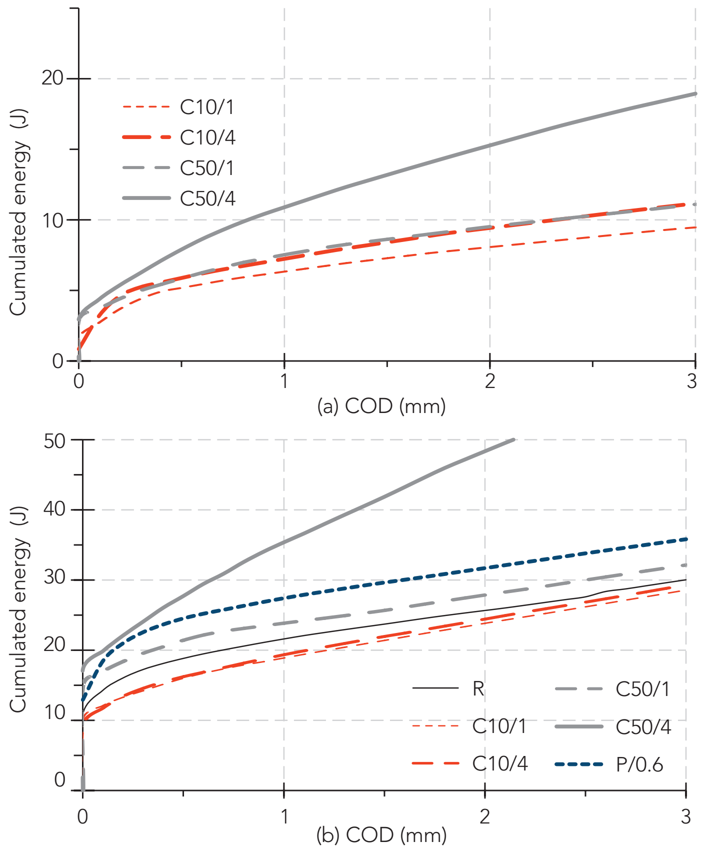

Figure 5: Mean impact cumulated energy-COD curves from GIL tests, performed with span length of 350 mm (a) and 160 mm (b)

R P/0.6 C10/4 C50/4

Figure 4: Images of some specimens after ACI 544 impact test

from the impact test curves. It can be seen that there are no significant differences in the impact responses between plain concrete and most concretes incorporating fibers, except for concrete C50/4 prepared with 4 kg/m^3 of 50 mm long DCF. Note that a higher slope in the curves implies a lower crack growth rate during testing. Tables 4 and 5 summarise the mean values of the cracking (E_C), post-cracking (E_P), total (E_T) energies, crack opening after the first crack (COD_C), and the crack opening rate (V_C) corresponding to GIL tests using span lengths of 350 mm and 160 mm.

The results obtained using different spans between supports were consistent, considering that a span reduction from 350 to 160 mm increases total energy but with a higher variability (Tables 4 and 5). Lower variations were observed when the span between the supports was increased as found in a previous study on concretes reinforced with steel fibers [37]. Regarding the first crack (Phase 1), contrary to polymer microfibers, coconut fibers did not lead to a reduction in the initial crack width. Nevertheless, when considering the cracking rate (V_C) in the cracked state, no differences were observed for dosages of 1 kg/m^3 of fibers compared to the plain concrete. On the contrary, incorporating 4 kg/m^3 of coir fibers led to a significant reduction in V_C, indicating that for these dosages, the fibers governed the crack growth. Finally, comparing both impact procedures, it appears that the estimated energy values from the ACI 544 method were lower than those from the GIL test; this was expected since the ACI 544 test leads to higher energy losses [33].

Table 4: Mean values of GIL test results* (span length L=350 mm)

MIX	E_C (J)	COD_C (mm)	V_C (mm/J)	E_P (J)	E_T (J)
C10/1	6 (35)	753 (11)	568 (20)	5 (35)	11 (13)
C10/4	4 (17)	133 (67)	467 (23)	10 (8)	14 (11)
C50/1	6 (35)	738 (73)	463 (23)	6 (27)	12 (16)
C50/4	6 (35)	356 (68)	224 (28)	15 (27)	21 (18)

* COV mentioned within brackets

Table 5: Mean values of GIL test results * (span length L=160 mm)

Mix	E_C (J)	COD_C (mm)	V_C (mm/J)	E_P (J)	E_T (J)
R	17 (19)	342 (93)	238 (21)	15 (24)	32 (14)
C10/1	16 (22)	563 (55)	214 (36)	14 (30)	30 (18)
C10/4	15 (22)	434 (92)	203 (32)	16 (35)	31 (20)
C50/1	19 (0)	469 (53)	306 (58)	11 (20)	30 (11)
C50/4	24 (27)	325 (49)	79 (25)	39 (20)	63 (14)
P/0.6	19 (23)	140 (78)	221 (17)	18 (20)	37 (21)

* COV mentioned within brackets

In summary, the hardened concrete evaluation showed that incorporating an adequate dosage of coir fibers could benefit fresh concrete response and also contribute positively to mechanical behavior. No decrease in compressive strength was observed, as expected, with no increase in flexural strength. The most interesting fact is that with 50 mm length coir fibers, some contribution to crack growth control is observed, which can justify the improvement in the response under impact loading.

The results presented in this study were obtained a few weeks after 28 days of moist curing. However, it is expected that coir fibers will remain stable over time when incorporated into Portland cement concrete [38].

5. CONCLUSIONS

The effects of the incorporation of discarded coir fibers (DCF) on the hardened properties of paving concrete with similar slumps have been analysed and compared with those observed when polymer microfibers are added. From this study, the following conclusions can be drawn:

1. It is possible to design paving concretes incorporating DCF of similar slumps and strengths than plain concrete or concrete reinforced with polymer microfibers.
2. DCF enhance the cohesiveness of fresh concrete and prevent excessive bleeding, as similar to polymer microfibers. Both types of fibers can improve the surface quality of pavement slabs in terms of abrasion resistance among other benefits.
3. Although coir fibers, as polymeric microfibers, do not affect compressive or flexural strength in a significant way, some increase in residual bending capacity was observed with moderate contents (4 kg/m^3) of the 50 mm long coir fibers, which was higher (130 % for f_{R3}) than that observed with synthetic microfibers. This suggests a positive effect of the DCF on the control of crack growth, which is reflected in the improved response under impact loadings.
4. Both types of impact tests confirmed a positive effect on repeated impact loading response with the incorporation of a moderate content (4 kg/m^3) of 50 mm long coir fibers. As example, in this study the impact resistance of this concrete mix increases 137 % and 170 % in the ACI Committee 544 test and the Growing Impact Loads test respectively when compared with the same concrete mix incorporating polymer microfibers.

The studies performed on the fresh and hardened properties of paving concretes show that discarded coconut fibers could be a sustainable alternative to synthetic microfibers in terms of cost, technological and environmental points of view in India and other tropical countries around the world where the coconut coir is abundant.

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STATEMENTS AND DECLARATION

The authors declare that there is no conflict of interest.

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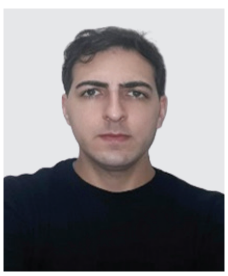

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