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Mechanical properties and sustainability aspects of coconut fiber modified concrete

Propiedades mecánicas y aspectos de sostenibilidad de concreto modificado con fibras de coco

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Artículo de investigación científica y tecnológica

***Abstract*— Coir fiber has been examined for their suitability as reinforcement of concrete. Mechanical properties and sustainability aspects of concrete composites were estimated after 7. 14, and 28 days of curing. Natural reinforcement of 0.46 and 0.62% by weight of coir fiber was added. Fibers were analyzed by means of scanning electron microscope (SEM). Besides, an Eco-audit tool has been used to estimate energy and carbon emission of material, manufacturing, transportation, and disposal phases. It was found that fibers additions lowered the compressive strength compared to plain concrete. However, failures of the composites exhibited good post-cracking behavior. The use of vegetable fibers affects positively the life cycle of the material. Eco-audit results indicate that there is a potential to reduce between 9.15% and 13.35% of embodied energy and between 9.61% and 13.94% of CO_2 during the material production phase. These suggest that coir fibers could be useful from the environmental view, although more studies regarding their durability are needed.**

***Index Terms*— coir fiber, concrete, compressive strength, Eco-audit.**

***Resumen*—Fibras de coco han sido examinadas por su sostenibilidad como refuerzo de concreto. Propiedades mecánicas y aspectos sostenibles de compuestos de concreto fueron estimadas luego de 7. 14, y 28 días de curado. Se adicionaron refuerzos naturales de 0.46 y 0.62% en peso de fibra de coco. Las fibras fueron analizadas mediante microscopía electrónica de barrido (SEM). Además, una herramienta de Eco-Auditoría se utilizó para estimar la energía y emisiones de carbono en las fases de material, manufactura, transporte y disposición. Se encontró que las adiciones de fibra disminuía la resistencia a la compresión comparado con el concreto normal. Sin embargo, las fallas de los compuestos exhibieron un buen comportamiento post-agrietamiento. El uso de fibras vegetales afecta positivamente el ciclo de vida del material. Los resultados de la Eco-auditoría indican que hay un potencial para reducir la energía incorporada entre 9.15% y 13.35% y el CO_2 entre 9.61% y 13.94% durante la fase de producción del material. Esto sugiere que las fibras de coco pueden ser útiles desde el punto de vista ambiental aunque son necesarios más estudios con relación a su durabilidad.**

***Palabras claves*— fibra de coco, concreto, resistencia a la compresión, Eco-audit.**

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I. INTRODUCTION

NATURAL fibers have been used in a different type of fields, especially in tropical countries where has been grown an interest in the research of their influence as reinforcing materials. The reason is that to its sustainable availability, low cost, low density, and low abrasive wear of processing machinery [1, 2]. One of such fields is the building industry which needs of renewable sources that allow reducing environmental impacts and increasing sustainable construction.

Concrete is a material which is usually reinforced with steel bars to overcome its lack of tensile strength. However, due to the permeable behavior of concrete, the material suffers concerning carbonation and chloride ion attack resulting in corrosion problems [3, 4]. Use of natural fiber-reinforced concrete may solve the corrosion problem and also may contribute to the elaboration of low-cost composites with a low thermoacoustic transfer, low specific weight [5], improve toughness and lightweight structures [6–9]. However, one of the disadvantages of using natural fibers is their variation on mechanical properties, which could lead to unpredictable concrete features [4, 10, 11]. Different fibers have different compositions, so the behavior inside a cement matrix could differ between them [1, 2].

Natural fibers are mainly composed of cellulose, hemicellulose, lignin, and pectin, with small amounts of extracts [12]. Coir fibers are generally brown and are extracted from the fibrous outer shell of a coconut. The individual fiber cells are narrow and hollow, with thick walls made of cellulose [13]. Table I shows typical properties of coir fibers according to literature.

Ramaswamy et al. [18] found that vegetable fibers such as jute, coir, and bamboo can be used with advantage in concrete similar to other types of fibers. They also found an improvement of the impact strength and increased ductility under static loading conditions. Yan and Chouw [19] studied the effect of coir fiber inclusion and flax fiber reinforced polymer thickness on the dynamic and static properties of polymer tube confined coir fiber reinforced concrete. They found that flax fiber significantly increases axial compressive strength and ductility of the confined concrete composite.

Lecompte et al. [20] studied the use of coir fibers as reinforcement in cementitious materials, which shows that such additions modify the mechanical properties of the composite in the hardened state. The enhancement was related to both physical and chemical properties of fibers. Islam et al. [21] study fiber-reinforced concrete mechanical properties using locally available natural fibers. They found that 0.5% and 1.0% coir fibers gives improved performance in flexural strength of the concrete also increase the ductility and toughness of concrete. Li et al. [22] also found that coir fiber reinforced cementitious composites exhibited higher energy absorbing ability and ductility than conventional cementitious materials.

TABLE I
PROPERTIES OF COIR FIBERS

Density, ρ (kg/m^3)	Modulus, E (GPa)	Tensile Strength (MPa)	Max. Deformation, ε (%)	Moisture Content at 20ºC (%)	Diameter (μm)
1177[a]	4-6[a]	182[a]	15-25[c]	10[e]	300[a]
1250[c]	2.8[b]	175[d]	25[f]	13.5[f]	270[e]
800[f]	6[c]	142[e]			250[f]
	2[e]	174[f]			

Note: [a]Arsene et al., 2007 [14]; [b]Guimaraes, 1984 [15]; [c]Buitrago et al., 2015 [12]; [d]Bisanda and Ansell, 1992 [16]; [e]Li et al., 2006 [10]; [f]Toledo Filho et al., 2003 [17].

Wang and Chouw [23] in a research about the behaviour of coir fiber reinforced concrete under impact loading found that the coir fiber length had an influence on the behavior of the composite specimens under repeated impact concluding that fibers with a length of 25 cm and 50 mm had better impact resistance compared with that of 75 mm.

On the other hand, life cycle assessment (LCA) is a useful tool to be aware of the environmental burden in the entire life of the materials, through the manufacture of the product, its use, and its subsequent disposal [13]. Another approach is to limit the impact categories to energy and CO_2 emission for auditing products [13]. An Eco-Audit is an initial assessment of the energy demands and carbon emissions of the life of a product [13, 24]. The assessment is a tool to identify which phase of life has the highest environmental impact regarding energy or CO_2 burden.

Sengupta et al. [25] assessed embodied greenhouse gas (GHG) emission for construction of residential buildings in India, and they found that there is ample scope of adoption of eco-friendly construction technologies for the reduction of GHG without any increase in the cost of construction. Alves et al. [1] demonstrate that natural fiber could be used as a replacement of fiberglass on automotive components after the environmental improvements estimated using LCA. It is essential to mention here that there is limited information in the literature regarding LCA studies for coir fiber reinforced concrete.

This work aims to estimate an Eco-Audit of concrete modified with coir fibers compare to plain concrete used as a reference and to contribute to the understanding of the environmental improvements regarding the use of this type of natural material. Also, laboratory experiments focusing on compressive strength were performed to obtain quantitative results to support the use of these compounds.

II. MATERIALS AND METHODS

Commercial Colombian coir fibers were trimmed to a maximum length of 50 mm. Moisture content was estimated by weighing approximately 0.25 g of coir fiber in a RADWANG PMR 210 WH moisture analyzer balance with an uncertainty of 1 mg. The fibers were subsequently, dried out in the balance from room temperature until 105ºC, and then it was maintained until the stabilization of weight was reached. A total of four independent moisture estimations were carried out. A scanning electron microscope (SEM) with JEOL JSM2490 CV device equipped with energy dispersive X-ray (EDX) spectroscopy (OXFORD INCAPentaFET-x3) was used to perform morphological observations on untreated coir fiber.

The specimens were made with 0.46 and 0.62% (w/w of cement) of coir fibers. The composite mix was designed using plain concrete with a ratio of cement, sand, and aggregates of 1:2:4 by weight, respectively. The water-cement ratio (w/c) used was of 0.6. After mixing ceramic components for 10 minutes, coir fibers were slowly dosed to guarantee the right mixing conditions avoiding fiber agglomeration. A SIKAPlast 5000 superplasticizer was used to improve the rheological properties of the concrete, increasing the workability of the mix. A ratio of superplasticizer/cement of 0.015 was used. Then, the composites were poured into cylindrical steel molds of 15 mm of diameter and 30 mm height. For each layer of composite, it was used 25 strikes following the procedure described in ASTM standard C39. After that, the composited were allowed to settle for three days at 25 ºC. Then, the samples were removed from the molds and located inside a curing water tank. For each composite sample, it was performed a density measure and a compressive test.

All cylinders were tested in an ADR 1000 compression testing machine at 25 ± 0.05 MPa/s to determine compressive strength (σ) after 7. 14, and 28 days of curing. Triplicate samples were used for each composite. Three additional samples without any natural fiber were tested after 28 days of curing for comparison purposes.

Assess of energy (MJ) and CO2 (kg) emission of material, manufacturing, transportation, and disposal phases (Eco-audit) was performed. The use phase was not taking into account because a study of the durability of coir fiber inside a concrete environment is needed. Studies are currently on-going in the author’s laboratory to estimate coir fiber degradation in alkaline environments.

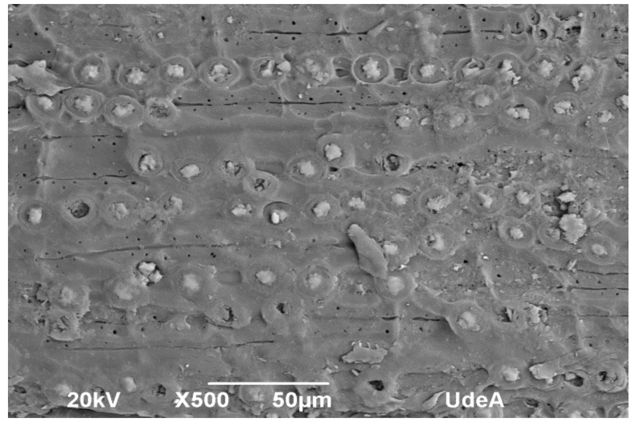

Fig. 1. SEM micrograph of the surface morphology of coconut fiber.

III. RESULTS AND DISCUSSION

A. Moisture content

An average of 13.82 % ± 0.159 of moisture content was found on the fibers. The reported value is entirely closed to the reported by Toledo Filho et al. [17] (See Table 1). According to the literature [26, 27], coir fibers have a low affinity with water due to a high quantity of lignin. In this study, the coir fibers were pre-soaked in water before mixing to avoid workability problems.

B. Morphological observations

An average of 13.82 % ± 0.159 of moisture content was found on the fibers. The reported value is entirely closed to the reported by Toledo Filho et al. [17] (See Table I). According to the literature [26, 27], coir fibers have a low affinity with water due to a high quantity of lignin. In this study, the coir fibers were pre-soaked in water before mixing to avoid workability problems.

Fig. 1. The image exhibits a surface with a slightly rough exterior, which suggests that coir could have excellent adhesion with the concrete. The protrusions on the fibers can also offer extra anchoring points such that the fiber can withstand stresses from the matrix (Li et al., 2006) and even higher contact area. Fibers have an average diameter of 391 µm, which is similar to the one reported in the literature (see Table I. Surface pits can also be seen in Figure 1. Same morphology results have been published before by Rout et al. [28] and John et al. [9].

According to the EDX analysis, carbon and oxygen are detected on the fibers. Most of the pits seen on the fibers exhibit silicon occlusions (white dots in Figure 1) in agreement with the results of John et al. [9] and Anggraini et al. [29]. The authors suggest that pits are filled with fatty substances that hold the unit cells in the fiber. According to Calado et al. [30] when the outer layer of the fiber is removed, a rougher, and more ordered structure is revealed with white dots on the surface as it is seen in this investigation. The silica-rich material has been identified as tyloses, and it is evidence that the fibers were not over treated [31]. In this work, the presence of silicon was confirmed employing EDX, as can be seen in Fig. 2. The local spectrums were taken in two different points on the surface: inside the white dot (Spectrum 1 in Fig. 2b) and outside the pits (Spectrum 2 in Fig. 2c). Fr a) the SEM micrographs could be expected that composites have good mechanical behavior between the fiber and the cement matrix.

C. Visual appearance

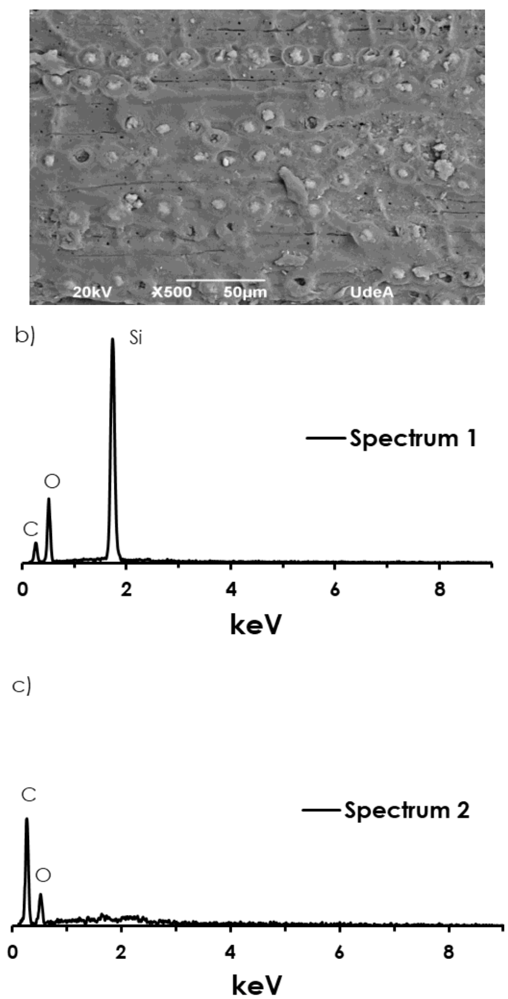

Fig. 2. SEM micrograph of coconut fiber from (a) external wall and EDX results for two different local spectrums from (b) inside the white dot and (c) outside the pits.

Fig. 3a-b shows the visual appearance of tested composites after 28 days of curing for 1 and 3% of coir fiber, respectively.

As can be seen, the structure is held by the coir fibers avoiding total failure of the cylinders. The fiber reinforced concrete remained in one piece retaining their shape and continuity. As increase the fiber content, the cracks due to the compressive test diminish.

D. Compressive test and density

Fig. 4 shows the behavior of composites with and without coir fiber against curing time. The results are the average values obtained after each sample fails by compression. There is no statistical difference for early curing time as can be seen from the error bars. Standard deviation is lower for little fiber content, but when it is increased, the variation is more significant which could be associated with some agglomeration of the fiber during the preparation of the samples, and it was more pronounced for 0.62% of coir fiber. However, plain concrete evidence even larger error bars which could be associated to be within the equipment error.

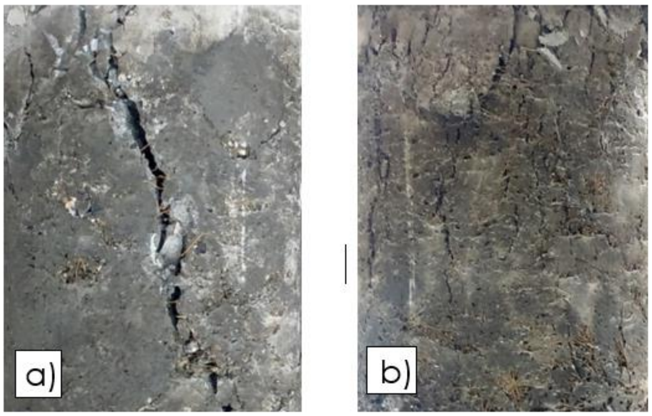

Fig. 3. Visual appearance of concrete samples after failure for a) 0.46% and b) 0.62% or coconut fiber content.

After 28 days of curing time, samples with fiber contents exhibit lower compressive strength than the blank sample. Also, more considerable resistance was observed for 0.62% fiber reinforced concrete compared to 0.46% of fiber content. Nevertheless, in both cases, continuous growth in strength is found. These could be interpreted due to the water which had been absorbed by the fibers is available for further hydration of cement after 28 days of curing [18]. Another possibility is that incorporation of fibers reduces shrinkage and as a consequence inhibits some micro-craking formation. The maximum strength of composites is reached for 0.62% coir fiber with approximately 11.84 MPa after 28 days of curing. However, in any case, it is lower than un-reinforced concrete.

Experimental compressive strength was compared to theoretical values estimated using (1) [32, 33]:

$$E_{cf} = 3830\sqrt{f_{cf}} + 10^5 V_f \qquad (1)$$

Where Ecf is Young's modulus, fcf is the uniaxial compressive strength of concrete and Vf is the volume fraction of the fiber. Young's modulus was obtained by using a synthesizer tool of CES EduPack 2016. An error percentage for the average compressive strength of 7.53, 21.81, and 14.80% was found for concrete with 0, 0.46 and 0.62% (wt.) of coir fiber, respectively.

Regarding the degradation of natural fibers immersed in Portland cement, it is known that the high alkaline environment dissolves the lignin and hemicellulose phases [4]. The dissolution can cause the weakening the fiber structure [34]. These could explain that the ultimate strength reached by the composites is lower than expected. Although in this study coir fibers evidence some stability after 28 days of curing, it is necessary to perform a surface treatment on the fibers to improve their strength and durability.

Figure 5 shows density variation against curing time for all samples. Coir fiber concretes exhibited lower densities compared to plain concrete specimens. However, according to the scattering data, there is no statistical difference between vegetable fiber concretes with 0.46% and 0.62% of coir fiber. Density reductions of 9.56% and 13.87% were reached compared to the plain concrete after 28 of curing for 0.46 and 0.62% of coir fiber respectively. These could be an advantage from the sustainability point of view regarding diminishing of energy and carbon footprint (see eco-audit results below).

The increase in the volume of the composites is related to the rise of natural fiber [35] and the results exhibited in Fig 5

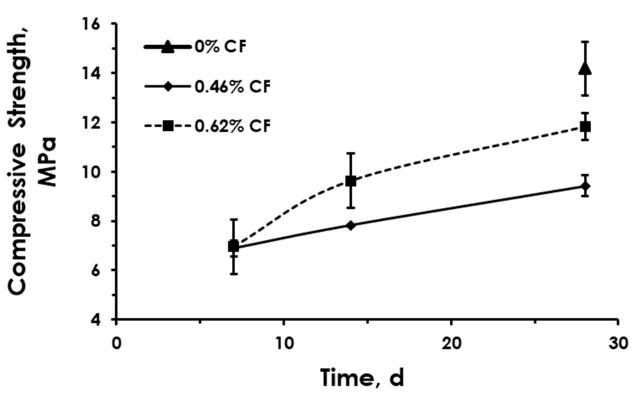

Fig. 4. Composites compressive strength after 7, 14, and 28 days of water curing with different coconut fiber content.

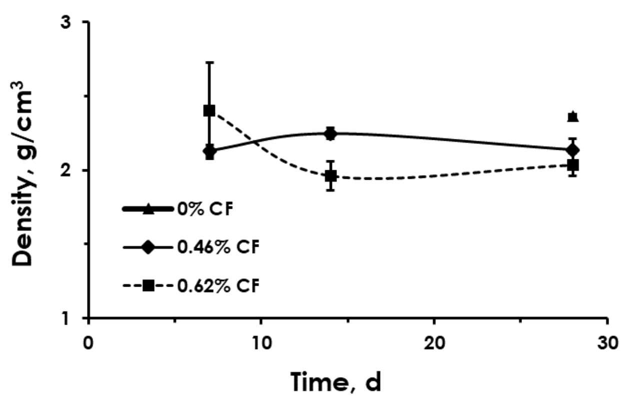

Fig. 5. Density for different coconut fiber content after 7, 14, and 28 days of water curing.

are in agreement with that statement and previously reported density values of cement composites which decreases with the increasing content of natural fiber [36].

E. Eco-audit

Microsoft Excel software was used to estimate the Eco-Audit of the composites, and the following conditions were used. A volume of 1 m3 was considered for each composite, and the density values after 28 days of curing were of 2364 kg/m3, 2138 kg/m3 and 2036 kg/m3 for plain, 0.46% CF and 0.62% CF, respectively. For material phase, it was used an embodied energy and carbon footprint for primary production of each component of the composites from Table II The manufacture of Portland cement is usually made by two different methods, wet and dry processes with different embodied energy associated [37]. In this case, an average of 6.15 MJ/kg has been used. Embodied energy for crushed stone and sand were chosen to be 0.137 and 0.064 MJ/kg, respectively. The origin of the raw material was the same place as the construction site. A value of 7.58 MJ/kg of embodied energy for primary production of coir fiber was used [13]. CO_2 footprint for each material was calculated according to average values in Table II.

For manufacturing phase, the estimation was focused on primary production with embodied energy values of 0.02 MJ/kg and 2.605 MJ/kg and carbon footprint of 0.002 kg/kg and 0.208 kg/kg for concrete and coir fiber respectively [13]. For all systems, it was assumed that the construction energy of concrete would be the same. Transportation phase was assessed by considering a 100 km distant following the methodology of an environmental product declaration [43]. A 14-metric ton truck was used for all assessment with an embodied energy of 0.85 MJ/kg and carbon footprint of 0.11 $kgCO_2$/metric ton.km [13]. Disposal phase was considered to be landfill in all cases, as is more usual in the region of study (Colombia) with recollection energy of 0.2 MJ/kg and carbon footprint of 0.07 kg/kg [13].

Figure 6 shows the energy results for the composites. The more significant contribution of energy is related to the production of the material that is used to make the composites, following by disposal, transport, and manufacturing phase. Energy demand for material phase is nearly 49, 45, or 44 times more than for the manufacturing phase for 0, 0.46 and 0.62% of CF respectively. This result is the most extreme regarding the comparison with any other stages, which means that the Eco-Aware design regarding materials choice should be prioritized with the replacement of cement or aggregates with low-energy materials, such as natural fibers. The energy of the material phase was found to represent around 76% of the total energy for all composites.

TABLE II
EMBODIED ENERGY AND CO_2 FOOTPRINTS OF THE MATERIALS

Material	Embodied energy (MJ/kg)	CO_2 footprint (kg/kg)
Cement	4.6-7.7[a-f]	0.83[e]-1.05[a]
Aggregate	0.124-0.15[c,f]	0.005[g]
Sand	0.0285-0.1[d,f-g]	0.005[g]
Coir fiber	7.58[h]	0.45[h]

Note: [a]Yu et al., 2011 [24]; [b]Reddy et al., 2003 [37]; [c]Goggins et al., 2010 [38]; [d]Kofoworola et al., 2009 [39]; [e]Hammond and Jones, 2008 [40]; [f]Gonzalez et al., 2009 [41];[g]Baird and Alcorn, 1997 [42]; Ashby, 2012 [13].

The use of coir fiber as a replacement for cement produces a decrease of 191 MJ and 278 MJ in material energy for 0.46% and 0.62% coir fiber respectively. On the other hand, transportation and disposal phases are also linked to the choice of the material which means that there is a potential to reduce energy and carbon emissions with lightweight concrete and recycling to recover energy at the end of the life. Disposal type selection also plays an essential role in energy and carbon emissions, especially for concrete, which could be recycled as aggregate in other types of composites.

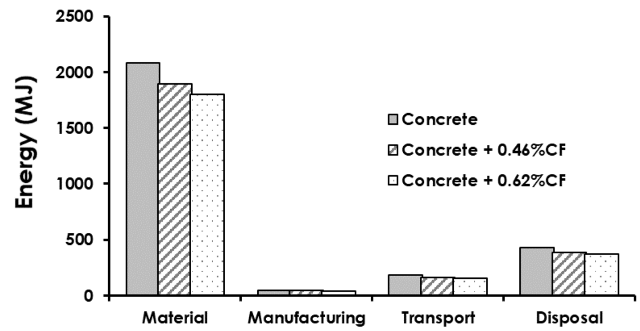

Fig. 6. Embodied energy of the different fiber content composites.

CO_2 footprint follows the same trend as energy as can be seen in Fig. 7. Savings of carbon emission during the material phase are close to 28 and 40 kg for 0.46% and 0.62% of coir fiber respectively. The carbon footprint of the material phase was found to represent around 83% of the total CO2 emitted for all composites. In general, the embodied energy or CO_2 footprint on a volumetric basis increases with the increasing density.

The outcome of the global Eco-audit indicates that there is a potential to reduce between 9.15% and 13.35% of the embodied energy and between 9.61% and 13.94% of carbon emission during the production of the material necessary to

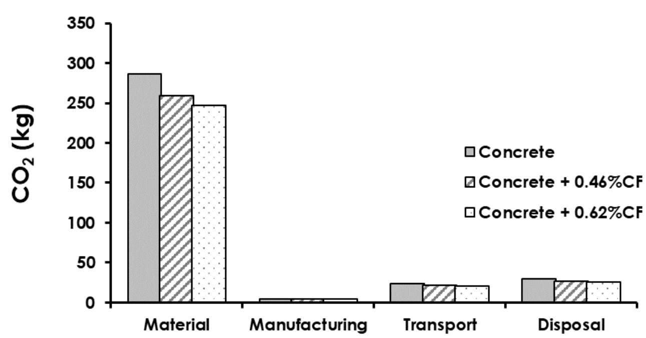

Fig. 7. Carbon emission of the different fiber content composites

build the composites. Coir fiber has the advantage related to their renewable nature and its high output in local sourcing. Also, the effect of reinforcing concrete matrix causes a more flexible behavior, which can be an advantage to absorb energy in lightweight structures.

IV. CONCLUSIONS

The results of different experiments with coir fiber reinforced concrete shows that this type of vegetable fiber can be used with some advantages in concrete and can be lead to the following conclusions:

1. Coir fiber exhibits good mechanical response as aggregate to concrete composite due to post-crack load bearing capacity. Failure of modified composites seems less drastic than plain concrete due to the additional toughness produced by the coir fibers.

2. As increase coir fiber volume inside composite the more compressive strength is obtained. After 28 days of water curing composites with 0.46% and 0.62% fiber produces a compressive resistance of 9.43 MPa and 11.84 MPa respectively. However, both values are below the plain concrete.

3. The use of natural reinforcement affects positively to all life cycle of the material, especially for material and disposal phase. Coir fiber composites exhibit lower embodied energy and carbon emissions showing a potential to reduce between 9.15% and 13.35% and between 9.61% and 13.94%, respectively.

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