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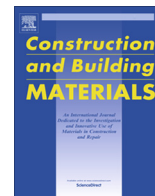
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Using alternative waste coir fibres as a reinforcement in cement-fibre composites

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HIGHLIGHTS

- Coir fibres can be a good replacement of wood fibres.
- Pre-treatment affect the physical properties and the composition of fibres.
- Pull-out test shows a good bonding between cement and pre-treated fibres.
- Mechanical and physical properties of coir boards are close to WWCB.

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ABSTRACT

Wood-wood cement boards (WWCB) have been extensively used as ceiling tiles or insulating walls thanks to their good thermal and acoustic properties. Nowadays, the trend is to use sustainable materials like waste fibres. These waste fibres are widely available at a low cost and despite their good properties, are usually landfilled or incinerated. Among them, coir fibres, extracted from the husk of the coconut, are a good candidate to replace conventional fibres in composite materials. However, preliminary results have shown that despite their good physical properties and great cement compatibility, coir fibres cement boards have poor mechanical performances. This is mainly due to the poor interface between the cement and the fibre, leading to a very weak fibre/matrix load transfer. The objective of the present study is to produce coir fibres cement boards having the required mechanical properties in order to be used as insulated interior wall or ceiling panels. First, the interfacial properties between the fibres and the cement will be investigated and improved by modifying the surface of the fibres thanks to chemical pre-treatments. Then, the process and design of cement boards will be studied in order to optimize the process, improving the overall properties of the boards. Finally, the mechanical and physical properties of these boards will be measured and compared to conventional WWCB.

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1. Introduction

Cement-wood composites have been used as a construction material for more than 70 years [1]. Among the new generation of cement-wood composites, wood-wool cement board (WWCB), made from wood-wool (also called Excelsior), Portland cement, water and additives are commonly used thanks to their good properties. Due to their high thermal insulating and sound absorbing properties with high porosity and low density ($300\text{--}500\text{ kg/m}^3$), the boards are mainly used as sound absorbing ceiling, thermal insulation ceiling and as wall panels [2,3]. They can be also used indoor or outdoor as decoration or in permanent shuttering and roofing. Among the two types of wood that are used to

manufactured WWCB, poplar (*Populus*) and spruce (*Picea*) wood [4], spruce wood is mainly used in Europe because of its availability and overall better properties. It has lower swelling, causes no problems during the manufacturing process and has a very good cement-wood compatibility [5,6].

Wood fibres have many benefits like renewability, biodegradability, low cost and availability but on the other hand, they also have some disadvantages: For instance, during the manufacturing process of WWCB (Fig. 1), quality controls of the wood prior to cutting them to wood wool or after the processing show many problems related to the biodegradation of the wood. These degradations are caused by changes in the cell walls, which can significantly alter wood properties (e.g. strength, water absorption) and appearance. Therefore, the wood cannot be used anymore for composite applications [7]. Moreover, the transportation of wood logs around Europe, which is the most energy consuming

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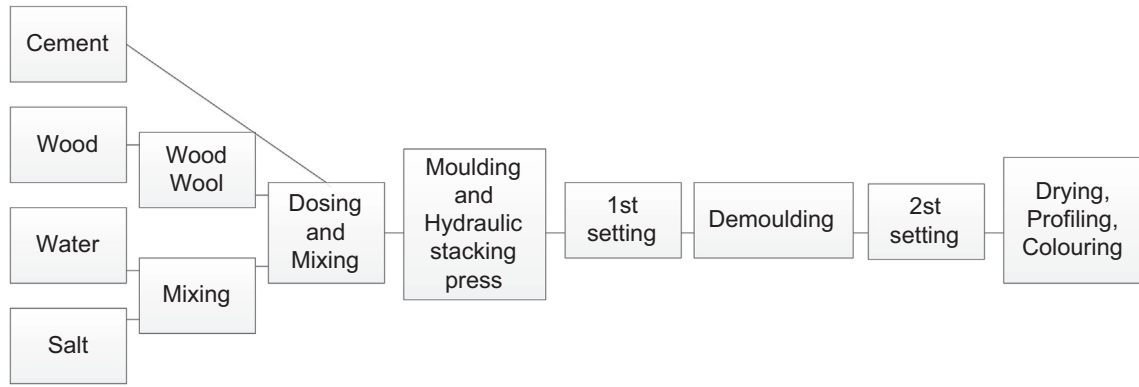


Fig. 1. The manufacturing process of WWCB.

operation in the wood-wool processing requires energy, which depends on the type of vehicle, the road and the weather conditions. For example, using a tractor and a truck for shipping the wood trunks produce 0.94 to 8.53 kg.m⁻³ CO₂ emission per unit transported volume [8]. Moreover, growing just one selected type of wood leads to monocultures and the associated problems of low ecological diversity and spread of diseases of pests [9]. To solve these issues, using organic waste fibres (OWF) in order to substitute wood in composite materials is a good way to reduce primary materials, energy and reduce the cost of the raw materials and its processing.

Organic waste materials are known as lignocellulosic materials since they mainly consist of cellulose, hemicellulose and lignin. They can be obtained from wood or plants, as depicted in Fig. 2. Cellulosic fibres can be separated between waste fibres and plants, which are grown to be used as lignocellulosic fibres for specific composite applications. OWF include a lot of different materials such as rice, wheat, barley, oat, coir, oil palm or bagasse fibres. Moreover, hemp or flax fibres can also be considered as an OWF in different countries when they grow these plants for yield and not for their fibres. Nowadays, in many countries, agricultural waste is becoming an environmental problem because these

resources are growing fast and are eventually burned or buried, which makes the cost of OWF very low. Using OWF can be a way to recycle and reuse them in a more sustainable way. They are worldwide available, biodegradable, non-toxic, eco-friendly and could be a good candidate to replace the currently used fibres [10–12]. Due to those benefits, OWF is a good source of a new type of materials in the production of cement-fibre composites. Short fibres can be used as a replacement of wood in dense boards whereas long fibres could replace wood in lightweight boards and could also act as a reinforcement in lightweight concrete. On the other hand, OWF have also some major disadvantages, which limit their potential applications. The main problem comes from the carbohydrates and water-soluble sugars in the fibres which can leach out and slow down or even stop the hydration of cement by forming a thin layer on the surface of cement grains and the nucleation poisoning of hydrate surfaces [13–18]. This problem can be solved by using pre-treatments or adding additives to cement composites [18–20].

Among the available candidates, one of the most promising waste fibres as wood replacement in cement-fibre composites is the coir fibre, extracted from the husk of coconut shell. The processing of coir fibres from coconut husks is very simple and inexpensive.

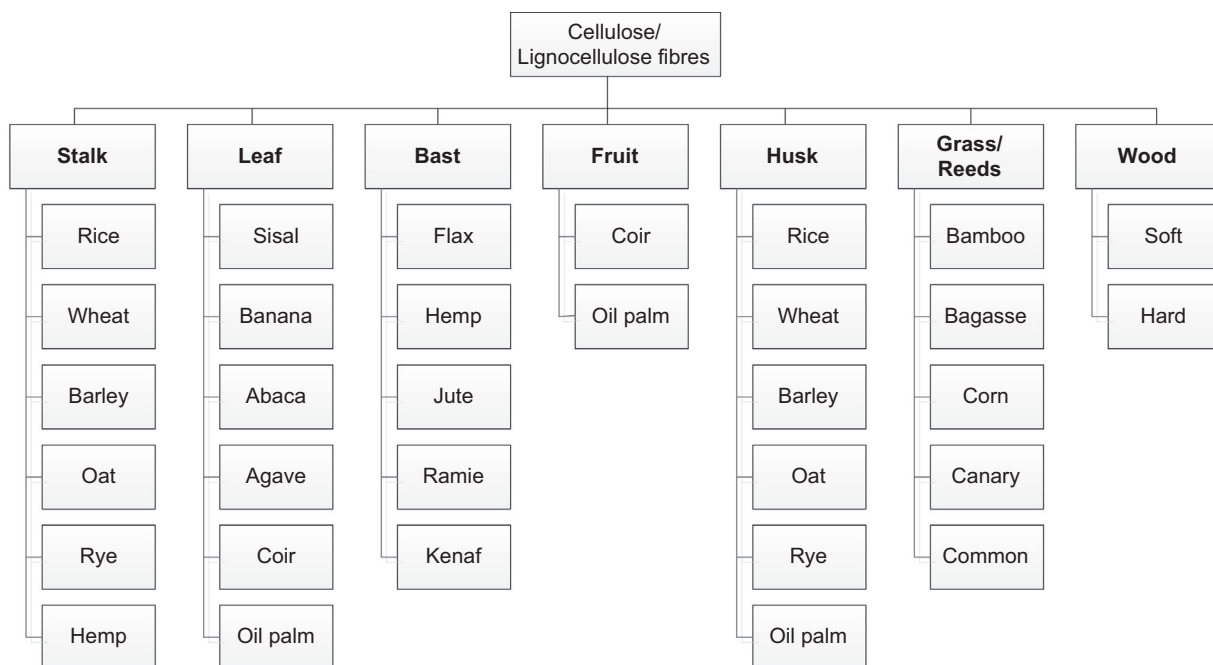


Fig. 2. Summarisation of lignocellulosic fibres.

The first step consists of crushing the nuts and remove the white meat, then husks are dried for 7–10 days and finally the coir fibres are processed by a crushing machine extracting the fibres [21]. Those fibres have low cellulose and high lignin contents, which make these fibres strong and flexible. Due to its low density and high thermal conductivity, the coir fibres have a good predisposition for the manufacture of cement-coir composites [11,22]. Cement-coir composite made with coir fibre can have low density and would be inexpensive because most of the raw material needed to process it is coming from waste. According to Van Dam et al. in 2004, 40 million tons of coconuts yield more than 2 million tons of fibres, but only a small fraction of them are reused for composite material applications although the chemical compatibility with cement has been proven to be unproblematic [23]. The total amount of soluble sugars in the fibre leads to the high compatibility level of coir fibre with cement because it is much lower as compared to other OWF (e.g. bagasse, oil palm) [6]. Also, the expected mechanical properties of coir fibres are reported to be higher than wood fibres, meaning that coir fibre boards would have better flexural strength than WWCB [11]. But only few studies focus on the utilization of coir fibres in composite materials and using this raw resource for cement-fibre board would be a new way of valorising OWF. Because of the lack of literature about this topic, characterization of the material and optimization of the process are needed to create a composite which fulfils the existing standards.

The aim of this work is to characterise the interface and the interactions between cement and coir fibres in order to solve the potential problems in the cement-coir composites process. These new composites should at least match the physical and mechanical properties of conventional WWCB. It is known that coir fibre does not have strong a retardation effect of cement hydration. However, a pre-treatment with calcium hydroxide ($\text{Ca}(\text{OH})_2$) is applied in order to modify the surface properties of the fibre for a better bonding between cement and fibre. Calcium hydroxide ($\text{Ca}(\text{OH})_2$) is used in this study due to widely availability and more sustainability in comparison to the other pre-treatments and can extract polysaccharides. Due to saturated solution, the liquid can be used several times. The strength of the coir fibres is analysed before and after this pre-treatment. Scanning Electron Microscopy (SEM) and pull-out tests are performed to characterize the bonding strength between cement and fibre. Finally, the mechanical properties of cement-coir boards are measured as well as their thermal properties.

2. Materials and methods

2.1. Materials

In this study, CEM I 52.5 R white is used as a binder and is provided by ENCI, the Netherlands. Its chemical composition is given in Table 1. Untreated and treated coir fibres are used with a length of 40–50 cm. The chemical composition and the monomeric sugars and uronic acids concentration of untreated coir and spruce fibres are given in Table 2 [6]. Spruce wood is provided by Knauf Insulation, the Netherlands and coir fibres are provided by Wageningen Food & Biobased Research, the Netherlands. Calcium hydroxide (min. 96% $\text{Ca}(\text{OH})_2$) provided by Merck, is used for the pre-treatment of coir.

2.2. Methods

2.2.1. Pre-treatment

A saturated solution of $\text{Ca}(\text{OH})_2$ is used for pre-treatment of coir with a pH close to 12. Untreated fibres are soaked in the solution for 24 h at 20 °C. After pre-treatment, two conditions are studied:

Table 1

Chemical composition of ordinary Portland cement CEM I 52.5R white used in this study.

Chemical composition	[wt%]
CaO	62.21
SiO ₂	20.93
Al ₂ O ₃	3.90
Fe ₂ O ₃	0.45
K ₂ O	0.12
Na ₂ O	0.11
SO ₃	2.92
MgO	0.43
TiO ₂	0.33
Mn ₂ O ₄	0.02
P ₂ O ₅	0.51

Firstly, the coir fibres are removed from the solution and put to in an oven, those pre-treated fibres are called non-washed fibres.

Secondly, the coir fibres are removed from the solution and washed once with tap water and then put in the oven, those fibres are called washed fibers. Both treated fibres are dried at 60 °C.

2.2.2. Boards processing of the cement-coir composites

Based on a calculation of the surface area of the coir fibre, the optimal fibre/cement (f/c) and water/cement (w/c) ratios are applied in the mixture design. Three different ratios for w/c (0.7, 0.8, and 0.9) and f/c (0.53, 0.62, and 0.75) are chosen in order to evaluate the optimum condition to maximize the mechanical, physical and thermal properties of cement-coir composites. The fibres are mixed with cement paste and placed into a mould (dimension: 15 × 30 cm) and then pressed for 24 h. Then, the composite is cured in plastic sheets for seven days and then dried for three days at a room temperature. Composites are dried in the oven for 2 h at 50 °C prior to analyses. This procedure is similar to the production of commercial WWCB.

2.2.3. Fibre characterization

A Phenom Pro X Scanning Electron Microscope (SEM) and Energy Dispersive X-ray (EDX) are used to analyse the surface of untreated, treated fibres as well as fibres covered with cement. Micrographs are recorded by using a backscattering electron detector at 15 kV. Spots of treated fibres were measured three times.

Samples of untreated and treated dried and milled coir fibres were tested by two different methods. X-Ray Diffraction analysis is performed using a D2 (Bruker) with a Co anode and a Lynx eye detector in order to analyse structural changes between untreated and treated fibres. Fourier Transform Infrared Spectroscopy (FT-IR) spectra are recorded using a Perkin Elmer Frontier FT-IR with a GladiATR diffuse reflectance device in order to characterize the effect of the pre-treatment at the fibres' surface. Eight scans are acquired with an optical retardation of 0.25 cm and a resolution of 4 cm^{-1} from 400 to 4000 cm^{-1} .

2.2.4. Tensile properties of fibres

The tensile strength of fibres is measured using an INSTRON 5967 machine with a 100 N load cell. The measurements are conducted with a crosshead speed of 5 mm/min. Untreated and treated fibres are mounted between the grips where each of the upper and lower jaws covers 2 cm of the sample. The distance between the jaws (l_0) is set at 100 mm. More than 15 specimens are tested, and the average strength of the fibres is determined. The tensile test is measured as a function of the linear density (tex) of the fibre by measuring the length and the weight of the fibre.

Table 2

a) Chemical composition of the organic fibres measured by HPAEC after H₂SO₄ hydrolysis; b) Monomeric sugars concentration in the leachates measured by HPAEC after H₂SO₄ hydrolysis and uronic acids concentration in the leachates measured by CG after methanolysis [6].

a)		Fibres	
		Coir	Spruce
Cellulose	[%]	36.6	41.6
Hemicellulose		37.0	37.3
Lignin		22.2	19.4
Ash		1.9	0.4
Extractive		4.2	1.7

b)		Fibres							
		[mg/ml]							
		Arabinose	Galactose	Glucose	Xylose	Mannose	Total sugars	GAA	GLA
Coir		0.21 ± 0.02	0.08 ± 0.01	0.04 ± 0.01	0.56 ± 0.05	0.02 ± 0.01	0.91 ± 0.1	0.02	0.07 ± 0.01
Spruce		0.03 ± 0.01	0.04 ± 0.01	0.03 ± 0.01	0.12 ± 0.01	0.07 ± 0.01	0.29 ± 0.05	0	0.01 ± 0.01

2.2.5. Pull-out test

The pull-out test is conducted to determine if the fibres in the cement matrix pull-out or break when the load is applied to the reinforced cement samples. The value, which is obtained from this test, is tensile strength (cN/tex). Eight fibres of three bunch of fibres (untreated, treated with washing and treated without washing) are embedded in the mould at a spacing of 3 cm on each side and filled by cement (Fig. 3a). The length of fibres inside the cement matrix is set at 3 cm, which correspond to 50% of the total fibre length. The moulds are covered with a plastic foil for 24 h and tested after 7 days. An INSTRON 5967 machine equipped with a 100 N load cell is used to test the bonding strength of the samples (Fig. 3b). The test specimen is placed to the bottom and the free end of the fibre is held by the upper grip. The fibre-held jaw is moved upward at a rate of 5 mm/min until failure.

2.2.6. Flexural strength of the composites

The bending strength of composites is measured at 10 days by a three-point flexural test on samples with dimensions of 5 × 20 × 1.5 cm by using an INSTRON 5967 bench. The testing speed is set at 1.5 mm/min with a support span of 15 cm. Four samples of each w/b and c/f ratio and untreated, treated, non-washed and washed are tested. As a reference, WWCB with a maximum thickness of 15 mm should have a minimum bending strength of 1.7 MPa according to the BS EN 12089, *Thermal insulating products for building applications* standard.

2.2.7. The thermal conductivity of composites

Thermal conductivity is measured on cement-fibre composites with a thickness of 15 mm by a heat transfer analyser ISOMET

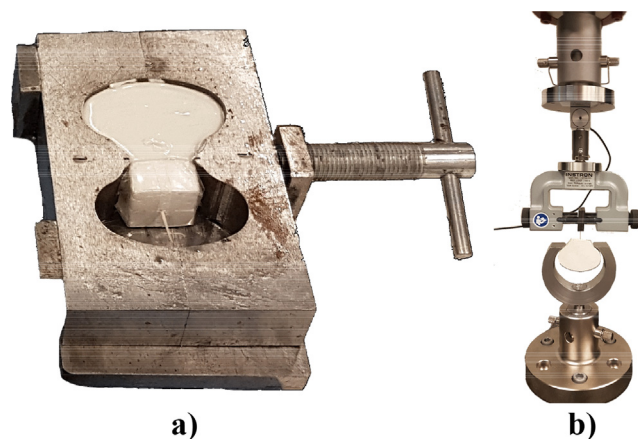


Fig. 3. a) Pull-out mould; b) Test set-up designed for pull-out testing.

2104. As a reference, WWCB with a thickness between 15 and 30 mm have a thermal conductivity range of 0.08–0.11 W.m⁻¹ K⁻¹ according to the BS EN 12089, *Thermal insulating products for building applications* standard.

3. Results and discussion

3.1. Characterization of fibres before and after pre-treatment

3.1.1. Chemical characterization of coir fibres

FT-IR spectroscopy can be used as a semi-quantitative analysis for cellulosic fibres [24]. In this study, the influence of the pre-treatment on the fibre surface is studied by comparing FT-IR spectra of untreated and treated fibres. The main known problem from the literature is the hemicellulose, which has an effect on cement hydration. Moreover, wax and others impurities on the surface can also affect the cement/fibre interaction [6].

Fig. 4 shows a summary of the effect of the pre-treatment on the coir fibres observed by FT-IR. Table 3 summarizes the major peaks characterized in the FT-IR spectra. The FT-IR spectra of untreated and treated coir fibres are mostly similar, and the main differences are seen with the peaks at 2980–2800 cm⁻¹, corresponding to wax on the surface of fibres, as well as with the peak at 1750–1730 cm⁻¹, corresponding to the hemicellulose. Peaks at 1150–1400 cm⁻¹, corresponding to pectin, lignin and hemicellulose also almost disappear after pre-treatment. Ca(OH)₂ is not observed in these spectra since its characteristic peaks are known to be at 2507, 1795, 1423 and 871 cm⁻¹, and are not visible in Fig. 4 [25].

The XRD measurements of untreated and treated coir fibres are presented in Fig. 5. [29,30,31]. The untreated coir fibre shows the broad peaks of crystalline cellulose together with traces of quartz. The peak at 30.32 °2Theta could not be identified. The amorphous content of the fibres decreases after the treatment, as can be seen by the lower background. This is mostly due to the removal of hemicellulose and other amorphous constituents, while the cellulose remains largely unaffected. No remaining Ca(OH)₂ or CaCO₃ from the pre-treatment can be detected in the fibres.

When an alkali treatment is applied, it has an impact on morphology, molecular and supramolecular properties of cellulose. Consequently, fibres are stiffer, accessible and they have changes in crystallinity and pore structure [29].

3.1.2. Surface characterization of fibres

A surface characterization of the fibres is accomplished in order to evaluate the effect of the pre-treatment on the morphology of the coir fibre. Fig. 6a–g shows the surface morphology of untreated and treated coir fibres by SEM.

The pre-treatment led to morphological changes due to the removal of compounds like wax and hemicellulose. From the

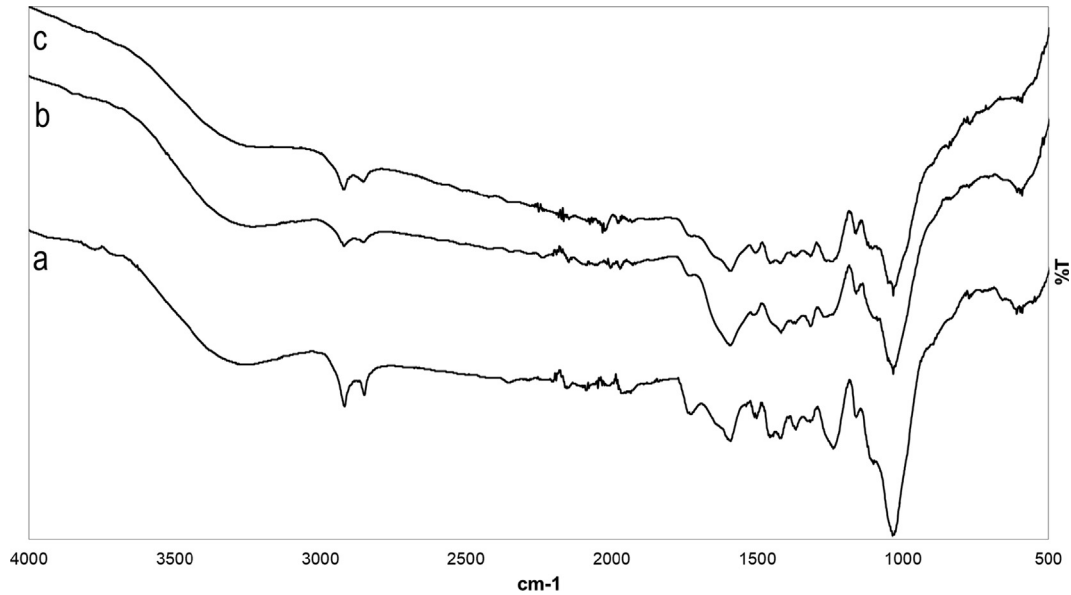


Fig. 4. FT-IR spectra 4000–500 cm⁻¹ of coir fibres: a) Untreated fibre; b) treated, non-washed fibre; c) treated, washed fibre.

Table 3
Infrared absorption frequencies of untreated and treated coir fibres [24,26–28].

Wavenumber [cm ⁻¹]	Vibration	Source
3300	O–H linked shearing	Polysaccharides
2980–2800	CH ₂ symmetrical stretching	Wax
1650–1630	OH	Water
1750–1730	C=O stretching	Hemicellulose
1595	Aromatic ring vibration + C=O stretching	Lignin
1505	C=C aromatic symmetrical stretching	Lignin
1465	C–H deformation	Lignin
1425	CH ₂ symmetric bending, C=C stretching in aromatic groups	Pectin, lignin, hemicellulose
1370	CH bending	Polysaccharides
1320	C–O aromatic ring	Cellulose
1240	C–O aril group	Lignin
1160	C–O–C asymmetrical stretching	Cellulose, hemicellulose
1035	C–O, C=C, C–O–C stretching	Cellulose, hemicellulose, lignin

literature, it appears that a thick layer covers the fibre (Fig. 6a and b) which is characterized as wax and oil [19,32,33]. Fig. 6c shows the treated, non-washed coir fibre, where the wax is entirely removed but a residue is still visible around the pits. EDX analyses are performed at the surface of the fibre (Table 4a) in order to characterize the composition of these residues and it appears that these compounds are calcium based (Fig. 6d) coming from the Ca(OH)₂ that crystallised on the fibre surface pores when the saturated solution dries. On the other hand, in Fig. 6e, no calcium residues are visible showing that the washing step realized after the pre-treatment helps to remove the remaining Ca(OH)₂. However, traces of unknown micrometric particles inside the pores can also be seen. By doing an EDX characterisation (Table 4b), it is discovered that the particles are silica-bodies (Fig. 6g) which tend to be concentrated in pores [34]. This process is not unusual because coir fibres naturally absorb inorganic compounds as a biological process [35]. It is noticeable that a long pre-treatment (24 h) with washing can be harmful to some fibres, as seen in Fig. 6f where the fibre is clearly damaged. However, the same pre-treatment (Fig. 6e) also shows a clean surface without larger damage.

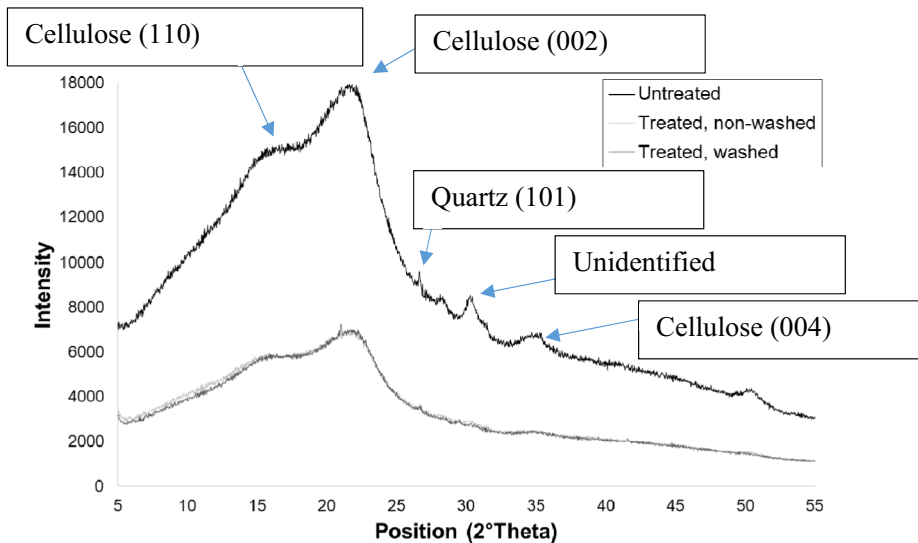


Fig. 5. XRD analysis of untreated and treated coir fibres.

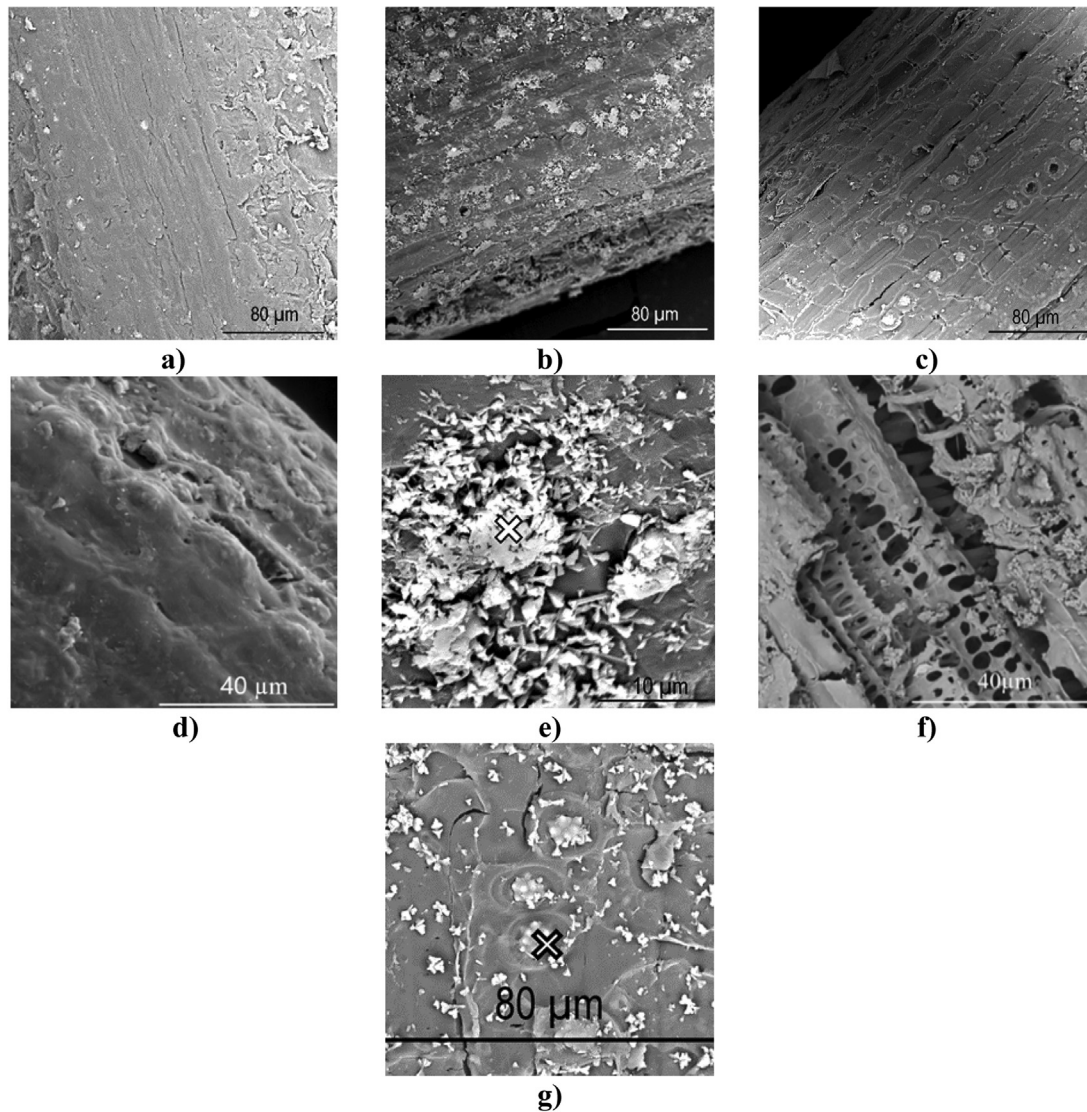


Fig. 6. SEM: a) Untreated coir fibre 80 µm; b) Treated, non-washed coir fibre 80 µm; c) Treated, washed coir fibre 80 µm; d) Detail on untreated coir fibre 40 µm; e) Detail on treated, non-washed coir fibre 40 µm; f) Treated, washed coir fibre 10 µm, measured spot by; g) Treated, washed coir fibre 80 µm, measured spot by EDX.

Table 4

Semi-quantitative EDX characterization: a) Treated, non-washed coir fibre; b) Treated, washed coir fibre.

	Element Name	Atomic Conc.
a)	Calcium oxide	7.1 ± 4.4
b)	Silicon oxide	13.2 ± 5.2
	Calcium oxide	1.2 ± 1.2

In overall, pre-treatments can remove some constituents of the coir fibre that appears to be wax, oil and hemicellulose. Moreover, the morphology of the fibres changes as pre-treatments roughen their surface. Moreover, they also almost removed all silica-bases and calcium residues, which eventually may improve the cement/fibre interaction.

3.1.3. Mechanical properties of fibres

The tensile strength of untreated and treated fibres is shown in Fig. 7. The average stress/strain curves of each samples are showed in Fig. 8. The tensile strength of the untreated fibres is compared with the tensile strength of treated fibres with two different condi-

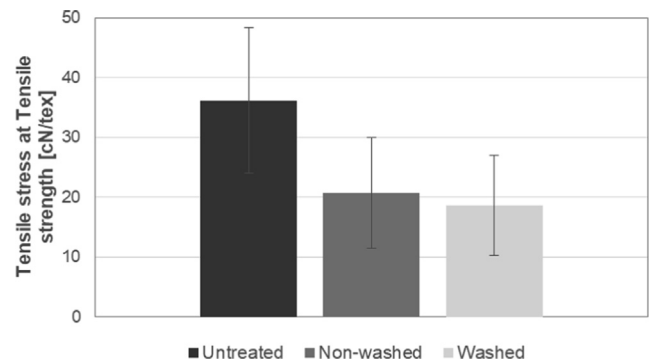


Fig. 7. Tensile strength of untreated and treated coir fibres.

tions, namely non-washed and washed in order to evaluate the efficiency of rinsing the remaining the residual $\text{Ca}(\text{OH})_2$ that could stay on the fibre. It must be noticed that the standard deviation of these tests is very high (34–45%), which is quite common with heterogeneous cellulosic fibres.

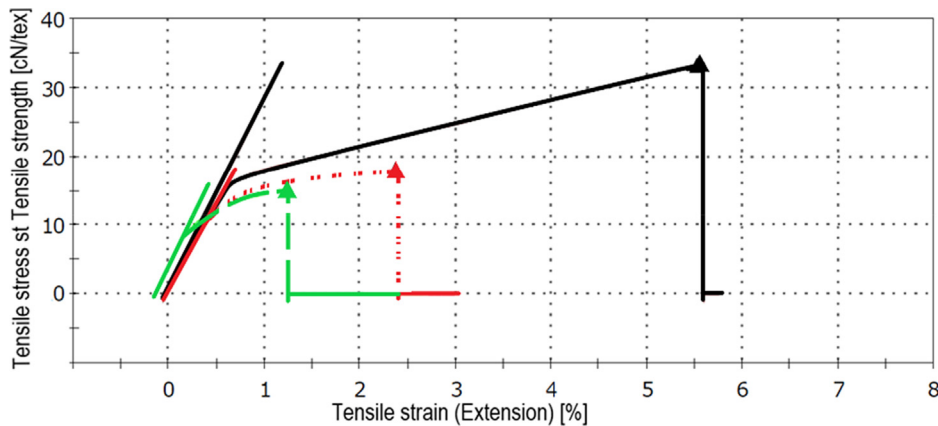


Fig. 8. Characteristic tensile stress at tensile strength curves. In black solid line: untreated fibre, long dash green line: treated, non-washed fibre, doth red line: treated, washed fibre.

Fig. 7 shows a substantial reduction in tensile strength of treated fibres (43 and 49%) meaning that the pre-treatment causes a decomposition of the fibres which has a significant effect on the tensile strength of the fibre. The maximum reduction is observed when the fibre is washed, with a tensile strength decrease of 49%, which was slightly higher than non-washed fibres (−43%). Statistically, even the lowest tensile strength value of the untreated coir fibres is higher than the average tensile strength of treated fibres. The significantly lower strength can be characterised by a chemical dissolution of lignin in the alkaline environment. Another explanation may be as an absorption of the alkaline solution into pores making the fibres more brittle, as it can be seen in Fig. 8 [36].

Physical and mechanical properties of organic fibres are defined by their chemical composition (i.e. cellulose, hemicellulose and lignin) as well as the organization of the cell walls that can be measured with a cell wall/lumen ratio [37]. The strongest and stiffest component in organic fibres is cellulose whereas the hemicellulose does not have that significant effect as cellulose due to its solubility in water and high water absorption, and the lignin is mainly a bonding agent, acting as the matrix in this cellulosic composite [38]. As characterized by FT-IR and SEM, pre-treatment does change the hemicellulose content, as well as the surface of the fibres. The wax is also removed leading to rougher surfaces. Because of these reasons, treated fibres have significant lower tensile strength than the untreated fibres.

From these results, it can be concluded that the strength of the fibre is significantly lower after pre-treatment which could influence the final composite. On the other hand, the hypothesis in this study is to significantly change the fibre micro-structure, in order to achieve better bonding between cement and fibres, meaning that this drop in mechanical properties is necessary in order to improve the composite strength.

3.2. Bonding between cement and coir fibres

3.2.1. Single fibre pull-out test

The bonding strength between cement and different coir fibres is determined by pull-out test. The tensile stress at the cement-fibre bond strength is calculated by dividing the maximum pull-out load by the surface area of the fibre. The average and characteristic pull-out curves for each condition are shown in Fig. 9. The average results for untreated and treated coir fibres in cement matrix is shown in Table 5. The highest pull-out strength has been measured for treated and non-washed coir fibres. As compared to other fibres, the reduction is about 2% for untreated coir fibres and

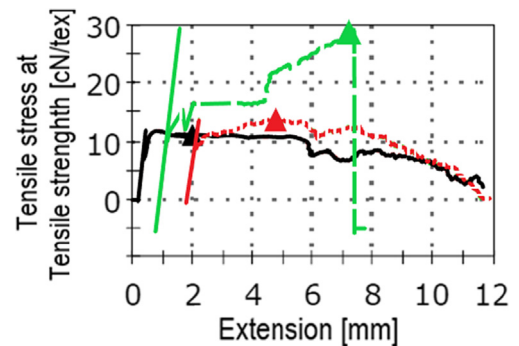


Fig. 9. Characteristic tensile stress at tensile strength curves of pull-out test. In black solid line: untreated fibre, long dash green line: treated, non-washed fibre, doth red line: treated, washed fibre.

Table 5

The pull-out test of untreated and treated coir fibres.

Pre-treatment	Tensile stress at Tensile strength [cN/tex]
Untreated	13.8 ± 4.2
Treated, non-washed	14.1 ± 6.3
Treated, washed	12.6 ± 3.4

11% for treated, washed fibres. As seen in previous tensile testing of fibres, the standard deviation with organic fibres is very high, with more than 30% of deviation. During pull-out tests, a few untreated and treated, washed fibres are broken, where the tensile strength of those broken fibres was lower than the tensile strength of single fibre in the previous test of single fibres. The reason can be explained by the variation of the cross-section dimensions of these fibres.

Nevertheless, the pull-out strength of untreated and treated coir fibres cannot give additional information to assess the interface. In order to study the true behaviour at the interface, stress/strain curves must be analysed, as shown in the literature by Beltran and Schlangen [39] and Radho [40]: During the pull-out test, a fibre can have four different behaviours, namely constant friction, slip softening, slip hardening or fibre failure, as it can be characterized in Fig. 10.

Following this hypothesis, the behaviour of untreated and treated fibres is characterized for each sample and is summarized in Fig. 11.

All samples undergo mostly a slip hardening behaviour for more than 50% of the time, which means that when the fibre is pulled

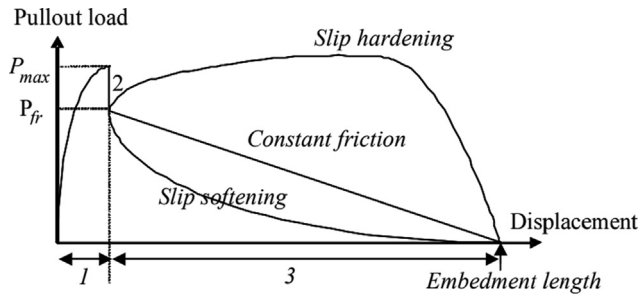


Fig. 10. Schematic description of the four different fibre pull-out behaviour, as shown by Beltran and Schlagen.

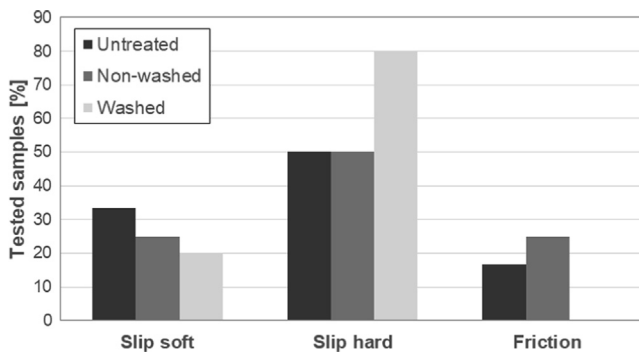


Fig. 11. The pull-out test behaviour of untreated and treated coir fibres.

out, an increasing load resisting the fibre debonding occurs. However, the treated and washed coir fibres show no friction during the pull-out test and almost all tested fibres have a slip hardening behaviour (more than 80% of the washed and treated fibres). Untreated fibres undergo a slip softening behaviour 33% of the time, which identifies the bad interface between these fibres and the matrix because it shows that when the fibres are pulled out, no further load is applied meaning that the debonding is easier.

Overall, among all conditions, the treated and washed coir fibre have a better bonding strength, mostly explained because the unwanted substances are removed from the surface (i.e. wax, oil, silica bases), helping the cement hydration to occur inside the pores, increasing the interface strength between the fibre and the matrix.

3.2.2. Fractography

Fig. 12a–c show SEM micrographs of coir fibre embedded in cement matrix. The fibres are removed from cement-coir composite after tensile testing prior to SEM characterization.

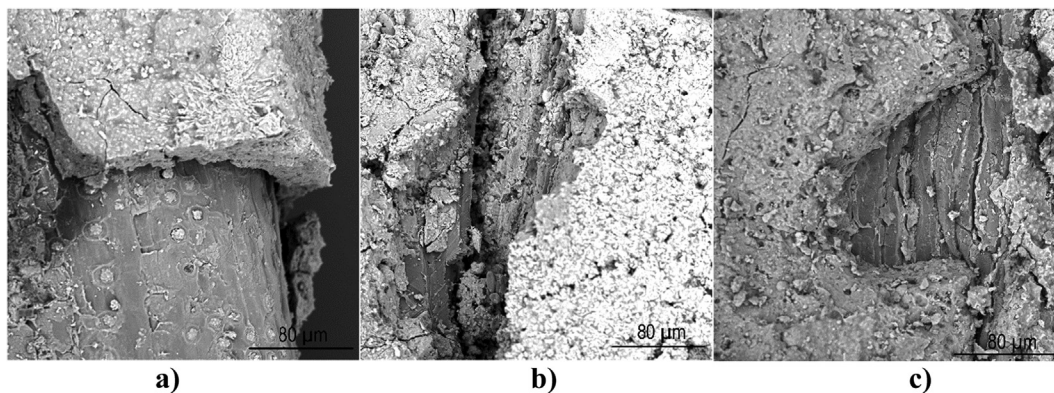


Fig. 12. SEM of bonding between cement and coir fibres: a) Untreated coir fibre; b) Treated, non-washed coir fibre; c) Treated, washed coir fibre.

In Fig. 12a, a visible gap between the untreated coir fibre and the surrounding cement matrix can be seen, showing the poor fibre/matrix interfacial adhesion. On the other hand, treated fibres (Fig. 12b and c) show that in both cases, the fibre/matrix interfacial gaps are significantly reduced, showing a better interfacial bonding. It is clear that the pre-treatment affects the interface between the cement and fibre, mostly because of the impurities removed from the surface. Moreover, the calcium residue, which remains on the surface, could help forming better bonding between the fibre and the cement coating. From these results, the best fibre/matrix interfacial adhesion was characterized with treated and washed fibre (Fig. 12c), where the impurities such as silica-based particles or unwanted constituent of the fibre are removed from the surface, allowing the cement matrix to penetrate into the pores and crystallised inside the fibre, confirming the observations made after the pull-out tests.

3.3. Mechanical and physical properties of the composites

3.3.1. Mechanical performance of the composites

Fig. 13 shows manufactured cement-coir composites, which are cut and used for testing the properties of the composites. The cement-coir composites mechanical performances are depicted in Fig. 14, showing the flexural strength as a function of the density of manufactured cement-coir composites.

As described in the BS EN 12089 standard, the acceptable bending strength for WWCB is 1.7 MPa. From the graph (Fig. 14), it is observable that the bonding strength is highly dependent of the density and some cement-coir, depending of their composition, can be above the limit or way below. These results can be divided



Fig. 13. The cement-coir composites made for the different conditions.

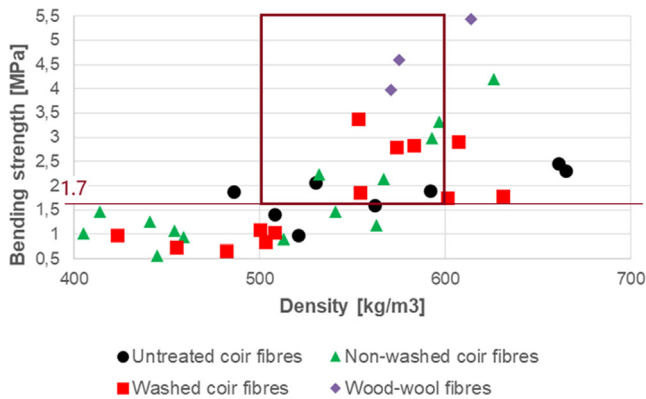


Fig. 14. Bending strength/ density of cement-coir composites.

into three different density range. The first density range (400–500 kg/m³) shows very low bending strengths with all treated samples, caused by the low cement content. These samples are manufactured with a low fibre to cement ratio ($f/c = 0.53$) and a high-water content ($w/c = 0.9$). The second density range is around 600–700 kg/m³ and all the samples are above the strength limit. However, the standard also requires density below 600 kg/m³ due to the potential applications (e.g. ceiling) of these materials. The weight of the material is explained by a manufacturing process that is not optimal, where an excess of cement is used. In both situations (i.e. the different density ranges), problems come from the cement and fibre distribution in the composites.

The last density range is 500–600 kg/m³, which is ideal for the composites, as described in the standard. The composites with untreated coir fibres are mostly below the limit and range from 1 to 2.1 MPa. This result confirms the necessity of a fibre treatment for the manufacture of coir/cement composites. When treated, fibres have better bonding with the cement, as seen with fractography or pull-out tests. However, the difference between non-washed and washed coir fibres is minor in composites. Samples without washing range from 0.9 to 3.3 MPa and with washing from 0.8 to 3.4 MPa. It appears that the decrease of the tensile strength of the fibre does not affect these results significantly or are mostly counterbalanced by the beneficial effect of the higher roughness of treated fibres and the removal of unwanted constituent at the fibre surface. In comparison, wood-wool cement boards were made with the same method as cement-coir composites for control and added to Fig. 14.

In overall, the treated fibres provide good results as compared to untreated fibres. Although it could be improved, since some samples are still slightly below the strength limit. From Fig. 13, it is evident that the distribution of fibres in the composites should be better, which can be obtained using a different and more consistent processing method. In this study, a wet method is used (i.e. first the cement is mixed with water and then fibres are added) and a dry method (i.e. first the water is mix with fibres and then cement is added) can minimize the clustering of fibres.

3.3.2. Physical properties of the composites

Thermal conductivity as a function of composite density for all the composites is displayed in Fig. 15. These results indicate a dependence of thermal conductivity and density.

As seen in the previous section, the density of the acceptable cement-coir composites range between 500–600 kg/m³. Subsequently, with the properties of the composite, the thermal conductivity are the following: 0.126 W/m.K for the untreated fibres, 0.109 W/m.K for the treated, non-washed fibres and 0.116 W/m.K for the treated, washed fibres. WWCB are used in a variety of industrial and residential application where good thermal proper-

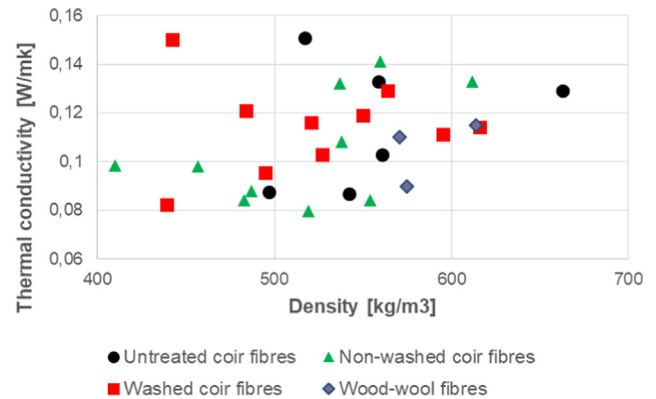


Fig. 15. Thermal conductivity of cement-coir composite as a function of board density.

ties are necessary. The range for thermal conductivity standard of WWCB is between 0.08 and 0.11 W/m.K, meaning that the thermal conductivity of WWCB and the cement-coir composites are in the same range. However, composites made of untreated fibres are slightly offlimit, showing once again the necessity and the benefit of using treated fibres.

4. Conclusion

This study shows that composites made of coir fibres, an organic waste material, have adequate thermal and mechanical properties and can be used in the building industry for diverse applications. Moreover, the following conclusions can be drawn:

- Pre-treatments cause significant physical and mechanical changes to the coir fibres. It appears that the hemicellulose is removed from the surface of the fibre, as well as wax, oil and silica-based compounds. Due to those changes, the tensile strength of treated fibres significantly decreases (–46% in average).
- Morphological analyses done by SEM show that the fibres roughness significantly change with a treatment. Moreover, residues of calcium is visible after the pre-treatment and can explain the influence of a washing step after the pre-treatment.
- Pull out tests are performed in order to characterize the cement/fibre interaction. It appears that pre-treated fibres have a better interface with the cement than untreated fiber, with less slip softening and more slip hardening behaviour during the tests. Washed fibers have also a better interface than unwashed fibers because of the removal of unwanted constituents.
- Thermal and mechanical properties of the cement-coir composites are very close to conventional WWCB. The standard limit for bending strength (1.7 MPa), in the acceptable density range (500–600 kg/m³), is achieved with treated fibres with both conditions: non-washed, washed. The thermal conductivity is in the range 0.08–0.11 W/m.K. The benefit of pre-treatment is thus proven since the overall properties of the boards are improved.

Declaration of Competing Interest

None.

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