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Cement composite plates reinforced with nonwoven fabrics from technical textile waste fibres: Mechanical and environmental assessment

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ABSTRACT

In this work, we present the development and characterisation of new cement-based composite panels reinforced with fibres recovered from wastes of protective technical clothing. The developed panels present a flexural strength (~15 MPa) and fracture toughness (~3.5 kJ/m^2) that are suitable for their application on ventilated façades. The environmental impact of these panels was evaluated through the life-cycle assessment (LCA) from a cradle-to-gate approach and was compared with similar engineered materials and commercial materials used for ventilated façades (fibre cement facing tiles, ceramic tiles, and natural stone plates). Two functional units were assessed: the panel necessary to cover 1 m^2 of façade, and the panel necessary to cover 1 m^2 of façade providing a maximum bending stress of 17 or 24 MPa. For 17 MPa, the new composite developed has presented similar environmental performance to fibre cement facing tiles and significantly better than the traditional ceramic tiles and natural stone plates.

1. Introduction

Currently, there is an increasing global concern about environmental problems that is motivating many industries to find more sustainable alternatives. One of them is the construction and building sector, which is known to have a large impact on climate change. It is estimated that this sector produces around 36% of the CO_2 emissions and 40% of the energy consumed in the EU (Comission, 2019), and around 39% of CO_2 emissions and 36% of all energy consumption in the world (Global-ABCIEA and UNEP, 2020). The impact is mainly generated during the construction and the operational phases of buildings. A possible means of reducing the impact of the construction phase is the use of more sustainable building materials and, particularly, the reduction in the required amount of cement. Moreover, to reduce the operational phase's impact, there are certain building solutions to consider, such as ventilated façades. These consist of cladding panels fixed onto a metallic structure that is mounted on the external wall, which leaves a ventilated chamber between the cladding and the wall. Ventilated façades provide excellent performance in terms of thermal and acoustic insulation, assembly easiness, and durability, but their construction requires the use of thin panels, which must cope with rising demands in terms of sustainability, performance, durability, cost-effectiveness and safety.

In this context, fibre-reinforced cementitious composite plates can play a key role as a cladding material. It is known that the reinforcement of cement matrices with well-dispersed short fibres is very effective in strengthening building materials such as pavements to avoid cracking. A high variability of fibres has been used to reinforce cement composites: glass fibres, steel fibres, polypropylene fibres, as well as a large variety of vegetal fibres, among others (Bartos, 2017; Ardanuy et al., 2015; Onuaguluchi and Banthia, 2016; Ali et al., 2020), and there is a growing interest in increasing the sustainability of these materials. In the literature, fibrous vegetal waste materials (Savastano et al., 2005), recycled polyester fibres (Won et al., 2010), and waste fibres from end-of-life (EOL) textile products (Sadrolodabaee et al., 2021a), among others, have been proposed for cement composite reinforcement. In fact, the use of textile waste as a source of raw materials for reinforcements leads to an interesting synergy between the textile and the construction and building sectors.

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In order to obtain thin panels of high tensile and flexural strength for ventilated façades, it is preferable to use reinforcements that are structured in multiple forms such as unidirectional fibre strands, meshes, woven fabrics or nonwoven fabric, among others (Claramunt et al., 2016; Strauss Rambo et al., 2016; Fidelis et al., 2016; Silva et al., 2010; Mobasher, 2011; Olivito et al., 2014). In this regard, the production of nonwoven (NW) fabric is low-cost and adaptable to many fibre sources. Moreover, the use of a fabric reinforcement eases the production of the composites through automated processes, provides excellent flexural strength and ductility and allows for a greater reduction in the amount of cement used (Claramunt et al., 2016). The difficulty of producing this type of composite material lies in achieving a good amount of infiltration of the cement matrix in the fabric reinforcement, and also lies in achieving a good physical and chemical adhesion between the fibre and the matrix (Claramunt et al., 2016; Peled et al., 1994).

Around 2 million tons of textile waste are generated in the EU each year according to the *Mistra Future Fashion Research Program* (Roos et al., 2019), and the estimations for the global production of textile waste are between 35 million (Fundation, 2017) and 92 million tons (Niinimäki et al., 2020). However, despite the large amount of waste generated, the recycling of EOL textile products has some difficulties – such as fraction recovery, sorting, disassembly difficulties, differences in functional and aesthetic properties, high variability of materials and problematic fibre blends, among others (Roos et al., 2019; Niinimäki et al., 2020) – which are translated into a low recyclability index. Waste management is often too complex or expensive to be economically profitable and, as such, the textile products end their life discarded in landfills or incinerated rather than recycled. To avoid this from happening, it is necessary to find alternative applications to repurpose large amounts of EOL textile wastes and create products of interest for the industry, where the construction and building sector can offer a large market for the applications of such products.

In a previous study done in our research group, some cement composites reinforced with NW fabrics produced with fibres from shredded EOL garments – hereafter fashion textile waste (FTW) – were studied (Sadrolodabaee et al., 2021b). In the present work, we explore another EOL textile waste, recovered from fire-protective technical clothing – hereafter technical textile waste (TTW) – as a reinforcement for cement composites. To this end, we optimised the NW fabrics that were made of 100% TTW fibres, which had been produced by carding and further needle punching. These fabrics were then used to produce a sandwich-like structure with a Portland cement matrix, and the composite plates obtained were characterised by means of flexural testing in order to determine their suitability for application as high-performance thin panels in ventilated façades. The results were compared to those materials with FTW that were presented in previous works done by the research group (Sadrolodabaee et al., 2021b).

In addition, life-cycle assessment (LCA) proved to be a very useful methodology to study the environmental impact of either a product or the function that a product is designed to perform. Indeed, LCA is a tool widely used by researchers and practitioners to compare – in terms of the environmental point of view – composite materials made from a wide variety of matrices and reinforcements, and more specifically to assess the environmental impact of building materials and industry (Abd Rashid and Yusoff, 2015; Carcassi et al., 2022; Singh et al., 2022; Li et al., 2022; dos Santos et al., 2022; Penadés-Plà et al., 2017; Duan et al., 2022). In this study, a Life-Cycle Assessment (LCA) was used to assess the environmental sustainability of the TTW-4L composite plates developed, which were compared with the FTW-4L plates – developed in previous studies – as well as engineered commercial fibre cement and other traditional materials used as cladding in ventilated façades.

2. Materials and methods

2.1. Part I: production and characterisation of composite plates

2.1.1. Raw materials

The cement used as a matrix was Portland cement, Type I UNE-EN 197–1:2011 52.5R "Super Dragon", which was kindly provided by *Cementos Molins Industrial S.A.* (Spain).

Technical textile waste (TTW) fibres were obtained by shredding EOL protective polo shirts from firefighters' daily uniforms. These shirts have a composition of 93% meta-aramid fibres, 5% para-aramid fibres and 2% of antistatic fibres (Fig. 1, left). Short fibres, between 0.5 and 6 mm mainly constituted the TTW (see Fig. 1, right). The morphology of the waste allowed for the production of nonwoven fabrics using only TTW fibres (100% TTW).

2.1.2. Preparation and characterisation of nonwoven fabric reinforcements

The nonwoven (NW) fabrics were produced using a two-step process of carding and needle punching (Fig. 2).

In the first step, the webs were obtained. To achieve this, 60 g of TTW fibres (Fig. 2a) were processed in a lab scale carding machine (*Platt Brothers*, UK) (Fig. 2b), which produced the opening and alignment of the fibres and resulted in a regular web (Fig. 2c). In the second step, to obtain NW fabrics with enough tensile strength to be used as reinforcement (Fig. 2f), the webs were consolidated by needle punching with the needle punching loom from a DILO OUG–II–6 pilot plant (*Dilo Group*, Germany) (Fig. 2d and e). The needle punching parameters used were a stroke frequency of 1060 strokes/min and a punching density of 970 punches/cm^2.

The thickness, areal weight, moisture content and tensile strength of the NW fabrics were determined. The samples were conditioned at 20 ± 2 °C and a relative humidity (RH) of 65 ± 2% for 24 h prior to testing was ensured. The moisture content was obtained by means of a MOC63u moisture analyser (*Shimadzu*, Japan), which noted the difference in percentage between the conditioned sample and its weight after drying at 105 °C. The mechanical characterisation by tensile testing was performed according to the UNE-EN ISO 13934-1 standard through the use of a Synergie MTS dynamometer (*MTS Systems*, USA).

2.1.3. Preparation and characterisation of cement composite plates

The cement composite plates were manufactured following a procedure similar to the Hatschek process (Fig. 3) – the production method of fibre cement plates/facing tiles –, which consists of the following steps; *Step 1: Matrix preparation*. For the matrix, a Portland cement paste with a water/cement ratio of 0.85 was prepared in an LH stirrer (*VELP Scientifica*, Italy). *Step 2: Layering*. Four layers of the TTW-NW fabric reinforcement were cut to 300 mm × 300 mm. Each layer was soaked in the Portland paste (Fig. 3a) and layered – alternating the (machine and cross) NW direction – inside a mould (Fig. 3b). A vacuum was applied by means of a vacuum pump (*Comecta*, Spain) during the piling process in order to reduce the pore appearance and to increase the homogeneity between layers. *Step 3: Compaction*. The mould was then placed in an electro-mechanical press (*Incotecnic Lab-Pre*, Spain) to apply a homogeneous pressure of 3.5 MPa to the plate for 24 h (Fig. 3c). *Step 4: Curing*. The plate was removed from the mould and cured in a humidity chamber (>95% RH, 20 ± 1 °C) for 28 days. This composite production methodology has been defined in previous works (Claramunt et al., 2016, 2017).

Eight TTW composite plates were produced for the characterisation of the material. To evaluate its durability, four of these cured TTW composite plates were further subjected to an accelerated ageing process, which consisted of immersing the samples for 6 h in water at 20 °C and then drying the samples for 18 h in an oven at 60 °C, as described in previous works (Claramunt et al., 2011).

Twelve specimens were cut from each plate. The dimensions of each specimen (150 mm × ~40 mm × ~10 mm) were accurately measured

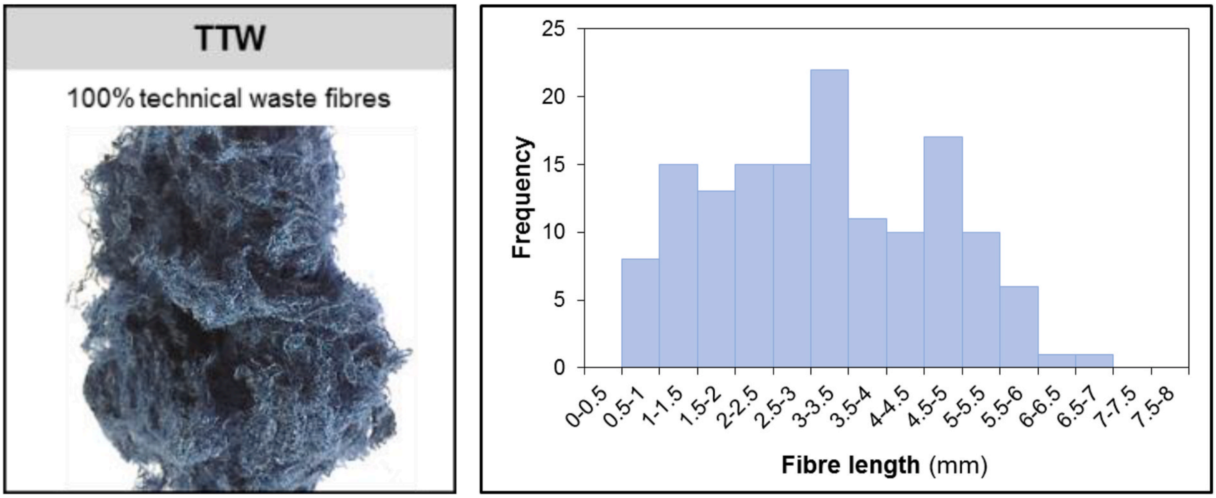


Fig. 1. Technical textile waste (TTW) fibres used for reinforcement production (left), and histogram for the length distribution of the TTW fibres (right).

with a calliper due to slight variabilities in their wide and thickness. To determine the flexural behaviour of both unaged (TTW-4L) and aged (TTW-4L/A) specimens, three-point bending tests were carried out following the RILEM TFR1 () and TFR4 (TFR4- The determination of energy, 1984) standards, using a Metrotec universal testing machine (*Techlab Systems*, Spain) at a cross-head speed of 5 mm/min, with a 100 kN load cell and a major span (L) of 100 mm. The displacement measurements were carried out using linear variable differential transformers/sensors (LVDTs) with a 0.01 mm resolution and an error of 0.15%. From the bending tests, the following parameters were determined: a) the limit of proportionality (LOP), defined as the flexural strength value when the first crack appeared; b) the modulus of rupture (MOR), which corresponds to the maximum flexural strength at the point of fracture; c) the modulus of elasticity (MOE) as the slope of the elastic zone in the flexural strength-strain curve; and d) the specific fracture energy absorbed by the composite, which is determined as the area under the load-displacement curve between the origin and the point corresponding to a reduction of force equivalent to the 40% of the MOR, divided by the cross-section area of the specimen. From the 24 curves obtained in total, two representative curves – those with values closer to the average ones – were selected to represent the composites' behaviour in the unaged and aged states.

2.1.4. FTW composite plates used for comparative purposes

As previously mentioned, the cement composite plates presented in this work were compared with a cement composite material described in a previous study (Sadrolodabaee et al., 2021b).

In this case, the NW fabric reinforcement was a mixture of fibres recovered from waste clothes (FTW), which had a composition of ~72% of cellulosic fibres and ~28% polyester fibres, as well as virgin flax fibres. The FTW presented a heterogeneous length distribution (see Fig. 4), with average lengths shorter than the TTW. This was because of their short length, to which it was necessary to add 35% of longer fibres (flax fibres with a length of ~6 cm) to allow for a proper formation of the web in the carding process.

The FTW-NW fabric reinforcement was prepared under the same conditions explained in Section 2.1.2 for the TTW-NW fabric reinforcement and the FTW/cement composite plates were produced using the same materials and methodology explained in Section 2.1.3 for the TTW/cement composite plates (Sadrolodabaee et al., 2021b). In this work, the results of the mechanical performance of the composite samples reinforced with 4 layers of nonwoven fabric after curing, and after curing plus being subjected to accelerated ageing – hereafter FTW-4L (unaged) and FTW-4L/A (aged) -, which were obtained in a previous study (Sadrolodabaee et al., 2021b), were compared to the new TTW composites produced.

2.2. Part II: environmental analysis

An environmental analysis was performed according to ISO 14040 (ISO/TC 207, 2006a) and ISO 14044 (ISO/TC 207, 2006b) standards, establishing the four basic phases of the life-cycle assessment (LCA) methodology: goal and scope definition, life-cycle inventory, life-cycle impact assessment, and interpretation. The software SimaPro 9.1.0.11 (*PRé Sustainability*, The Netherlands) and the methodology ReCiPe 2016 v1.1 midpoint, Hierarchist version were used to develop the LCA analyses.

2.2.1. Goal and scope definition, functional unit and system boundaries

The main goal of the LCA conducted was to determine the environmental performance of the composite plates presented in this study (i.e., TTW-4L). In addition, the LCA aimed to carry out a comparison of this material with other new solutions – the FTW-4L plates developed by the authors in previous studies (Sadrolodabaee et al., 2021b) – and with other market-available materials that are conventionally used in ventilated façades and that are available in the database – some traditional materials (i.e., ceramic tiles and natural stone plates) and another engineered material (fibre cement facing tiles) –, in order to determine which cladding material presented the best environmental performance.

To this end, the LCA was carried out considering a cradle-to-gate approach as the use and end-of-life phases were both left out of the scope.

The functional unit (FU) is a key point of the comparative LCA since it defines the equivalence for the quantification of inputs and outputs. Therefore, to compare different systems – materials in this case –, it was necessary for those systems to perform the same function (Cooper, 2003). In this study, two FUs were considered and assessed.

The first functional unit considered (FU1 hereafter) was defined as the panel necessary to cover 1 m^2 of a ventilated façade – only the facing plates/tiles, no auxiliary elements such as joints or structures were considered. For the TTW-4L and FTW-4L materials, the FU1 was determined experimentally, dividing the weight of the specimens by the product of their length and width (area), which were measured with a calliper, in order to determine a mass per unit area ratio. For the database materials (i.e., fibre cement facing tiles, ceramic tiles and natural stone plates), the mass (*m*) required to provide an equivalent covering performance was calculated according to Eq. (1).

$$m = (b \cdot l \cdot h) \cdot \rho \quad (1)$$

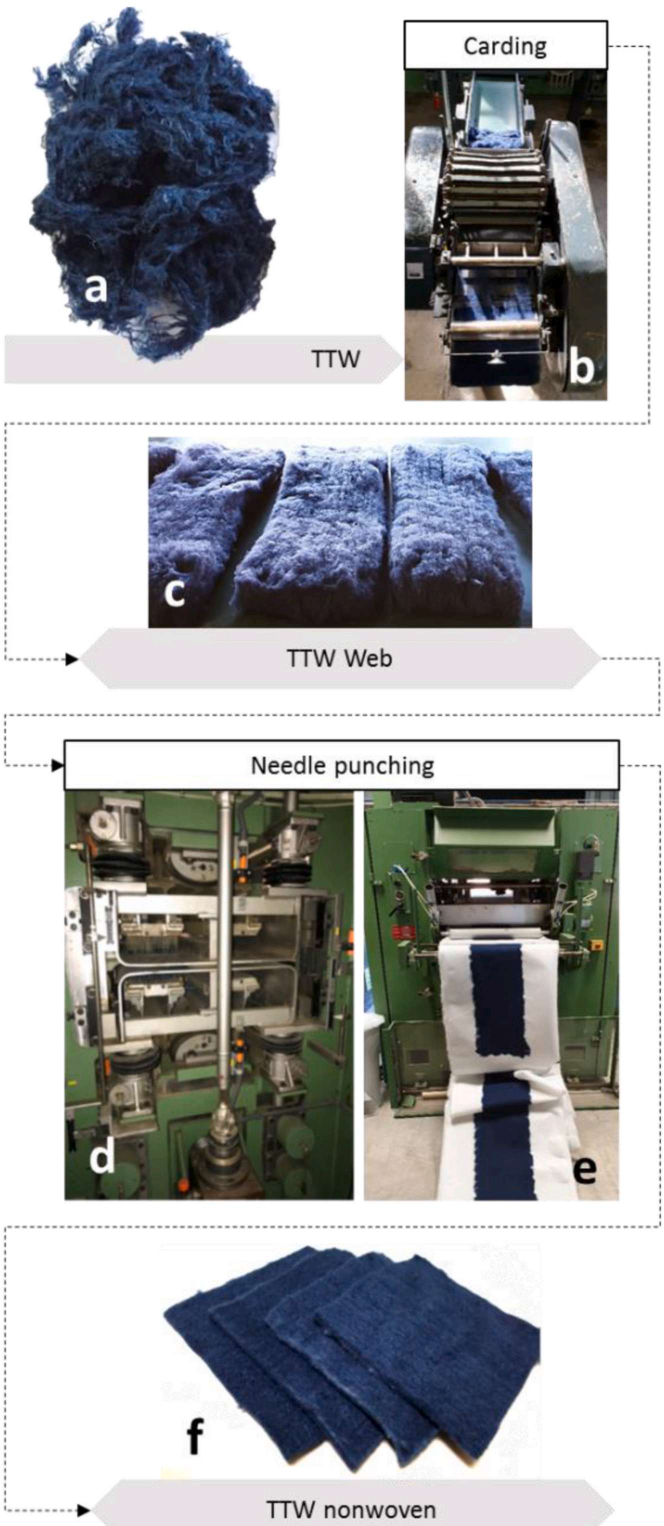


Fig. 2. Process for the production of NW fabrics.

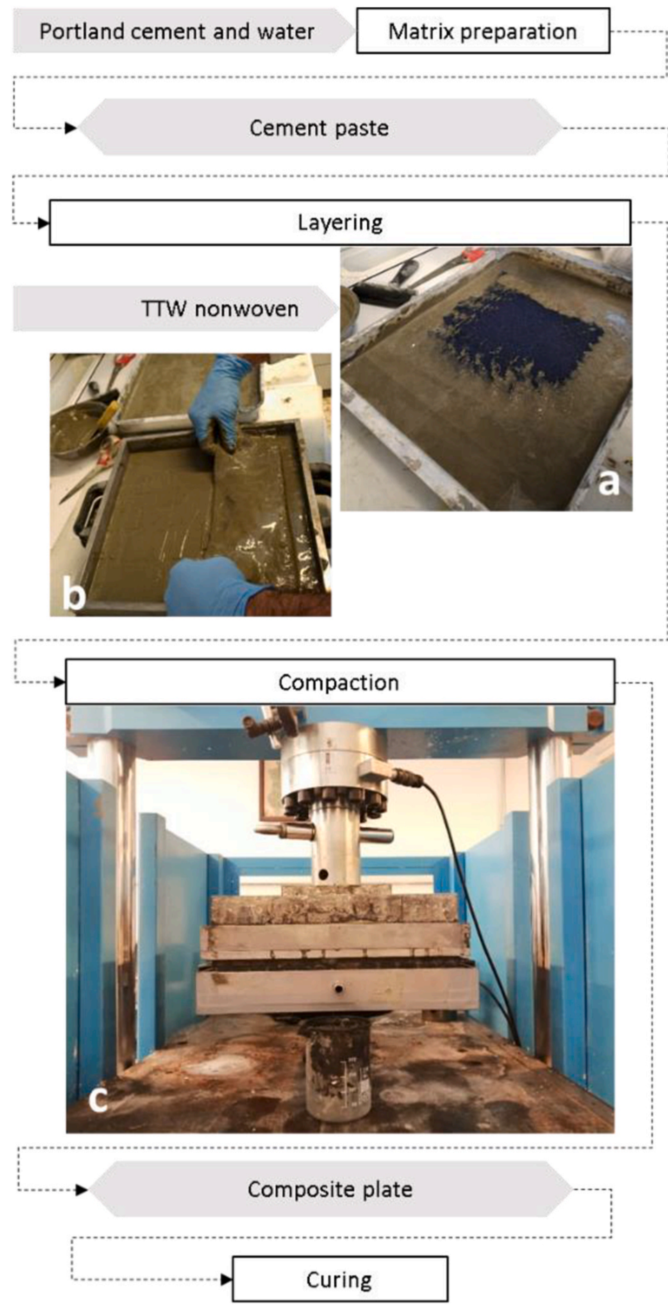


Fig. 3. Process for the production of the cement composite plates.

where ρ is the density, and the volume is calculated as the product of the width ($b = 1$ m), length ($l = 1$m) and thickness (h) of the plate or tile.

Therefore, FU1 allowed for the comparison, from the environmental point of view, of conventional solutions – both traditional and engineered materials – that are already available in the market in plate formats, with the composite plates – also engineered materials – developed in this research. All these plates, despite presenting different mechanical performances (see Table 6), manage to successfully fulfil the function defined: to cover 1 m^2 of a ventilated façade.

However, it is worth mentioning that the engineered materials developed can be tailored to meet specific requirements. As such, another FU was introduced to include the mechanical needs in the defined function in order to provide a more accurate comparison between the engineered plates for this specific application. This FU2 allowed for the comparison, from the environmental point of view, of different engineered solutions with the same mechanical performance, as recommended by Cooper (2003).

This functional unit (FU2) was defined considering the mechanical needs of a ventilated façade due to the effect of wind loads, which involves the flexure strength of the composites. In this case, the fibre cement facing tiles were used as the reference engineered solution. Therefore, the developed composites (TTW-4L and FTW-4L plates) were compared only to the market-available fibre cement facing tiles. To

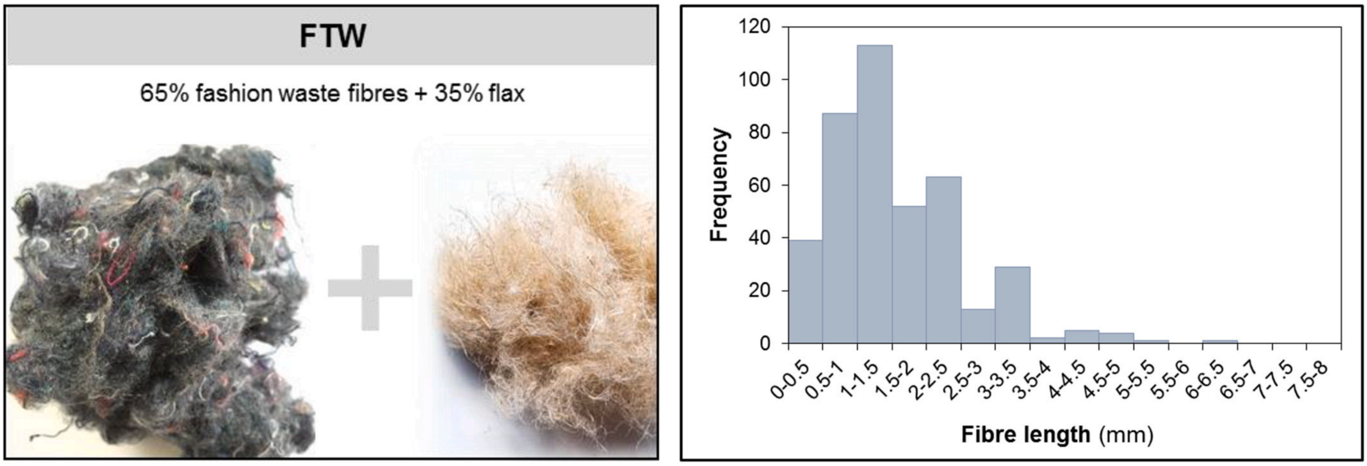


Fig. 4. Fashion textile waste and flax fibres used for the production of the FTW reinforcement (left), and histogram of the length distribution of the FTW fibres (right).

carry out the comparison, the mass equivalences were defined according to Ashby's material selection methodology. With the assumption that: a) in a ventilated façade, the plates are mainly supported by two ends; b) there is a wind force that generates a flexural load to the plates; and c) the constriction scheme can be simplified as equivalent to the one produced in the flexural test (see Fig. 5), the mass equivalences were determined as follows.

The maximum bending stress (σ) can be determined as:

$$\sigma = \frac{M}{W_{el}} \quad (2)$$

where M is the maximum moment about the neutral axis, and W_{el} is the elastic section modulus. Since the plates have a rectangular cross-section, W_{el} can be calculated as:

$$W_{el} = \frac{1}{6} \cdot b \cdot h^2 \quad (3)$$

where b is the width, and h is the thickness of the plate, in this case. Those geometrical parameters are related to the mass (m) and density (ρ) as described in Eq. (1). Combining Eq. (2) and Eq. (3), and substituting h according to Eq. (1), the moment M can be calculated as:

$$M = \sigma \cdot \frac{1}{6} \cdot b \cdot h^2 = \sigma \cdot \frac{1}{6} \cdot b \cdot \left(\frac{m}{b \cdot l \cdot \rho}\right)^2 \quad (4)$$

It is subsequently possible to determine the mass equivalent of a material (m_i) by comparing it to another material considered as a base (with a mass m_b), given equal conditions of load – same M – and plate size (i.e., same b and l):

$$\frac{\sigma_i \cdot m_i^2}{\rho_i^2} = \frac{\sigma_b \cdot m_b^2}{\rho_b^2} \quad (5)$$

which can also be expressed as:

$$m_i = m_b \frac{\rho_i \sqrt{\sigma_b}}{\rho_b \sqrt{\sigma_i}} \quad (6)$$

where the maximum bending stress of the TTW and FTW composites (σ_i) and of the fibre cement facing tiles (σ_b) are the MOR values. The mass equivalent described in this equation is in agreement with the one defined in (Cooper, 2003) for bent beams of a specified load, length and width.

Therefore, to summarise, two functional units were used: FU1, defined as the "panel necessary to cover 1 m^2 of a ventilated façade" – without taking into account any mechanical need –; and FU2, defined as the "panel necessary to cover 1 m^2 of a ventilated façade providing the same maximum bending stress as commercial fibre cement facing tiles". In the latter case – where the fibre cement tiles are used as a reference for the engineered solution –, in order to evaluate if a variation in the bending properties of the reference material implies significant environmental differences, two bending stress values were considered: a lower limit of 17 MPa and an upper limit of 24 MPa. These two limits correspond to the bending stress value range for fibre cement facing tiles (Euronit, 2009).

As previously mentioned, the LCA considered a cradle-to-gate approach. Two main phases can be differentiated in the production system for the composite plates under study: a first phase for the production of the NW fabric reinforcement, and a second phase for the production of the plates.

Fig. 6 shows the system boundaries. The solid waste and dust/air emissions caused by shredding, carding and needle punching were considered negligible with respect to the whole process (Euronit, 2009) since they accounted for less than around 1% of the total input mass. The textile wastes used (i.e., fashion textile wastes or FTW and technical textile wastes or TTW) are considered as a co-product of previous systems with a negative market value for the end-of-life product (i.e., a waste treatment fee is to be paid). A cut-off allocation was applied and, therefore, no manufacture or EOL burdens from previous systems were taken into account. The cut-off method argues that each product should only be assigned environmental impacts directly caused by that product. For this reason, it was considered that the burdens carried by textile wastes were only those associated with the necessary processes to transform them into recycled fibres first, and nonwoven fabrics later. No

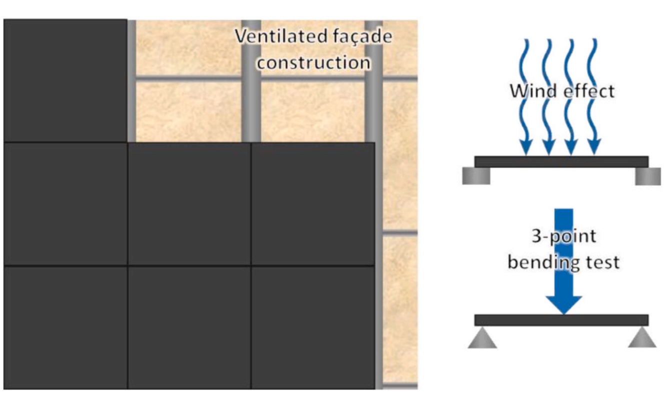


Fig. 5. Scheme of the mechanical constraints of the composite plates installed in a ventilated façade by the action of the wind.

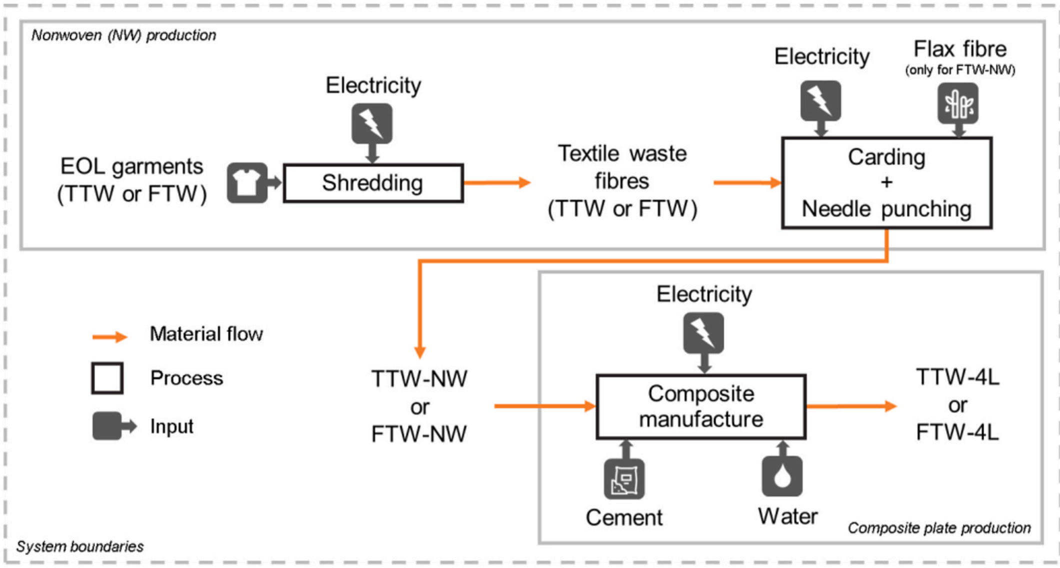


Fig. 6. System boundaries.

recycling credit is accounted for in the cut-off approach, even though recycling could lead to a lower impact due to a reduced consumption of primary materials.

The electricity required to power the shredding and nonwoven fabric processing machinery and the flax fibre raw materials required for the production of the FTW were taken into account as system inputs.

2.2.2. *Data source and quality*

The background Life-Cycle Inventory data for *electricity*, *water*, *flax fibre*, *fibre cement facing tile*, *natural stone plates* and *ceramic tiles* were taken from the Ecoinvent v 3.6 database (Ecoinvent, 2019). Table 1 shows the selected Ecoinvent processes.

For the manufacturing of the composite plates, the Ecoinvent's *fibre cement facing tiles* data were used as a reference and modified (see Table 2) in order to simulate an industrial production of the TTW-4L and FTW-4L composite plates.

2.2.3. *Selected impact assessment method*

The selected method to assess and compare the different materials for façade covering was the ReCiPe 2016 v1.1 midpoint approach, Hierarchist version, excluding infrastructure processes and long-term emissions. The ReCiPe 2016 approach was developed in a collaboration between the Dutch National Institute for Public Health and the Environment (RIVM), Radboud University Nijmegen, the Norwegian University of Science and Technology, and PRé. The method considers the following impact categories: Global warming, Stratospheric ozone depletion, Ionizing radiation, Ozone formation-Human health, Fine particulate matter formation, Ozone formation-Terrestrial ecosystems, Terrestrial acidification, Freshwater eutrophication, Marine eutrophication, Terrestrial ecotoxicity, Freshwater ecotoxicity, Marine ecotoxicity, Human carcinogenic toxicity, Human non-carcinogenic toxicity, Land use, Mineral resource scarcity, Fossil resource scarcity and Water consumption.

The ReCiPe midpoint assessment method is a widely used assessment method in the construction sector (Poranek et al., 2022; Dias et al., 2022) and, according to Pimentel et al. (Tinoco et al., 2022), the most common life-cycle impact assessment (LCIA) method used.

Table 1
Background data.

INPUT	ECOINVENT PROCESS
WATER	Included in "Fibre cement facing tile, small format (RoW)[a] production"
ELECTRICITY	Electricity, medium voltage (ES)[a] market
FLAX FIBRE	Fibre, flax (GLO)[a] market for fibre, flax
FIBRE CEMENT FACING TILE	Fibre cement facing tile, small format (RoW)[a] production
NATURAL STONE PLATES	Natural stone plate, cut (RoW)[a] production
CERAMIC TILES	Ceramic tile (RoW)[a] production

[a] The acronyms ES, RoW and GLO refer to the geography represented in the Ecoinvent data set (ES: Spain, GLO: Global, and RoW: Rest of the World).

Table 2
Modifications made to the Ecoinvent's *fibre cement facing tiles* data for the simulation of the manufacturing of composite plates.

INPUT	MODIFICATION	JUSTIFICATION
VYNIL ACETATE	Excluded	Raw material not used in the production of TTW nor FTW composite plates
SULFATE PULP	Excluded	Raw material not used in the production of TTW nor FTW composite plates
LIME	Excluded	Raw material not used in the production of TTW nor FTW composite plates
PORTLAND CEMENT	Modified amount	Input corrected to the required amount in each case

3. Results and discussion

3.1. *Part I: characterisation results of the composite plates*

3.1.1. *Mechanical performance of the TTW composite plates*

The typical bending curves of the TTW composite plates before (TTW-4L) and after ageing (TTW-4L/A) are shown in Fig. 7. The values of the bending modulus of elasticity (MOE), the limit of proportionality (LOP), the modulus of rupture (MOR) and the specific fracture energy – both before and after ageing – are summarised in Table 3.

As shown, the composites presented multiple-cracking behaviours before the complete rupture of the specimens. Regarding the unaged composite behaviour (TTW-4L plates), the MOE value of ~3.46 GPa is in agreement with previous results (Claramunt et al., 2016). The appearance of the first crack allowed for the identification of the LOP value, which is ~10.7 MPa. The low stress drop after the LOP points to the good effectiveness of the reinforcement with a good fibre-matrix adhesion (Toledo Filho et al., 2009). After the stabilisation of the first crack, the curve revealed a flexural hardening behaviour until reaching the MOR

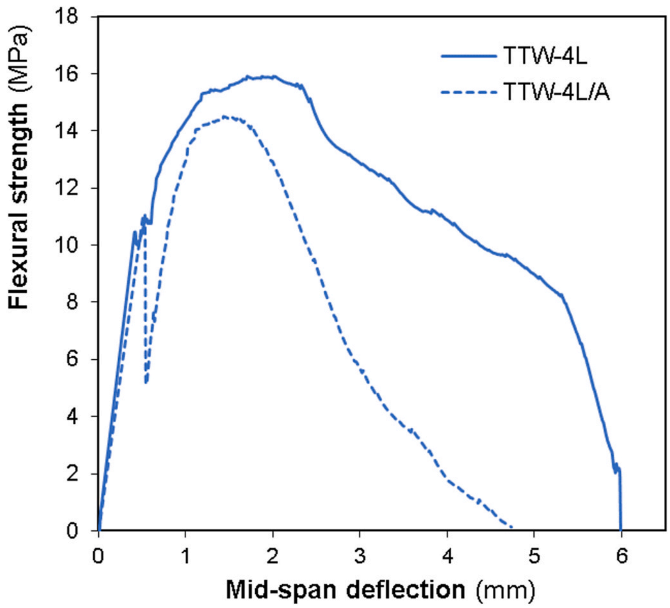


Fig. 7. Representative flexural strength vs mid-span deflection curves of the TTW plates before (TTW-4L) and after (TTW-4L/A) ageing.

Table 3
Results for the mechanical characterisation of the TTW plates.

SAMPLE	TTW-4L **(BEFORE AGEING)**	TTW-4L/A **(AFTER AGEING)**
MOE **(GPA)**	3.46 ± 0.71	2.41 ± 0.58
LOP **(MPA)**	10.7 ± 1.1	12.0 ± 2.7
MOR **(MPA)**	15.4 ± 1.4	15.3 ± 2.4
SPECIFIC FRACTURE ENERGY **(KJ/M^2)**	3.5 ± 0.3	2.7 ± 1.1

value (~15 MPa). This value is in the range of those obtained in composites with similar reinforcements and is generally higher than for other composites reinforced with short disperse fibres (see Table 4). The maximum strength of the material was found to be 31% above the LOP value. This is crucial considering the application of the material for façade panels since the plates of the ventilated façade would reveal damage before reaching dangerous loads, increasing the safety factor of the material. Once the MOR was reached, the specimens decreased their strength progressively until the moment of total rupture, absorbing a large amount of energy as a consequence of the effect of the fabric reinforcement. In this sense, the specific fracture energy (~3.5 kJ/mm^2) was higher than the typical values obtained with short disperse fibre reinforcements (see pulp reinforcements in Table 4) (Savastano et al., 2001, 2003; Tonoli et al., 2009; Coutts and Ni, 1995; Xie et al., 2015), although was also smaller than the values for oriented longer fibre reinforcements (nonwoven fabric reinforcement mixing waste fibres and flax, Table 4) (Sadrolodabaee et al., 2021b; Li et al., 2007).

Regarding the behaviour of the material after ageing (TTW-4L/A), the slight variation in MOE and LOP values – properties mainly governed by the matrix behaviour in cement composites – is considered not significant given the corresponding standard deviations. The slight increase in the average value of the LOP can be attributed to a higher hydration of the matrix during the ageing process. The MOR values remained practically constant, revealing good durability with ageing in terms of strength. However, the specific fracture energy decreased 23% with respect to the unaged sample TTW-4L, indicating a decrease in the toughness of the material after ageing. As can be observed in Fig. 7, after the MOR, the aged sample TTW-4L/A revealed a severe decrease in strength, while the unaged TTW-4L presented a less severe decrease. This, in addition to the sudden drop that followed the LOP value for the aged sample, notes a decrease in fibre-matrix adhesion caused by the ageing process.

However, the TTW-NW fabric reinforcement – mainly made of aramid fibres – was found to be an effective reinforcement with a fair overall durability regarding accelerated ageing.

3.1.2. Comparison with other textile-waste reinforced composite plates

In Fig. 8, the mechanical parameters obtained from the bending tests of the TTW composites are compared to those known for the equivalent material reinforced with 4-layers of FTW-NW fabric reinforcement determined in previous studies of the group (Sadrolodabaee et al., 2021b).

As can be observed, the TTW composites presented higher LOP and higher MOR values, but lower MOE values and less fracture energy than the FTW composites. The differences in behaviour can be mainly attributed to differences in the reinforcement. In Table 5, the properties of the reinforcing fabrics are compared, showing large differences in both the tensile strength and the elongation of the reinforcements.

On the one hand, the aramid fibres used in the reinforcement of the TTW composite have a higher breaking force than the polyester and cotton fibres used for the FTW composite reinforcement fabric. This would have led to a higher MOR and LOP of the TTW composites. On the

Table 4
ComparativeComparison of MOE, MOR, LOP and specific fracture energy values of the different fibre-reinforced cementitious composites (BSF means blast furnace slag).

MATRIX	*FIBRE*	*REINFORCEMENT TYPE*	*REF.*	MOE **(GPA)**	MOR **(MPA)**	LOP **(MPA)**	SPECIFIC FRACTURE ENERGY **(KJ/M^2)**
PORTLAND CEMENT	technical textile waste	nonwoven	–	3.46	15.4	10.7	3.5
PORTLAND CEMENT, METAKAOLIN, SILICA FUME	flax	nonwoven	Claramunt et al. (2016)	~3.3–4.3	~4.5–12.5	~2–5.5	~0.06–0.13
PORTLAND CEMENT	textile waste flax	nonwoven	Sadrolodabaee et al. (2021b)	6.8–11.4	8.1–19.8	3.6–7.6	3.9–12.0
MORTAR	coir	nonwoven	Li et al. (2007)	–	5.17–7.72	4.96–5.34	0.51–13.42
UNSPECIFIED	various reviewed	unspecified	Vo and Navard (2016)	22	2.78–12	–	–
PORTLAND CEMENT OR BFS, GYPSUM, LIME	sisal, banana, *Eucalyptus*	pulp	Savastano et al. (2003)	~3–11	~10.6–21.5	–	0.6–1.7
PORTLAND CEMENT OR BFS, GYPSUM, LIME	softwood, sisal agro-waste	pulp	Savastano et al. (2001)	~4.3–7.8	~14.7–24.5	–	~1.1–2.3
PORTLAND CEMENT, GROUND CARBONATE	*Eucalyptus*	pulp	Tonoli et al. (2009)	13.3–18.6	7.5–12.1	6.3–7.8	0.13–0.86
PORTLAND CEMENT, SILICA	bamboo	pulp	Coutts and Ni (1995)	–	~12.1–22	–	~0.08–1.2
PORTLAND CEMENT	rice straw, bamboo	pulp	Xie et al. (2015)	–	~8–13	–	~0.1–3

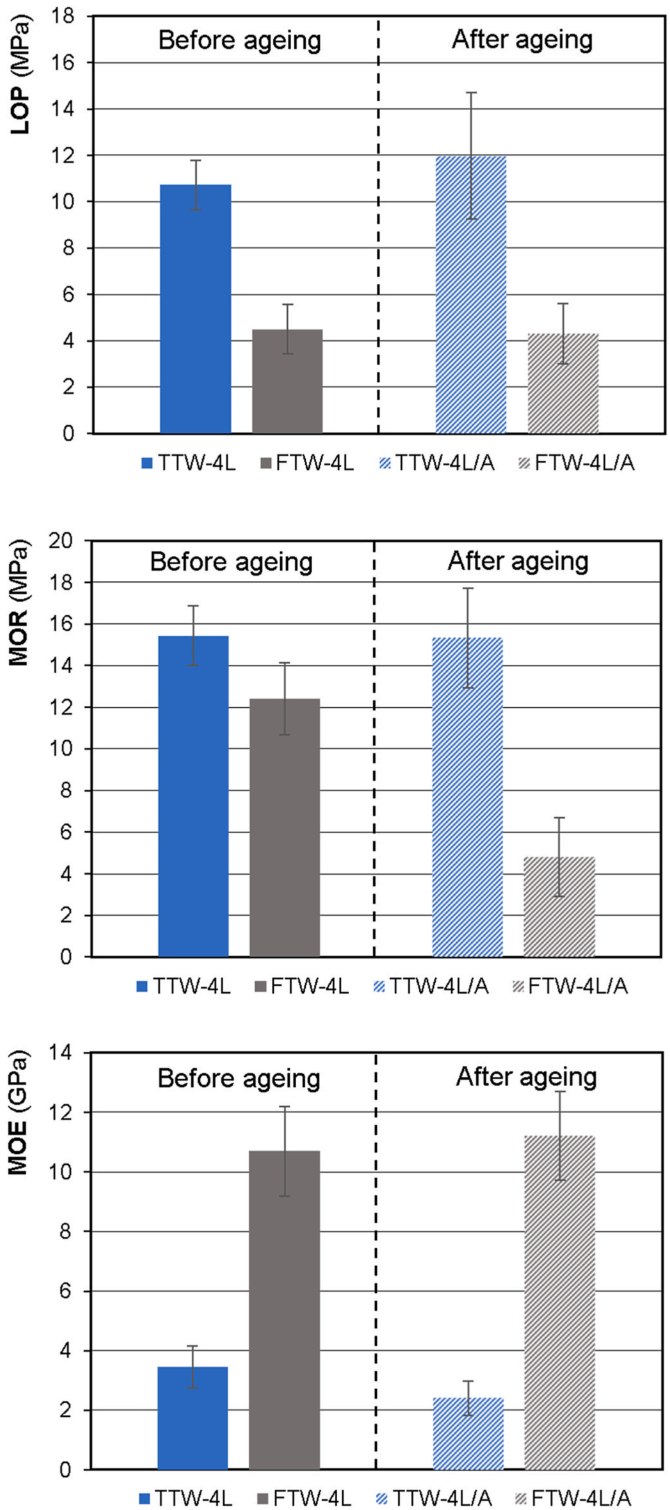


Fig. 8. Comparison of LOP, MOR and MOE values for the TTW composites presented in this work, and the FTW values from (Sadrolodabaee et al., 2021b).

other hand, the incorporation of considerably longer fibres (flax) into the reinforcement of the FTW composite could have led to a higher fracture energy for those composites.

Moreover, the ageing produced a negligible decrease in the MOR for the TTW composites, while led to a decrease of around 10% for the FTW composites (Fig. 8). These differences can be attributed to the performance of the reinforcement due to the very nature of the raw materials; TTW reinforcement mainly based on aramid fibres can provide a better

Table 5
Characterisation results for the nonwoven fabrics used as reinforcements.

SAMPLE	REINFORCEMENT FABRIC FROM TTW	REINFORCEMENT FABRIC FROM FTW
AREAL WEIGHT (G/M^2)	~150	~165
THICKNESS (MM)	2.0 ± 0.2	2.3 ± 0.1
MOISTURE ABSORPTION (%)	5.5 ± 0.5	6.4 ± 0.3
TENSILE STRENGTH (N)		
MACHINE DIRECTION	58.6 ± 15.2	4.0 ± 0.6
CROSS DIRECTION	15.6 ± 2.5	n.a.
ELONGATION (%)		
MACHINE DIRECTION	49 ± 6	20 ± 4
CROSS DIRECTION	147 ± 14	n.a.

chemical resistance than the FTW mainly based on polyester and cellulosic fibres.

From these results, it can be concluded that the TTW composites developed in this study present a better performance in terms of mechanical performance and durability than the FTW composites.

3.2. Part II: life-cycle assessment of facing materials for ventilated façades

3.2.1. Functional unit calculation

As previously mentioned, the "panel necessary to cover 1 m^2 of a ventilated façade" (FU1) was determined by means of Eq. (1) for the typical materials (i.e., ceramic tiles, natural stone plates, fibre cement facing tiles), and experimentally for the new engineered materials (FTW-4L and TTW-4L). Moreover, for TTW-4L and FTW-4L, the "panel necessary to cover1 m^2 of a ventilated façade providing the same maximum bending stress as commercial fibre cement facing tiles" – with a lower limit of 17 MPa ($FU2_{min}$) and an upper limit of 24 MPa ($FU2_{max}$) – was calculated using Eq. (6). The parameters used and mass equivalences obtained are summarised in Table 6.

3.2.2. Life-cycle inventory

The Life-Cycle Inventory (LCI) is the LCA step in which the data was collected and the calculations to quantify the inputs and outputs were done. Table 6 shows the LCI flows for the new materials under study (i.e., TTW-4L and FTW-4L) and each of the FU considered.

With regard to this LCI data (Table 7), the following considerations apply: i) all the data were obtained from a lab scale production of composite plates; ii) the LCI background data for the electricity and flax

Table 6
Density, thickness, and FU1 and FU2 values.

MATERIAL	*DENSITY* (G/CM^3)	*TYPICAL THICKNESS* (MM)	***FU1*** *M. EQ.* (KG)	***$FU2_{MAX}$ M. EQ.* (KG)**[b]	***$FU2_{MIN}$*** *M. EQ.* (KG)[c]
CERAMIC TILE	1.76	18.0	31.7	–	–
NATURAL STONE PLATE	2.75	30.0	82.5	–	–
FIBRE CEMENT FACING TILE	1.90	10.0	19.0	19.0	19.0
FTW-4L PLATE	1.81[a]	9.4[a]	17.0	25.2	21.2
TTW-4L PLATE	1.77[a]	10.4[a]	18.2	22.1	18.6

[a] Orientative data provided. Please note that the mass per square metre of these materials was determined experimentally.
[b] $FU2_{max}$ corresponds to the *upper limit*, in which $\sigma_b = 24$ MPa.
[c] $FU2_{min}$ corresponds to the *lower limit*, in which $\sigma_b = 17$ MPa.

Table 7
LCI for TTW-4L and FTW-4L.

Input/output	Unit	FTW-4L			TTW-4L		
		FU1	$FU2_{min}$	$FU2_{max}$	FU1	$FU2_{min}$	$FU2_{max}$
		1 m^2	1 m^2, 17 MPa	1 m^2, 24 MPa	1 m^2	1 m^2, 17 MPa	1 m^2, 24 MPa
Nonwoven fabric production							
Textile waste	kg	0.33	0.41	0.49	0.40	0.41	0.48
Flax fibre	kg	0.18	0.22	0.26	none	none	none
Electricity for shredding	kWh	0.09	0.11	0.13	0.10	0.11	0.13
Electricity for carding and needle punching	kWh	0.41	0.51	0.60	0.54	0.55	0.65
Composite plate production							
Cement	kg	16.5	20.5	24.4	17.8	18.2	21.6

fibre came from the Ecoinvent V 3.6 database (see Table 1); iii) the LCI background data for cement came from the Ecoinvent data on modified fibre cement facing tiles, as showed in Table 2, in order to simulate the industrial production of the developed TTW-4L and FTW-4L composite plates; iv) the electricity consumed (kWh) for shredding (E_S), and for carding and needle punching (E_{CNP}) was calculated according to Eq. (7) and Eq. (8), respectively.

$$E_S = \frac{P_S}{r_S} * TW \quad 7$$

where P_S is the shredding machine power (9.4 kW), r_S corresponds to the shredding rate (estimated as 36 kg/h), and TW refers to the amount of textile waste to be shredded for the given functional unit (in kg).

$$E_{CNP} = \frac{P_{CNP}}{r_{CNP} * W} * TWs \quad 8$$

where P_{CNP} is the machine power of the card and needle punching loom (29.8 kW), r_{CNP} is the carding and needle punching rate (estimated as 147 m^2/h), w corresponds to the nonwoven fabric weight (0.150 kg TTW-NW/m^2 and 0.165 kg FTW-NW/m^2), and TWs is the amount of textile waste processed for the given functional unit (kg). The mass losses between the shredding and the carding and needle punching processes were considered to be negligible (i.e., TW = TWs).

3.2.3. Life-cycle impact assessment

To translate the inputs and outputs of the elementary flows reported in the inventory into environmental impact indicators, the SimaPro 9.1.0.11 software was used, following the ReCiPe 2016 v1.1 midpoint approach.

The FU1 – set as "plate needed to cover 1 m^2 of a ventilated façade" – was used to compare the composite materials developed (i.e., TTW-4L and FTW-4L composite plates) with other traditional and engineered solutions available on the market that are typically used as façade cladding (i.e., ceramic tiles, natural stone plates and fibre cement facing tiles). A second functional unit (FU2) that considers both the covering and the mechanical requirements was used for a more comprehensive comparison of the LCA of all the engineered materials (i.e., the fibre cement tiles and composite plates developed).

Fig. 9 shows the environmental impact (in relative values) for all the materials studied, taking the FU1 as the reference functional unit. In this figure, 100% of each impact category was allocated to the material with the highest value while the percentages for the other samples were calculated in relation to the highest one.

The results of the analysis reveal a significant difference in the environmental performance of the traditional materials (i.e., natural

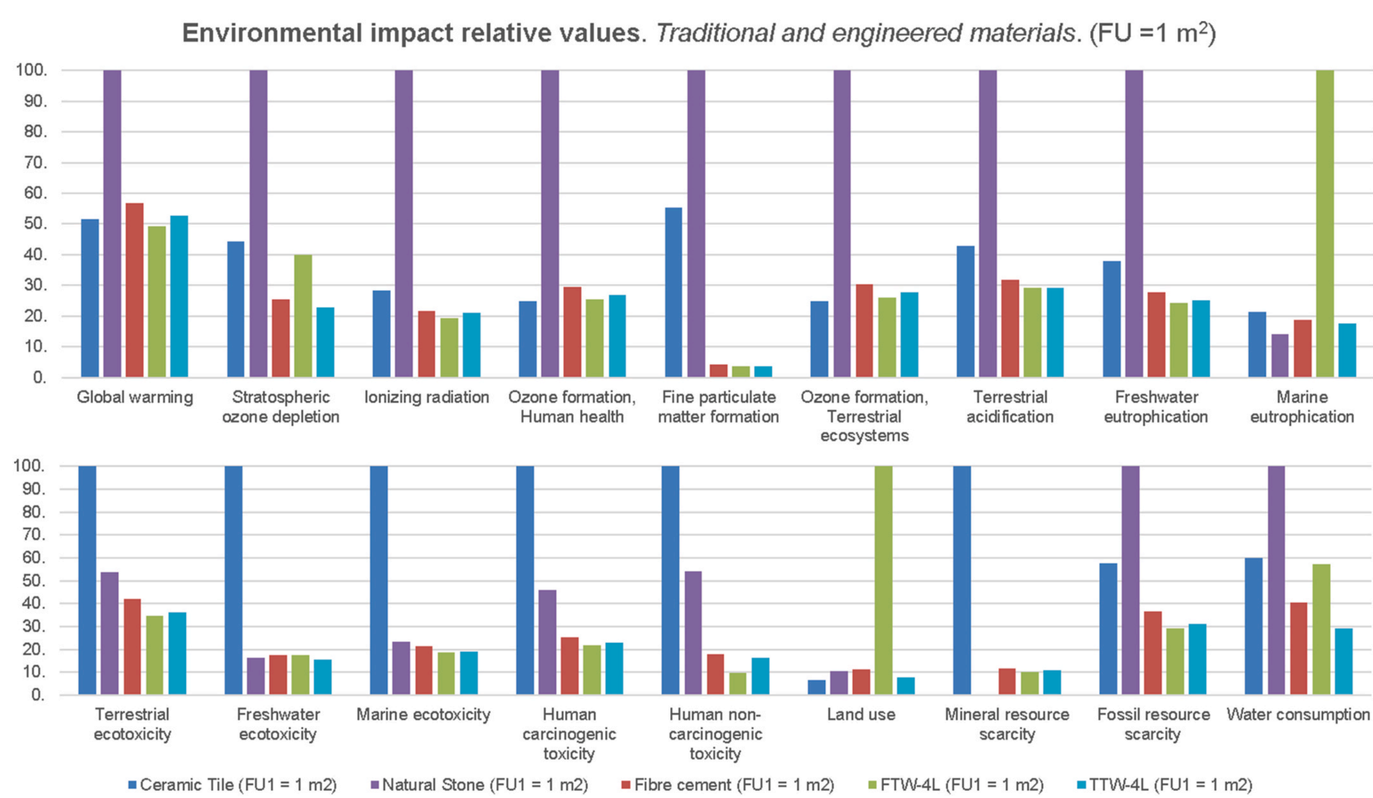


Fig. 9. Environmental impact. Traditional and Engineered materials. FU1 = 1 m^2.

stones and ceramic tiles) and the engineered ones (i.e., fibre cement facing tiles and the FTW-4L and TTW-4L composite plates), with the traditional ones having a higher environmental impact than the engineered ones for most of the impact categories considered.

In fact, natural stone is the material which contributes the most to: *Global warming*, *Stratospheric ozone depletion*, *Ionizing radiation*, *Ozone formation* (*human health* and *terrestrial ecosystems*), *Fine particulate matter formation*, *Terrestrial acidification*, *Freshwater eutrophication*, *Fossil resource scarcity*, and *Water consumption*. In this case, a thorough analysis revealed that this was mainly due to the energy consumption necessary for its manufacturing, and the manufacturing itself. Moreover, ceramic tile is the material which contributes the most to *Terrestrial ecotoxicity*, *Freshwater* and *Marine ecotoxicity*, and *Human carcinogenic* and *non-carcinogenic toxicity*, with this mainly being due to the consumption of titanium dioxide and the respective raw materials and water required to produce this dioxide.

Therefore, traditional materials were found to lead in 16 of the 18 impact categories analysed. Only the *Land use* and *Marine eutrophication* impact categories noted a great contribution of FTW-4L. In this regard, when inspecting the result of the modelling process, this fact was observed to be related mainly to the flax fibre content (see Fig. 11), with the impacts being derived from its crop and contributing to the impact categories with 84% for *Marine eutrophication* and 93% for *Land use*. However, for the rest of the categories, only slight differences were observed between the three engineered materials.

For a further analysis, the engineered materials were also assessed by taking the FU2 as the reference functional unit – which considers both the covering and mechanical requirements –, and comparing their equivalent masses to achieve an equal maximum bending stress (17 MPa for $FU2_{min}$ and 24 MPa for $FU2_{max}$). The results of the environmental impact (in relative values) are presented in Fig. 10. From this analysis, it can be observed that, for a certain maximum stress level – regardless if it is the minimum or the maximum -, FTW-4L has a higher impact than TTW-4L in all the impact categories except the *Human non-carcinogenic toxicity* category, which notes the influence of the use of flax fibres in the reinforcing structures in terms of the environmental impact of the composites – see the difference between FTW-4L and TTW-4L in Table S11 of the supplementary data. The uncertainty analysis through Monte Carlo simulation shows statistically significant differences between FTW-4L and TTW-4L for a certain maximum stress – see Figs. S3 and S4 in the supplementary data. Therefore, a further strategy to consider in the development of such materials would be the search for alternative materials with a lower impact to substitute the flax content. For instance, the repurposing of agro-wastes obtained as by-products from food crops could be an interesting option to be evaluated.

Moreover, in terms of the relative contribution of each process, it can be noted in Fig. 11 that the composite production – mainly attributed to cement as a raw material – is highly responsible for the environmental impact for all the categories considered – for the absolute values, see Tables S7, S8, S9 and S10 in the supplementary data. In this regard, it is worth noting that, when comparing the same material (TTW-4L or FTW-4L), the higher bending stress, the greater environmental impact – around 18–20% greater, see the difference between 24 and 17 MPa in Table S11 of the supplementary data – which are associated with a higher need of cement content, since the plates need to be thicker to withstand such a mechanical solicitation. Therefore, for a given maximum bending stress, the environmental impact of TTW-4L is lower than that of FTW-4L (Fig. 10). The uncertainty analysis through Monte Carlo simulation showed statistically significant differences between 24 and 17 MPa for a specific engineered material – see Figs. S1 and S2 in the supplementary data.

3.2.4. Uncertainty analysis

A quantitative uncertainty analysis through a Monte Carlo simulation was carried out in order to provide additional scientific information to ensure that the environmental differences observed between engineered materials were statistically significant.

For each environmental impact category, Fig. 12 shows the percentage of occurrences where the impact is greatest by comparing the two engineered materials with the fibre cement facing tiles – by pairs and for both bending stresses considered – based on the Monte Carlo parameter analysis for each impact category.

Assuming that 90–95% of the Monte Carlo runs are favourable for a material, the difference may be considered significant, and when comparing the materials developed with the fibre cement facing tiles, we can state, with 95% significance, that:

- There are no significant differences between the fibre cement facing tiles and the TTW-4L ($FU2_{min}$ = 1 m^2; 17 MPa) except in the *Stratospheric ozone depletion*, *Fine particulate matter formation*, *Terrestrial ecotoxicity*, *Human carcinogenic toxicity* and *Fossil resource scarcity* impact categories. In these impact categories, TTW-4L

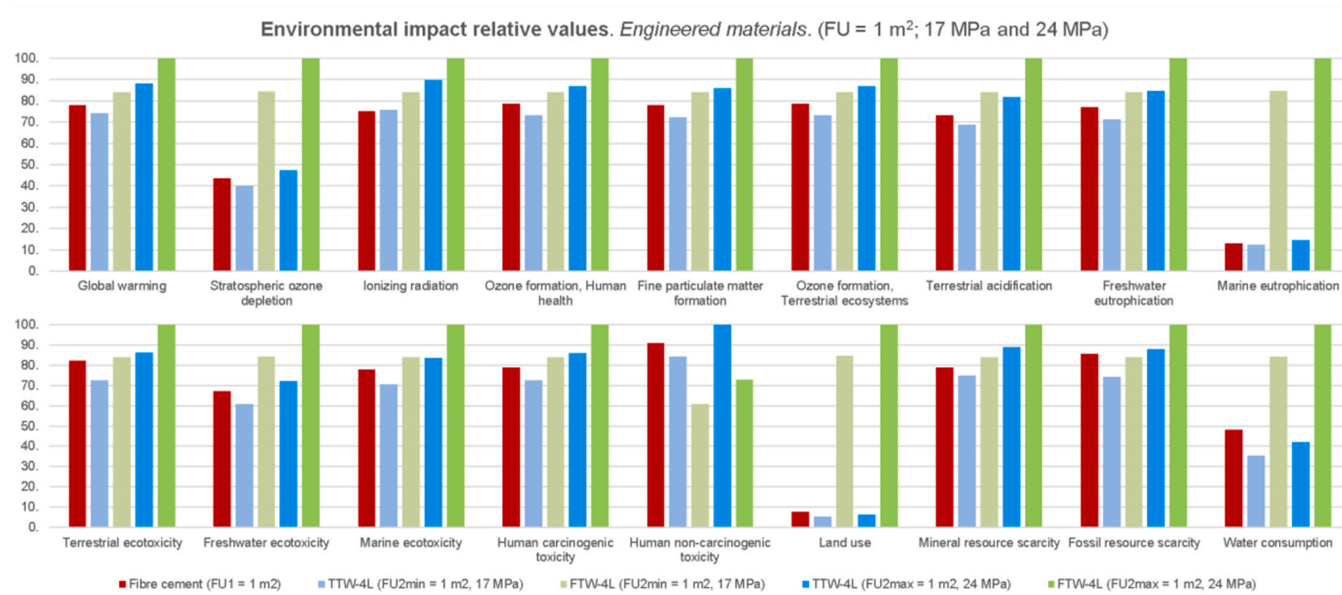


Fig. 10. Environmental impact. Engineered materials. FU2 = 1 m^2; 17 MPa ($FU2_{min}$) and 24 MPa ($FU2_{max}$).

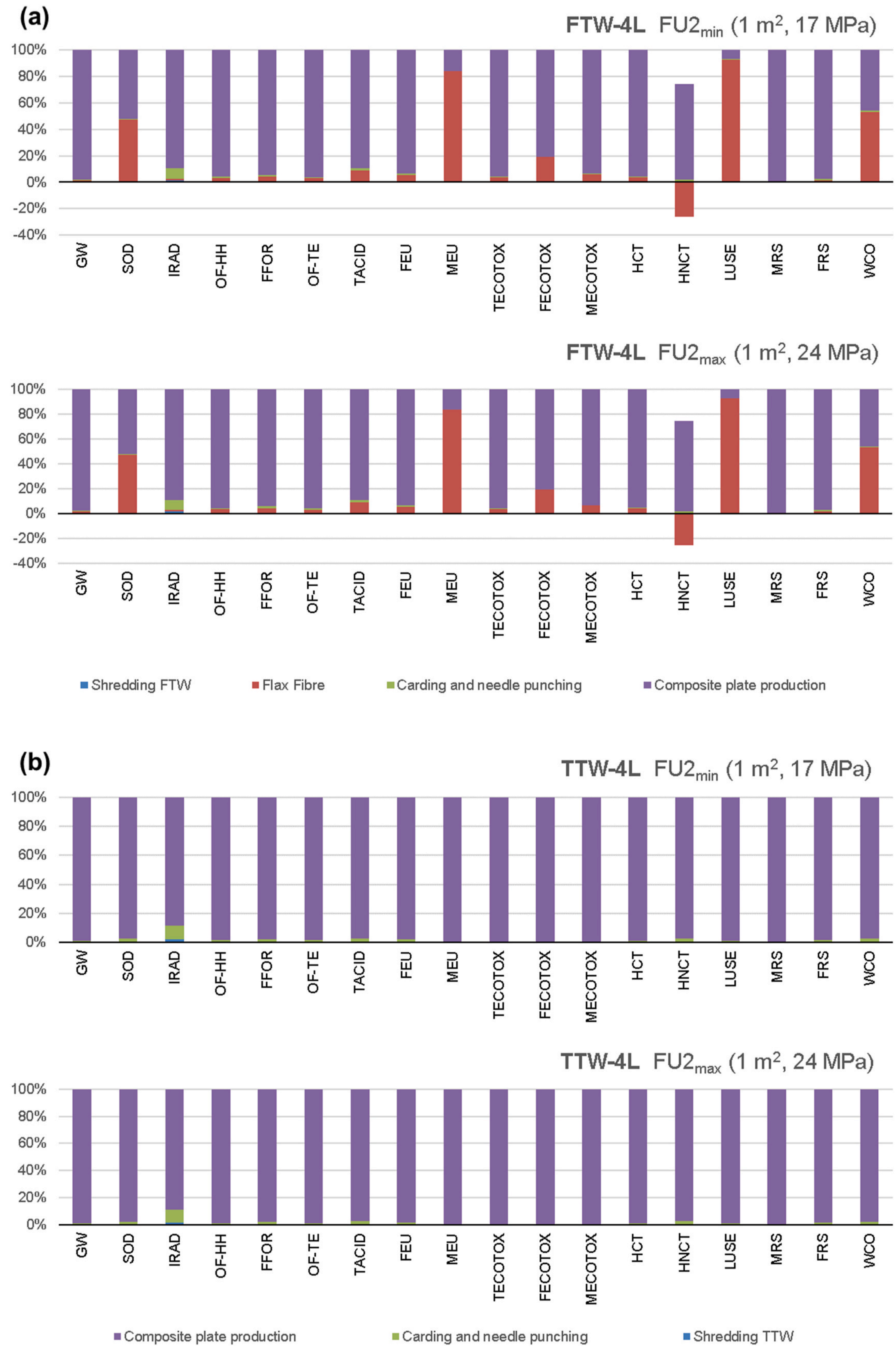


Fig. 11. Contribution of the production processes of the FTW-4L (a) and TTW-4L (b) composite plates to the environmental impact categories. GW Global Warming, SOD Stratospheric Ozone Depletion, IRAD Ionizing radiation, OF-HH Ozone Formation – Human Health, FFOR Fine Particulate Matter Formation, OF-TE Ozone Formation – Terrestrial Ecosystems, TACID Terrestrial Acidification, FE Freshwater Eutrophication, ME Marine Eutrophication, TECOTOX Terrestrial Ecotoxicity, FECOTOX Freshwater Ecotoxicity, MECOTOX Marine Ecotoxicity, HCT Human Carcinogenic Toxicity, HNCT Human Non-Carcinogenic Toxicity, LUSE Land Use, MRS Mineral Resource Scarcity, FRS Fossil Resource Scarcity, WCO Water Consumption.

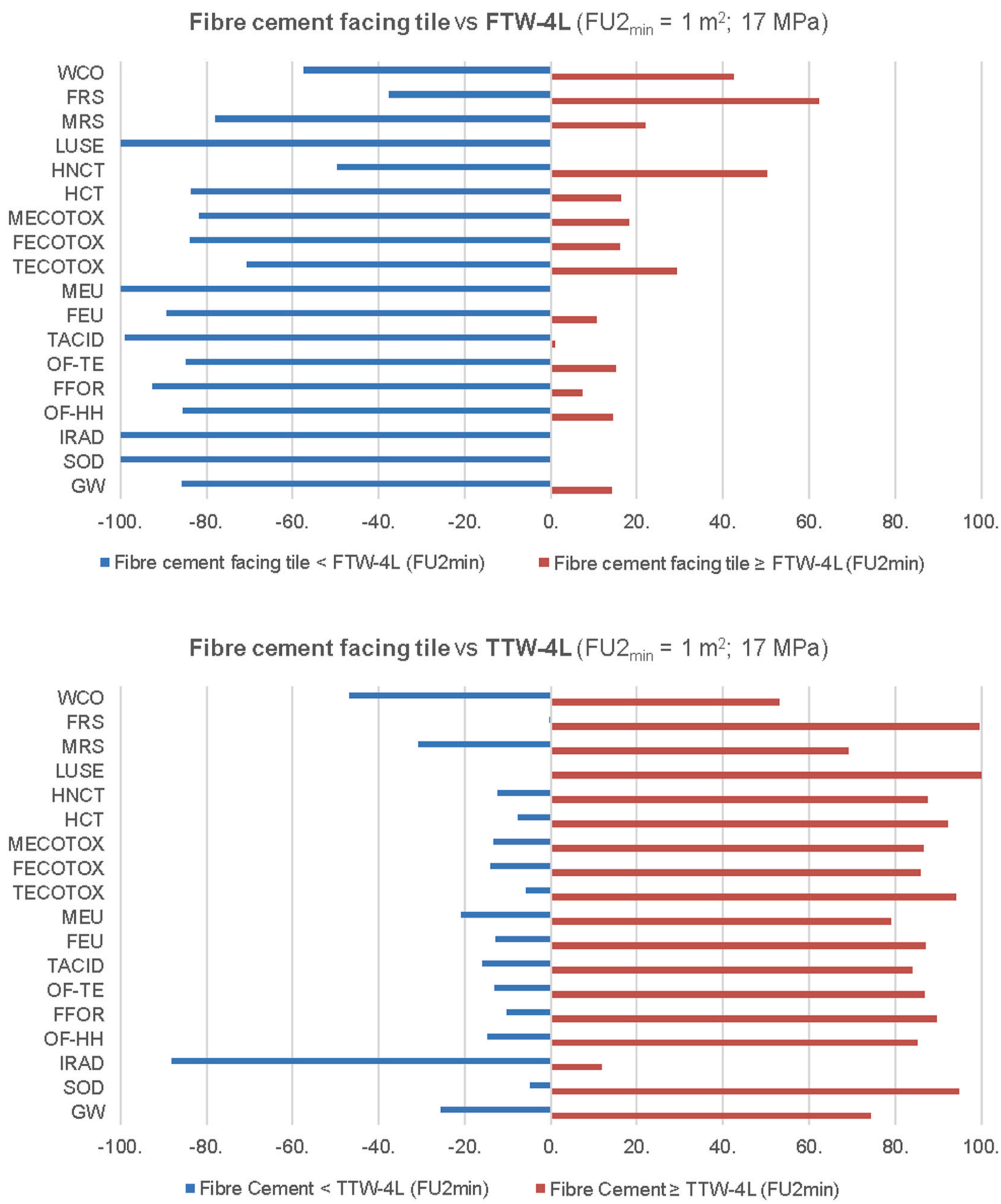
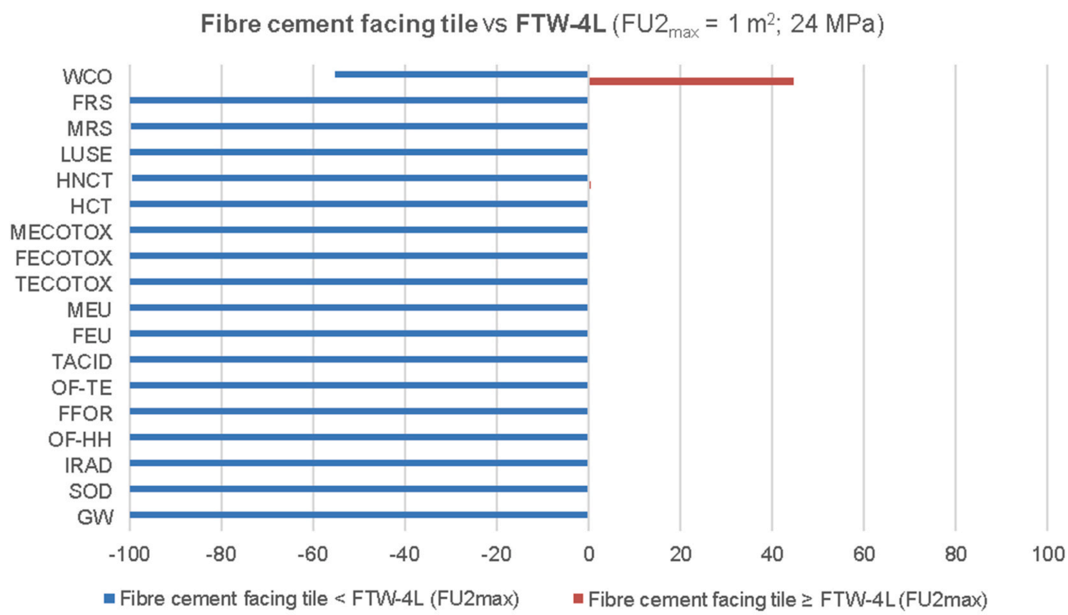


Fig. 12. Comparison between Fibre cement facing tiles and TTW-4L and FTW-4L. Monte Carlo results. (GW Global Warming, SOD Stratospheric Ozone Depletion, IRAD Ionizing radiation, OF-HH Ozone Formation – Human Health, FFOR Fine Particulate Matter Formation, OF-TE Ozone Formation – Terrestrial Ecosystems, TACID Terrestrial Acidification, FE Freshwater Eutrophication, ME Marine Eutrophication, TECOTOX Terrestrial Ecotoxicity, FECOTOX Freshwater Ecotoxicity, MECOTOX Marine Ecotoxicity, HCT Human Carcinogenic Toxicity, HNCT Human Non-Carcinogenic Toxicity, LUSE Land Use, MRS Mineral Resource Scarcity, FRS Fossil Resource Scarcity, WCO Water Consumption.

($FU2_{min} = 1\ m^2$; 17 MPa) has a better environmental performance than the fibre cement facing tiles.

- There are no significant differences between the fibre cement facing tiles and FTW-4L ($FU2_{min} = 1\ m^2$; 17 MPa) except in the *Stratospheric ozone depletion*, *Ionizing radiation*, *Terrestrial acidification*, *Marine eutrophication* and *Land use* impact categories. In these impact categories, the fibre cement facing tiles has a better environmental performance than FTW-4L ($FU2_{min} = 1\ m^2$; 17 MPa).
- There are significant differences between the fibre cement facing tiles and TTW-4L ($FU2_{max} = 1\ m^2$; 24 MPa). In this case, the fibre cement facing tiles have a better environmental performance for all the impact categories except for *Water consumption* and *Fossil resource scarcity* – with the differences not being significant – and for *Land use*, where TTW-4L ($FU2_{max} = 1\ m^2$; 24 MPa) has a better environmental performance.
- There are significant differences between the fibre cement facing tiles and FTW-4L ($FU2_{max} = 1\ m^2$; 24 MPa). In this case, the fibre cement facing tiles have a better environmental performance for all the impact categories except for *Water consumption*, despite the differences not being significant.

However, generally speaking, the results observed for the engineered materials are on a similar level, especially when comparing the FTW-4L to the fibre cement facing tiles for lower mechanical requirements. This



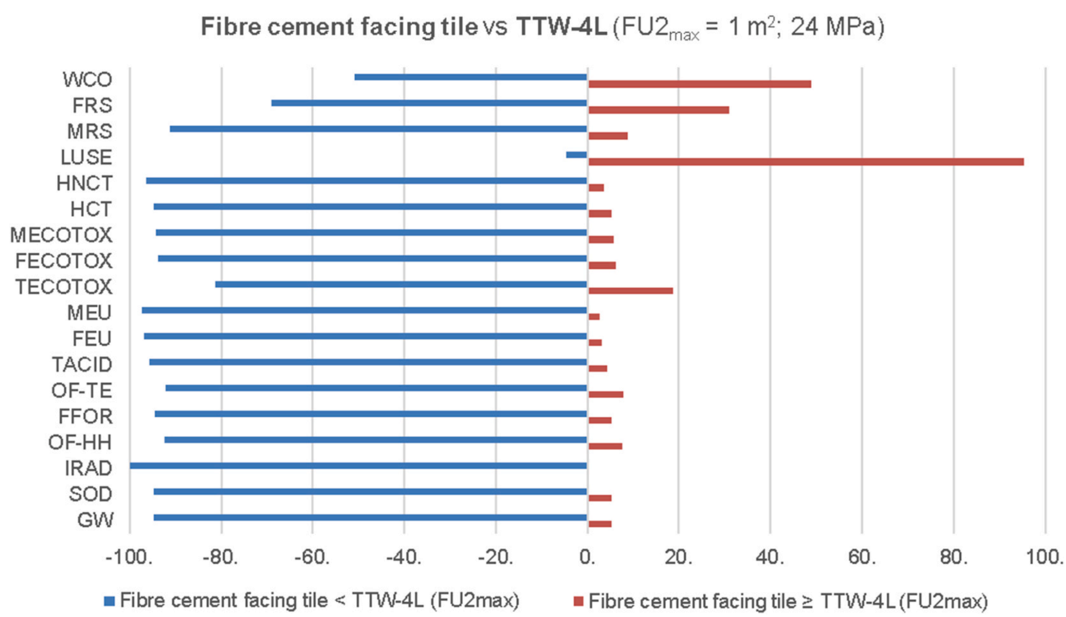


Fig. 12. (*continued*).

highlights that the materials developed have the potential to be considered as an alternative to the fibre cement facing tiles that are currently used, and that further developments for the improvement of such materials –such as the use of fibres from agro-wastes, the reduction of the cement content, or the improvement of the mechanical performance of the plates –can lead to the production of new engineered materials with a lower environmental impact than the ones currently available.

4. Conclusions

In this paper, post-consumer technical textile waste was successfully used to produce nonwoven fabric reinforcements for cement matrices. The composite plates obtained with the produced reinforcements presented a strain hardening behaviour with a high flexural strength (MOR) (~15 MPa) and toughness (~3.5 kJ/m^2) and fracture toughness. The first crack (LOP) appeared with a margin of ~30% with respect to the MOR, giving a good security factor for its use in the proposed application: high-performance plates for ventilated façades. The composite maintained the strain hardening behaviour after being subjected to wet/dry ageing, with a slight decrease in the specific fracture energy of around 23%, confirming the suitable durability of the material developed. The comparison of the composites developed (TTW) with other composite plates reinforced with other textile wastes from the fashion industry (FTW) with similar structures showed the effectiveness of the reinforcement under study.

In terms of the environmental point of view, the engineered materials (namely the composite materials of a cement matrix reinforced with fibres) present, in general terms, a significantly lower environmental impact than more traditional materials such as ceramic tiles or natural stone. Therefore, the development of such materials can lead to more sustainable solutions for the building industry.

The LCA concluded that the composite produced with the technical textile waste, TTW-4L ($FU2_{min}$ = 1 m^2; 17 MPa), is a material with a similar environmental performance to the fibre cement facing tiles. In comparison, the composite produced with the fashion textile waste, FTW-4L ($FU2_{min} = 1\ m^2$; 17 MPa), does not have such a favourable environmental performance, which is mainly attributed to the impact categories related to the flax fibres. Further development of other recycled fibres and/or fibres from agro-wastes must be considered for the development of greener materials for the building industry.

Moreover, it was found that the cement matrix is strongly connected to the environmental impact associated with these materials. In this case, the higher amount of cement required to obtain both TTW and FTW plates with a better maximum bending stress (24 MPa) has resulted in the fibre cement facing tiles material presenting a better environmental performance. Therefore, further developments and new approaches can be considered to minimise the cement content in order to improve the environmental performance of the materials developed.

CRediT authorship contribution statement

Heura Ventura: Methodology, Conceptualization, Writing – original draft, Writing – review & editing. **María Dolores Álvarez:** Methodology, Conceptualization, Formal analysis, Writing – review & editing. **Laura Gonzalez-Lopez:** Investigation. **Josep Claramunt:** Conceptualization, Methodology, Resources, Funding acquisition, Writing – review & editing, Supervision. **Monica Ardanuy:** Conceptualization, Methodology, Resources, Funding acquisition, Writing – review & editing, Supervision.

Declaration of competing interest

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Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.133652.

References

TFR1, November-December 1984. Test for the determination of modulus of rupture and limit of proportionality of thin libre reinforced cement sections. Mater. Struct. 17 (No. 102) n.d.

Abd Rashid, A.F., Yusoff, S., 2015. A review of life cycle assessment method for building industry. Renew. Sustain. Energy Rev. 45, 244–248. https://doi.org/10.1016/j.rser.2015.01.043.

Ali, B., Qureshi, L.A., Kurda, R., 2020. Environmental and economic benefits of steel, glass, and polypropylene fiber reinforced cement composite application in jointed plain concrete pavement. Compos. Commun. 22, 100437 https://doi.org/10.1016/j.coco.2020.100437.

Ardanuy, M., Claramunt, J., Toledo Filho, R.D., 2015. Cellulosic fiber reinforced cement-based composites: a review of recent research. Construct. Build. Mater. 79, 115–128. https://doi.org/10.1016/j.conbuildmat.2015.01.035.

Bartos, P.J.M., 2017. Glassfibre reinforced concrete: a review. IOP Conf. Ser. Mater. Sci. Eng. 246, 012002 https://doi.org/10.1088/1757-899X/246/1/012002.

Carcassi, O.B., Minotti, P., Habert, G., Paoletti, I., Claude, S., Pittau, F., 2022. Carbon footprint assessment of a novel bio-based composite for building insulation. Sustainability 14, 1384. https://doi.org/10.3390/su14031384.

Claramunt, J., Ardanuy, M., García-Hortal, J.A., Filho, R.D.T., 2011. The hornification of vegetable fibers to improve the durability of cement mortar composites. Cem. Concr. Compos. 33, 586–595. https://doi.org/10.1016/j.cemconcomp.2011.03.003.

Claramunt, J., Fernández-Carrasco, L.J., Ventura, H., Ardanuy, M., 2016. Natural fiber nonwoven reinforced cement composites as sustainable materials for building envelopes. Construct. Build. Mater. 115, 230–239. https://doi.org/10.1016/j.conbuildmat.2016.04.044.

Claramunt, J., Ventura, H., Fernández-Carrasco, L.J.L., Ardanuy, M., 2017. Tensile and flexural properties of cement composites reinforced with flax nonwoven fabrics. Materials 10, 215. https://doi.org/10.3390/ma10020215.

Comission, European, 2019. Energy Performance of Buildings Directive (EPBD) Factsheet. https://ec.europa.eu/energy/sites/ener/files/documents/buildings_performance_factsheet.pdf.

Cooper, J.S., 2003. Specifying functional units and reference flows for comparable alternatives. Int. J. Life Cycle Assess. 8, 337. https://doi.org/10.1007/BF02978507.

Coutts, R.S.P., Ni, Y., 1995. Autoclaved bamboo pulp fibre reinforced cement. Cem. Concr. Compos. 17, 99–106. https://doi.org/10.1016/0958-9465(94)00002-G.

Dias, J., Xavier, G., Azevedo, A., Alexandre, J., Colorado, H., Vieira, C.M., 2022. Eco-friendly ceramic bricks: a comparative study of life cycle impact methods. Environ. Sci. Pollut. Res. https://doi.org/10.1007/s11356-022-21292-w.

dos Santos, G.Z.B., Caldas, L.R., Melo Filho, J. de A., Monteiro, N.B.R., Rafael, S.I.M., Marques da Silva, N., 2022. Circular alternatives in the construction industry: an environmental performance assessment of sisal fiber-reinforced composites. J. Build. Eng. 54, 104603 https://doi.org/10.1016/j.jobe.2022.104603.

Duan, Z., Huang, Q., Zhang, Q., 2022. Life cycle assessment of mass timber construction: a review. Build. Environ. 221, 109320 https://doi.org/10.1016/j.buildenv.2022.109320.

Euronit, 2009. Equitone Natura Pro Product Brochure.

Fidelis, M.E.A., Toledo Filho, R.D., Silva, F. de A., Mechtcherine, V., Butler, M., Hempel, S., 2016. The effect of accelerated aging on the interface of jute textile reinforced concrete. Cem. Concr. Compos. 74, 7–15. https://doi.org/10.1016/j.cemconcomp.2016.09.002.

Fundation, E.M., 2017. A New Textiles Economy: Redesigning Fashion's Future. http://www.ellenmacarthurfoundation.org/publications.

GlobalABC, IEA, UNEP, 2020. GlobalABC Roadmap for Buildings and Construction 2020-2050, Paris. https://www.iea.org/reports/globalabc-roadmap-for-buildings-and-construction-2020-2050.

ISO/TC 207/SC 5 Life cycle assessment, ISO 14040:2006 Environmental Management — Life Cycle Assessment — Principles and Framework, 2006.

ISO/TC 207/SC 5 Life cycle assessment, ISO 14044:2006 Environmental Management — Life Cycle Assessment — Requirements and Guidelines, 2006.

Li, Z., Wang, L., Ai Wang, X., 2007. Cement composites reinforced with surface modified coir fibers. J. Compos. Mater. 41, 1445–1457. https://doi.org/10.1177/0021998306068083.

Li, X., Qin, D., Hu, Y., Ahmad, W., Ahmad, A., Aslam, F., et al., 2022. A systematic review of waste materials in cement-based composites for construction applications. J. Build. Eng. 45, 103447 https://doi.org/10.1016/j.jobe.2021.103447.

Mobasher, B., 2011. Mechanics of Fiber and Textile Reinforced Cement Composites. CRC Press. https://doi.org/10.1201/b11181.

Niinimäki, K., Peters, G., Dahlbo, H., Perry, P., Rissanen, T., Gwilt, A., 2020. The environmental price of fast fashion. Nat. Rev. Earth Environ. 1, 189–200. https://doi.org/10.1038/s43017-020-0039-9.

Olivito, R.S., Cevallos, O.A., Carrozzini, A., 2014. Development of durable cementitious composites using sisal and flax fabrics for reinforcement of masonry structures. Mater. Des. 57, 258–268. https://doi.org/10.1016/j.matdes.2013.11.023.

Onuaguluchi, O., Banthia, N., 2016. Plant-based natural fibre reinforced cement composites: a review. Cem. Concr. Compos. 68, 96–108. https://doi.org/10.1016/j.cemconcomp.2016.02.014.

Peled, A., Bentur, A., Yankelevsky, D., 1994. Woven fabric reinforcement of cement matrix. Adv. Cement Base Mater. 1, 216–223. https://doi.org/10.1016/1065-7355(94)90027-2.

Penadés-Plà, V., Martí, J.V., García-Segura, T., Yepes, V., 2017. Life-cycle assessment: a comparison between two optimal post-tensioned concrete box-girder road bridges. Sustainability 9, 1864. https://doi.org/10.3390/su9101864.

Poranek, N., Łaźniewska-Piekarczyk, B., Lombardi, L., Czajkowski, A., Bogacka, M., Pikoń, K., 2022. Green deal and circular economy of bottom ash waste management in building industry—alkali (NaOH) pre-treatment. Materials 15, 3487. https://doi.org/10.3390/ma15103487.

Roos, S., Sandin, G., Peters, G., Spak, B., Schwarz Bour, L., Perzon, E., et al., 2019. White Paper on Textile Recycling. https://doi.org/10.13140/RG.2.2.31018.77766.

Sadrolodabaee, P., Claramunt, J., Ardanuy, M., de la Fuente, A., 2021a. Mechanical and durability characterization of a new textile waste micro-fiber reinforced cement composite for building applications. Case Stud. Constr. Mater. 14, e00492 https://doi.org/10.1016/j.cscm.2021.e00492.

Sadrolodabaee, P., Claramunt, J., Ardanuy, M., de la Fuente, A., 2021b. Characterization of a textile waste nonwoven fabric reinforced cement composite for non-structural building components. Construct. Build. Mater. 276, 122179 https://doi.org/10.1016/j.conbuildmat.2020.122179.

Savastano, H., Warden, P., Coutts, R.S., 2001. Ground iron blast furnace slag as a matrix for cellulose-cement materials. Cem. Concr. Compos. 23, 389–397. https://doi.org/10.1016/S0958-9465(00)00083-4.

Savastano, H., Warden, P., Coutts, R.S., 2003. Potential of alternative fibre cements as building materials for developing areas. Cem. Concr. Compos. 25, 585–592. https://doi.org/10.1016/S0958-9465(02)00071-9.

Savastano, H., Warden, P.G., Coutts, R.S.P., 2005. Microstructure and mechanical properties of waste fibre–cement composites. Cem. Concr. Compos. 27, 583–592. https://doi.org/10.1016/j.cemconcomp.2004.09.009.

Silva, F.D.A., Filho, R.D.T., Filho, J.D.A.M., Fairbairn, E.D.M.R., 2010. Physical and mechanical properties of durable sisal fiber–cement composites. Construct. Build. Mater. 24, 777–785. https://doi.org/10.1016/j.conbuildmat.2009.10.030.

Singh, A., Charak, A., Biligiri, K.P., Pandurangan, V., 2022. Glass and carbon fiber reinforced polymer composite wastes in pervious concrete: material characterization and lifecycle assessment. Resour. Conserv. Recycl. 182, 106304 https://doi.org/10.1016/j.resconrec.2022.106304.

Strauss Rambo, D.A., de Andrade Silva, F., Toledo Filho, R.D., Ukrainczyk, N., Koenders, E., 2016. Tensile strength of a calcium-aluminate cementitious composite reinforced with basalt textile in a high-temperature environment. Cem. Concr. Compos. 70, 183–193. https://doi.org/10.1016/j.cemconcomp.2016.04.006.

TFR4- the determination of energy absorption in flexure of thin libre :reinforced cement sections. Mater. Struct. 17 (No. 102), November-December 1984 (n.d.).

Tinoco, M.P., de Mendonça, É.M., Fernandez, L.I.C., Caldas, L.R., Reales, O.A.M., Toledo Filho, R.D., 2022. Life cycle assessment (LCA) and environmental sustainability of cementitious materials for 3D concrete printing: a systematic literature review. J. Build. Eng. 52, 104456 https://doi.org/10.1016/j.jobe.2022.104456.

Toledo Filho, R.D., a Silva, F.D., Fairbairn, E.M.R., Filho, J.D. a M., 2009. Durability of compression molded sisal fiber reinforced mortar laminates. Construct. Build. Mater. 23, 2409–2420. https://doi.org/10.1016/j.conbuildmat.2008.10.012.

Tonoli, G.H.D., Rodrigues Filho, U.P., Savastano, H., Bras, J., Belgacem, M.N., Rocco Lahr, F.A., 2009. Cellulose modified fibres in cement based composites. Composer Part A Appl. Sci. Manuf. 40, 2046–2053. https://doi.org/10.1016/j.compositesa.2009.09.016.

Vo, L.T.T., Navard, P., 2016. Treatments of plant biomass for cementitious building materials – a review. Construct. Build. Mater. 121, 161–176. https://doi.org/10.1016/j.conbuildmat.2016.05.125.

Won, J.-P., Jang, C.-I., Lee, S.-W., Lee, S.-J., Kim, H.-Y., 2010. Long-term performance of recycled PET fibre-reinforced cement composites. Construct. Build. Mater. 24, 660–665. https://doi.org/10.1016/j.conbuildmat.2009.11.003.

Xie, X., Zhou, Z., Jiang, M., Xu, X., Wang, Z., Hui, D., 2015. Cellulosic fibers from rice straw and bamboo used as reinforcement of cement-based composites for remarkably improving mechanical properties. Compos. B Eng. 78, 153–161. https://doi.org/10.1016/j.compositesb.2015.03.086.