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NONWOVEN FLAX FIBER MATS AND WHITE PORTLAND CEMENT COMPOSITES FOR BUILDING ENVELOPES

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Abstract

Traditionally, architectural materials performance was the key point for developing materials; but nowadays, other criteria's as sustainability, availability and recyclability are being considered. By the other hand, the addition of fibres as polymers, steel or glass on cement based materials was proved to enhance their performance in terms of ductility, tensile strength, toughness, fatigue strength, impact resistance and energy absorption capacity of matrices. Actually, the use of vegetable fibres as reinforcement for cement composites is particularly attractive since they are widely available, are biodegradable, and inexpensive. The attractive mechanical and physical properties joint to their environmental benefits combination are the main drivers to use them as alternatives for conventional reinforcements. Bio-fibres as flax fibres have been large used mainly for automotive products. Plus other mentioned properties, the low density of these vegetable fibre composites induces to consider them as an interesting architectural material for envelope skill applications. This research deals with the manufacturing of façade pieces from white Portland cement and treated flax nonwoven fibre composites. The study of the physical properties, i.e. flexural, water permeability, dimensional change of these façade components were also analysed before and after 60 days outdoor exposition.

Keywords:

Vegetable fibres, nonwoven flax, white cement, building envelope

1 INTRODUCTION

Energy use in residential and commercial buildings is responsible for about 40% of EU's total final energy consumption and 36% of the EU's total CO$_2$ emissions [CEC 2008]. Innovations to improve the energy efficiency in buildings are then of practical importance.

To improve the energy efficiency of the building sector it becomes necessary on the one hand to develop more environmentally-friendly and high performance building materials, and, on the other one, to develop new constructive solutions to reduce the energy consumption during the useful life of buildings.

The energetic consumption resulting from the manufacture of materials for buildings does not exceed the 10% of the energy consumed during their lifetime. In this period, this consumed energy, is derived mainly from the air conditioning during warmer or colder periods. In the case of isolated residential buildings, with 25% of façade voids and the minimum transmittance established by the current regulations in Spain, the estimated percentage of energy loss through the façades is around 25% [CTE 2013]. The rest of the energy is lost through the windows (60%), the roofs (10%) and the floor (5%).

Nowadays, the most used constructive solutions of building envelopes are the “ventilated façade” systems, which have continuity between the thermic and impermeable envelopes, avoiding thermal bridges and consequently avoiding the energy loss and the presence of water vapour condensations. Moreover, the provision of an external continuous protective envelope, separated from the insulation layer, allows air ventilation and prevents the heating by the direct sunlight or by transmission through the coating layer surface, thus improving internal comfort of the building, especially in hot climates with intense solar radiation. This envelope should fulfil some requirements as strength, flexibility, ductility, lightness, permeability, thermal insulation and durability.

Currently, in Spain, the most common materials used for these envelopes are ceramics, natural stones, wood-resin and aluminium-resin and increasingly fibre cements. Each one of these materials has advantages in some requirements but not for all of them. For example, ceramics and natural stones have excessive weight and high stiffness, which limits their size and becomes necessary a complex supporting structure.

Furthermore, the partial breaking leading falling objects on public roads can be dangerous. The wood and aluminium composites are more flexible and lightweight but are less durable materials, have lower hardness, and are much more expensive compared to conventional building materials.

That is way it is of practical importance to develop new materials for envelopes with the maximum characteristics aforementioned, primarily strength, ductility, flexibility and durability, using environmentally friendly and low cost raw materials and processes.

One possible solution is the use of vegetable fibre cement reinforced composites. These materials have a good combination of strength, lightness, sustainability and low cost and constitute a very interesting option to replace these materials [Savastano 2003] [Ardanuy 2015]. However, although the scientific community is making great advances in this field, the problem of long-term durability of these composites has not been yet solved [Ferreira 2012] [Claramunt 2012] [Silva 2010] [Toledo Filho 2003].

There are basically two strategies for improving the durability of these composites: modifying the composition of the matrix in order to reduce or remove the alkaline compounds and/or treating the fibres to increase their stability in the cementitious matrix [Ardanuy 2015].

Concerning to the fibre form of the reinforcement in these composites, the most common one is the use of cellulose pulps homogeneously dispersed on the matrix [Ardanuy 2015]. This form provides good results, with some restrictions such as maximum fibre content and limited, but enough deformability of the composite. Other researchers describe the use of other fibre forms and structures as unidirectional long fibres [Silva 2010], woven fabrics [Fidelis 2014], sheets of paper [Mohr 2006] or nonvowens [Claramunt 2013] [Claramunt 2014]. These fibre forms provide higher deformability and strength. Moreover, the use of textile preforms as nonwovens could bring the benefit such as fabric hand-ability and easier applicability on automatized process [Claramunt 2014 b]

In this work we present the developing and characterization of façade pieces made of white Portland cement and flax nonwovens as reinforcement. The study of the water permeability, dimensional change and flexural properties of these façade components is analysed before and after a 60 days outdoor exposition.

2 MATERIALS AND EXPERIMENTAL PROCEDURES

2.1 Materials

UNE 80305:2012 Type BL I 52.5 R white cement supplied by Lafarge (Spain) was used as a cement matrix. Based on previous research, to improve the durability of the composites, metakaolin supplied for *Arcilesa Arcillas Refractarias S.A.* was used as pozzolanic addition to replace a 30 wt.% of the cement [Silva 2010]. The sand used, “quartz flour”, had a similar particle size distribution as the cement, and was supplied by Sibelco. Short flax fibres (average length of 5.9 cm) provided by Institut Wlokien Naturalnych (Poland) were used to prepare the nonwoven reinforcement.

2.2 Nonwoven preparation and characterization

Nonwoven fabric samples were prepared on a pilot plant double needle-punching machine DILO OUG-II-6, equipped with universal card clothing, cross-lapper, batt feeder model CBF 6 and needle-punching loom. The former contained 18,000 singer felting needles (divided into two needle-boards forming an entangled pattern) with the technical specification SNF 15 × 18 × 36 RB30.

The flax fibres were firstly opened and carded to form a thin web which was laid by the cross-laying method to form batts. These batts were consolidated on the needle-punching machine to form the nonwoven mats. The machine parameters to prepare these nonwovens were determined in previous research [Ventura 2014].

Based on previous studies [Claramunt 2012] a water treatment to stabilize dimensionally the fibres was performed as follows: 1) Wetting by soaking overnight in water bath at environmental temperature; 2) Drying in oven with air recirculation at 60 ºC for 4 hours. A total of five water treatments were applied. This treatment allowed obtaining composites with higher flexural strength and toughness.

2.3 Composite preparation and characterization

For the composite preparation, the methodology used was to apply the reinforcement by taking special care of wetting the nonwoven with the matrix. This was done in a mould with internal dimensions of 300 x 300 x 10 mm which was specially designed to apply homogeneous pressure (3.5 MPa) (Fig. 1). Laminates of 4 nonwoven layers placed cross-oriented were produced. One protective outer layer without fibres of 1 mmm thickness was placed on every face of the samples. The dosages of cement and binders for the outer and inner layers are shown in Tab.1. The excess of water was eliminated with vacuum followed by compression until a final thickness of 8-12mm. The specimens were cured 28 days at 20 ºC ±1 ºC in a humidity chamber (< 95% of relative humidity).

Fig. 1: Pictures of moulding procedure: laminating process (top) and compression step (bottom)

Tab. 1: Dosage of the components of the matrix on the outer and inner layers of the composite

Layer	Dosage	Cement	Metakaolin	Sand	Initial water
Outer	1:1:1.5	210 g	90 g	300 g	450 g
Inner	1:0.7	1,715 g	735 g	0	1,715 g

The characterization of the composites was done following the UNE-EN 12467:2013 standard. The water permeability was determined placing a 20 cm water layer on the surface of the plates and verifying that did not appear water droplets on the other face after 24 h and after 28 days. The dimensional change was measured determining the dimensions of the samples conditioned at 30±2% relative humidity until constant weight and comparing these dimensions with the same samples conditioning at 90±2% of relative humidity. The mechanical properties of the composites were determined under flexural tests. Three-point bending tests were carried out using an Incotecnic press equipped with a maximum load cell of 3 kN at a crosshead speed of 10 mm/min. The specimens were tested with a distance between supports of 260 mm and the displacement measurements were carried out using two LVDT's of 0.01mm of resolution and an error of 0.15%.

The durability of the composites after accelerated aging was tested after subjecting part of the specimens to wetting and drying cycles and another part to natural aging. The wet/dry cycle used was 16 h of soaking in water at room temperature followed by 6 h of drying in an oven provided with open air circulation at 60 °C. A total of 25 wet/dry cycles were performed. The natural aging consisted on subjecting the plates in vertical position to 60 days of outdoor exposition (between the 1st of August and the 29th of September 2014) on the following GPS coordinates: N41.2753203, E1.9852342). After the wet/dry cycles or the outdoor exposition the flexural behaviour under the same three-point bending test aforementioned was tested on the specimens. To determine the morphology of the fibres after aging the fracture surface of these composites was observed using a JEOL JSM-S610 microscope at an accelerating voltage of 10 kV

Tab. 2: Reference of specimens, test performed and water:cement+metakaolin ratio after moulding on the outer layer, inner layer and the average of the specimen.*

Specimen	Test*	Outer layer	Inner layer	Average
P1	1	0.86	0.40	0.42
P2	1,3	0.73	0.34	0.47
P3	1,4	0.81	0.38	0.44
P4	1,5	0.82	0.38	0.40
P5	2	0.76	0.36	0.42
P6	2	0.76	0.35	0.47

**1=* water permeability*, 2=* dimensional change*, 3=Flexural test after curing, 4= Flexural test after accelerated aging, 5=Flexural test after* 60 days outdoor exposition

3 RESULTS

All the specimens tested for water permeability met the standard UNE-EN 12467:2013 for both times tested, 24 hours and 28 days, it is to say, no dripping or wet spots were observed on the opposite face of the plate exposed to the water. These results demonstrate that the laminated system with nonwoven layers and cement paste on the inner of the composite and cement paste as protective outer layers is a successful system to obtain waterproof plates.

The values of the dimensional change of the plates under the test conditions are compiled in Tab. 3. As shown, the plates have low dimensional variation and all of the tolerance requirements of the standard are more than met. Unlike conventional fibre cements reinforced with pulp fibres, where the dimensional changes are more homogeneous in all directions, the reinforcement system with nonwovens placed in cross directions generates less deformation in the plane direction of the plate (0.15%) than in the perpendicular direction, which even shrinks (-0.71%).

Tab. 3: Values of dimensional variation.

Dimension	Average	s.d.
Height	0.15%	0.01%
Width	0.15%	0.01%
Thickness	-0.71%	0.63%

Concerning the mechanical properties of the composites and the effect of aging, Fig. 2 shows typical bending curves obtained for the specimens after 28 days curing compared with the specimens aged with wet/dry cycling and the ones aged with outdoor exposition. The values of modulus of proportionality (MOP), modulus of rupture (MOR), modulus of elasticity (MOE) and fracture energy determined from the curves are compiled in Tab. 4.

The unaged composite showed very high ductility with high capacity for deformation with formation of multiple cracking. Nonetheless, it was observed a lack of durability after aging, mainly after subjecting the plates to wet/dry cycling. As shown in Tab. 4 there is a reduction of the average values of MOP, MOE and MOR after aging, being this effect more significant after wet/dry cycling aging. Concerning the toughness, decreased for the composites aged with wet/dry cycling but increased for the ones subjected to outdoor exposition. This increase on the fracture energy could be related with an increase of the flexibility of the fibers due to water absorption during the outdoor exposition. This effect, which is beneficial for the performance of the material becomes harmful when, after wet/dry cycles the polymer of the fibers is degraded by the alkaline compounds of the matrix.

Fig. 3 shows the micrographs of the fracture surface of the composites before and after 25 cycles of wetting and drying. For the unaged composites it can be observed fibres pull-out and fibre breaking but with the fibres maintaining their strength and flexibility. However, the cavities presented in Fig. 3(b) indicated that most individual fibres or small groups have been cut near the surface. This behaviour indicates that the fibres have lost it performance due to the attack by calcium hydroxide [Toledo Filho 2009]. On the other hand, it can also be noted that the surrounding area of fibres cut near the surface is filled by the matrix, indicating good adhesion to the matrix due to the dimensional stability generated by the water treatment used to stabilize dimensionally.

These results indicate that the pozzonalic addition (metakaolin) and the previous treatment performed on the nonwoven to improve the durability of the composites was not enough effective.

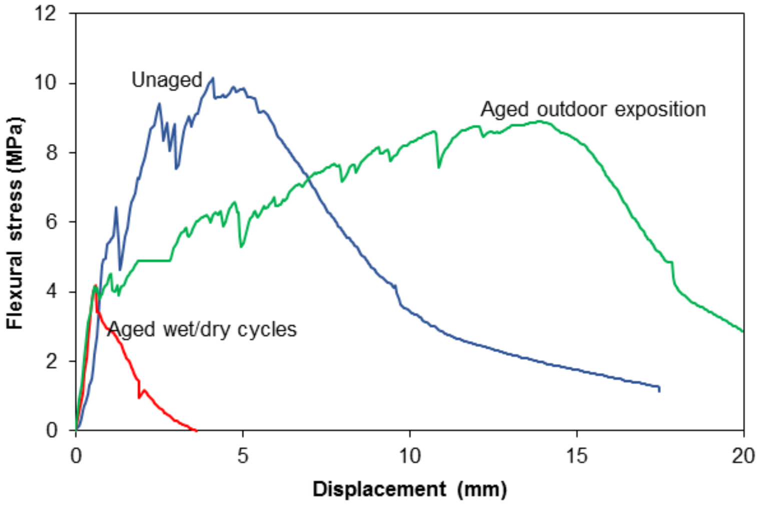

Fig. 2: Typical bending curves obtained for the nonwoven composites.

Tab. 4: Values of MOP, MOR, MOE and toughness obtained from the bending tests.

	MOP (MPa)		**MOR (MPa)**		**MOE (GPa)**		**Toughness (kJ/m^2)**	
	Average	s.d.	Average	s.d.	Average	s.d.	Average	s.d.
Unaged	6,37	1,27	9,58	1,39	9,27	0,84	2,78	0,86
Aged wet/dry cycles	4,52	0,56	8,87	0,94	5,75	1,18	3,81	1,54
Aged outdoor exposition	4,13	0,83	4,35	1,18	7,37	1,63	0,19	0,05

Fig.3: SEM Images of fracture surface of the unaged composite (a) and the composite aged with 25 wet/dry cycles (The arrows indicate fibres cut near the surface).

Fig. 4 shows in detail the fracture surface of the fibres of the unaged composite and the aged ones. As can be seen for the unaged composites (Fig. 4(a)) the fibres show a clean and surface whilst in the aged composites the surface appeared with higher roughness and surrounded by precipitation products (Fig. 4 (b-d)). This is due to the chemical attack of the calcium hydroxide and is more significant on the composites subjected to 25 wet/dry cycles compared with the ones subjected to 60 days of outdoor exposition The presence of this alkali compound can be easily checked spraying the surface with phenolphthalein (Fig. 5). This indicates that the pozzolanic reaction was not complete, i.e. part of the calcium hydroxide of the matrix has not been reacted with the metakaolin. Nonetheless, observing in detail (Fig. 5 (b) it can be seen as the most of the outer layer of protection has remained uncolorored This means that the pozzolanic reaction has been almost complete on the external layers meanwhile on the inner layers has not been reached. Although more research should be done to understand this effect, probably the presence of the fibres limit the extent of the reaction between the cement and the metakaolin.

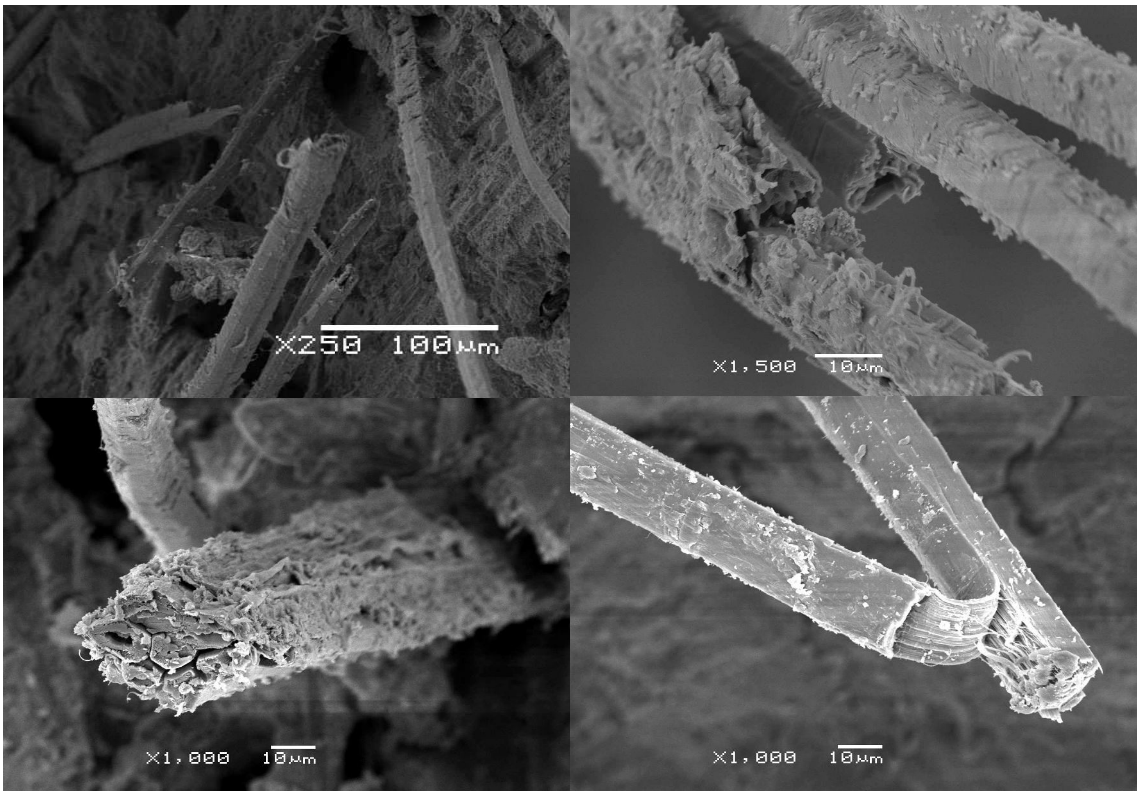

Fig.4: SEM Images of fracture surface of the fibres on the unaged composite (a), the composite aged with 25 wet/dry cycles (b) and the composite aged with 60 days outdoor exposition (c) and (d)

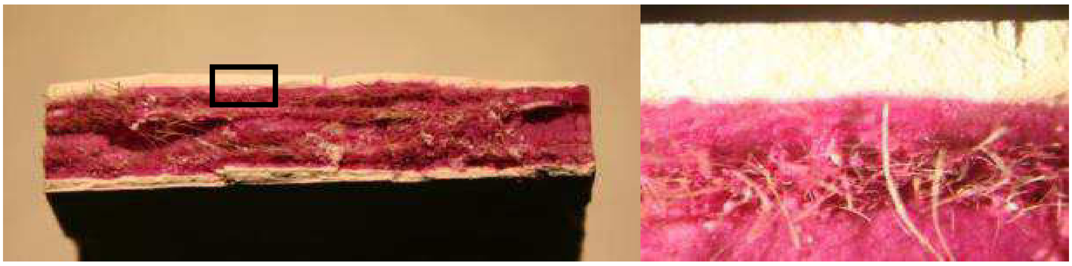

Fig.5: Picture of the fracture surface of the composite aged with 60 days outdoor exposition sprayed with phenolphthalein

4 CONCLUSIONS

The natural fibre nonwovens as reinforcement for cementitious matrix lead to an increase of the mechanical performance with respect to the conventional fibre-cements, especially increasing their ductility. Moreover, this form allows industrial automation of the manufacturing process.

The plates produced by this procedure met the requirements of impermeability and dimensional change of the UNE-EN 12467: 2013. Moreover have enough mechanical performance to be used as prefabricated panels for ventilated façades, reaching values of flexural strength close to 10 MPa.

The pozzonalic addition (metakaolin) was not enough effective to obtain durable composites.The high alkalinity of the matrix degraded the fibers mainly under accelerated aging with wet/dry cycling.

5 ACKNOWLEDGMENTS

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