DESIGN OF A MODULAR LOW-ENERGY BUILDING SYSTEM FROM A COMPOSITE MATERIAL BASED ON CEMENT-BONDED WOOD FIBRES

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DISEÑO DE UN SISTEMA CONSTRUCTIVO MODULAR BAJO CRITERIOS PASIVOS A PARTIR DE UN MATERIAL COMPUESTO POR FIBRAS DE MADERA AGLOMERADAS CON CEMENTO

ABSTRACT:

This paper presents the results of the characterization of a 400 kg/m^3 density composite material made of cement-bonded wood fibres for use as a structural element in a modular building system. To perform the mechanical characterization, various bending and compression tests were conducted in the three spatial directions with respect to the fibres' orientation. The design and characterization of the possible fixings between construction blocks were studied by means of tensile tests performed on 10-cm-diameter steel rods inserted into the composite material no deeper than 30 cm using different adhesives. Different bonding interfaces between the "rod-adhesive" and the composite material were studied. X-Ray Scanning Electron Microscopy was used to study the bonding of the fibres and the distribution of the bonding agent. The compressive strength is around 0.3 MPa, depending on the direction in which the load is applied, and the bending strength, 0.47 MPa. These results mean the material can be used as a structural element in housing of no more than 2 storeys. Fixings with quick-setting silicon-carbide mortar show a tensile strength of 100 kp. The thermal conductivity of the composite at 60% relative humidity is 0.128W/mK. The cement used as the bonding agent appears to form small isolated clumps that provide the material with a high level of porosity and hence a high thermal insulation capacity. A complementary analysis of the modular building system was also carried out to enable it to meet the requirements of the Passivhaus standard.

Keywords: Composite Material, Wood Fibres, , Thermal Conductivity, Passivhaus Standard, Hygrothermal Characterization, Structural Characterization, Modular Building System, Scanning Electron Microscopy.

RESUMEN:

En este trabajo se presentan los resultados obtenidos en la caracterización de un material compuesto, constituido por fibras de madera aglomeradas con cemento y una densidad de 400 Kg/m^3, para su empleo como elemento portante en un sistema constructivo modular diseñado bajo criterios pasivos. Para la caracterización estructural se realizaron ensayos de flexión y de compresión en las 3 direcciones del espacio debido a la orientación de las fibras. Para el diseño y caracterización de las posibles fijaciones entre módulos se realizaron ensayos de tracción sobre varillas de acero de 10 mm de diámetro insertadas en el material una profundidad de 30 cm. Se analizaron varias interfaces de unión entre el conjunto "varilla-adhesivo" y el material. Para estudiar la unión entre las fibras y la distribución del aglomerante se analizaron muestras en el microscopio electrónico de barrido con energía dispersa de Rayos X. La resistencia a compresión, según la dirección de carga en servicio, ronda los 0,3 MPa, y la resistencia a flexión alcanza los 0,47 MPa. Estos valores únicamente capacitan a este material para su uso portante en viviendas de 1 o 2 plantas máximo. Las fijaciones con mortero de fraguado rápido y naturaleza silico-carbonática resistirían unos 100 kp. La conductividad térmica con un 60% de humedad alcanzó los 0.128 W/mK. El cemento, que actúa como aglomerante, aparece formando pequeños "grumos", separados entre sí para favorecer una elevada porosidad en el material, y por tanto, un elevado nivel de aislamiento térmico. Como complemento, se propone una mejora en el sistema constructivo modular con el objetivo de dar cumplimiento a las exigencias del estándar Passivhaus

Palabras clave: Material Compuesto, Fibras de Madera,, Conductividad Térmica, Estándar Passivhaus, Caracterización Higrotérmica, Caracterización Estructural, Sistema Constructivo Modular, Microscopía Electrónica de Barrido.

1.- INTRODUCTION

A general objective in the building industry is the development of modular building systems which present a high level of thermal insulation and use local, environmentally-friendly materials in addition to being economical. With these goals in mind, the aim of this paper is to characterize a composite material made of cement-bonded wood fibres with the ultimate goal of designing a modular building system consisting solely of this material. To achieve this goal, the material should combine “load-bearing” properties as well as “functional” properties such as thermal insulation.

Composite materials comprising cement-bonded wood fibres or chips have been used in the building industry for many years now. They are used for their sound-absorbing properties, moisture resistance and fire resistance. They have recently been used with great success in Sweden as part of the thermal envelope of the building, though without “load-bearing” requirements [1]. However, there are very few experiences which include this material as the sole “load-bearing” element. Studies of this kind would allow the development of a modular building enclosure made entirely of this material with the absence of thermal bridges. Some developments have focussed on the design of economical building systems in underdeveloped areas that make use of local wood chips [2], vegetable fibres [3], or tropical timber fibres [4]. There are examples of similar composites such as “pulp” consisting of cement-bonded wood fibres, which contain an excessive percentage of cement to achieve high hardness and flexural strength [5]. The properties of these materials depend on the percentage distribution between cement and wood fibres, in addition to the characteristics of these elements. Some studies establish the optimal percentages as a function of the type of wood [6]. Normally, 3-point bending tests [7], compression tests [4], and thermal conductivity tests [8] are performed to characterize these materials. Densities of 280 kg/m^3 employing European wood fibres would achieve a flexural strength of around 27 kPa and a thermal transmittance of 0.19 W/m^{2}K [1].

The aim of this study is to design an economical, thermally-efficient modular building system based on a composite material made of cement-bonded wood fibres with a density of 400 kg/m^3 to act as the sole load-bearing and insulating element. To this end, bending and compression tests were carried out in the three spatial directions, studying different options for fixing the construction blocks together via tensile tests performed on steel rods “embedded” in the material to a depth of 30 cm, employing different bonding “interfaces” between the rod and the composite. The Basic Document on Structural Safety and Actions in Building (Spanish acronym, DB-SE-AE) of the Technical Building Code in force in Spain (Spanish acronym, CTE) was taken as the reference document to analyse these fixing systems. [9]. Furthermore, the thermal conductivity of the material was determined under different moisture conditions. The compressive strength in line with the in-service load-bearing direction is around 0.3 MPa, while the flexural strength reaches 0.47 MPa. The thermal transmittance of the material at 60% relative humidity can reach 0.322 W/m^{2}K. The use of a fast-setting silicon-carbonate mortar with an apparent density of around 2250 kg/m^3 is recommended to achieve the adhesive bond between the fixing rod and the material. Under this assumption, the tensile strength of each fixing would exceed 100 kp.

Buildings are major consumers of energy, especially in terms of heating demand. Consequently, the footprint of CO_2 emissions resulting from this consumption represents 36% of all such emissions in Europe. Minimizing heating demand constitutes the key to reducing these emissions [10]. For this reason, a complementary improvement to the building system is presented with the aim of reducing the overall thermal transmittance to values compatible with the German “Passivhaus” building standard [11]. To this end, an enclosure consisting of 30 cm of this composite material and an 8-cm inner layer of mineral wool is proposed, thus achieving an overall thermal conductivity of the enclosure of 0.06 W/mK. To ensure the absence of any possible condensation or high energy losses in the joint with the roof, the building solution was analysed using the Flixo Energy hygro-thermal software, the purpose-designed “joints” between the enclosure and the roof being found to be valid for this building system. More than 30,000 buildings have already been built in Europe based on the Passivhaus building standard. Since 2007, all public or rehabilitated buildings in the city of Frankfurt must be built following this standard. The same criterion has been in force in the German cities of Freiburg and Hannover since 2009. In the city of Brussels, this standard has been mandatory in public buildings since 2010. Furthermore, European Directive 2010/31/ EU introduced the concept of “Nearly Zero-Energy Buildings”, establishing 31 December 2018 as the deadline for its application in all newly-built public buildings, and 2020 for other types of buildings.

2. MATERIALS AND METHODS

The bending and compression tests were performed on an INSTROM 5582 machine, equipped with a 100 kN load cell. The bending specimens had a square cross-section, measuring 100 mm per edge, and the distance between supports was 250 mm. The compression specimens were cubes, each side measuring 150 mm. Figure 1 shows the conducting of these tests. Figure 2 shows the test directions and preferred orientation of the wood fibres in the tested specimens. The *z* axis is the in-service load-bearing direction of the material and also coincides with the filling direction during the manufacturing of the material. Note that the orientation of the fibres depends on the testing direction. Twelve bending tests and twelve compression tests were performed in each of the three spatial directions.

Fig. 1. (a) Bending test; (b) Compression test

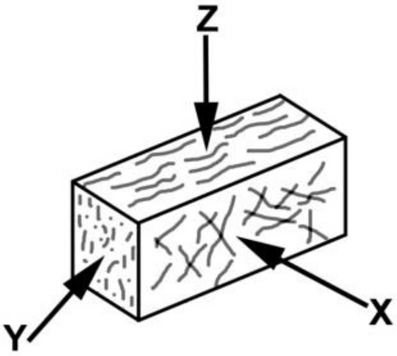


Fig. 2. Preferred orientation of the wood fibres in the tested specimens. The *x*, *y* and *z* axes represent the directions in which forces were applied during the bending and compression tests. The *z* axis coincides with the filling direction.

To obtain the plot of thermal transmittance versus moisture, the material was tested in a 1 m^3 calibrated “hot box” whose thermal envelope was fully insulated, following the ASTM C 1363-11 standard, connected to a climate generator to create a test environment under controlled conditions of temperature and humidity. A 40-cm-wide framework was used to support the test sample, which was placed on one side of the calibrated hot box and insulated. The relative humidity targets were 25%, 45% and 75%. The measuring equipment comprised:

1. A Sensirion EK-H3 data logger, allowing the application of 20 temperature and humidity sensors, and the simultaneous read-out of relative humidity and temperature.
2. Hukseflux HFP01 heat flux sensors, allowing the measurement of thermal resistance and thermal transmittance according to the ISO 9869, ASTM C1046 and ASTM 1155 standards.
3. Hukseflux LI19 read-out units with an integrated HFP01 sensor data logger, allowing the transmission of read-out data to a PC via a USB interface.

To design the joining of the different blocks of the building system, tensile tests were performed on 10-mm-diameter steel rods inserted into the material to a depth of 30 cm. For this purpose, it was necessary to make a 12-mm-diameter x

30-mm-deep hole in the block. The dimensions of the specimens were 500 mm x 390 mm x 400 mm. Four types of adhesives were applied to the drill hole to form a bonding "interface" between the steel rods and the material and were subsequently analysed. Three tests were conducted for each adhesive and angle between the rod and the wood fibre (0º and 90º). The tested adhesives were:

- Adhesive 1: with a styrene-free polyester base.
- Adhesive 2: with an epoxy resin base.
- Adhesive 3: with a mixed styrene-free polyester and quartz sand base.
- Adhesive 4: with a quick-setting silicon-carbonate bonding mortar base, with a particle size ranging from 0 to 2.5 mm, 4 l mixing water /25 kg and a bulk density of the mixture of 2250 kg/m^3. The approximate setting time was around 60-70 minutes.

To observe the arrangement of the binder on the fibres, micrographs were obtained on a scanning electron microscope (SEM) and the distribution of the main elements of the cement (Si and Ca) were analysed by energy dispersive X-ray (EDAX) spectroscopy, including a "mapping" of their distribution.

Complementarily, compliance with the Passivhaus standard of an enclosure consisting of 30 cm of this composite material and a 8 cm inner layer of mineral wool was tested. Table I shows the characteristics of the main components comprising the enclosure. Figure 3 shows the main structure of this enclosure and the proposed "joint" between the wall and the roof. The thermal transmittance of the enclosure was accordingly determined and the "joint" was evaluated using Energy Flixo hygro-thermal software to ensure the maintenance of the level of insulation and the absence of any possible condensation.

Table I. Component of the proposed building system to meet the Passivhaus standard.

	Thickness (cm)	Density (kg/m^3)	Modulus of Elasticity (MPa)	Fracture stress (MPa)	Thermal Conductivity (W/mK)
Composite	30	400	31.13	0.35	0.12
Mineral wool	8	60	-	-	0.03

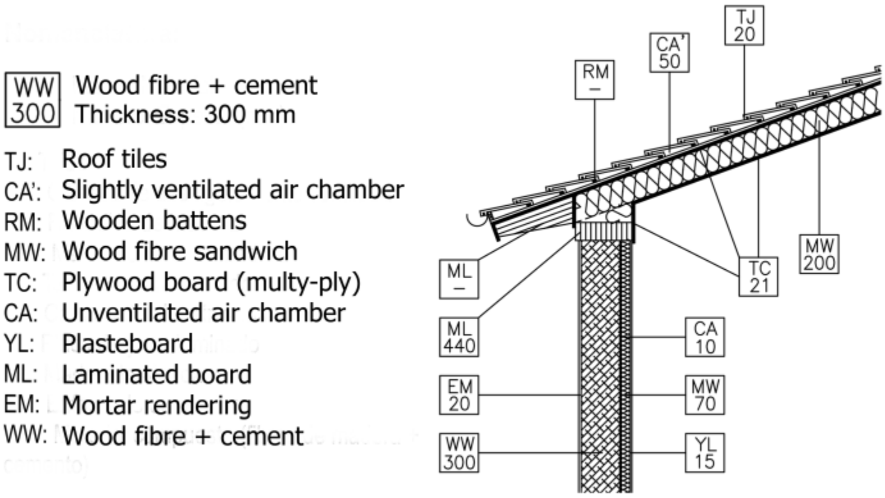


Figure 3. Structure of the proposed building system to meet the Passivhaus standard. Each building element is identified by means of two letters and a number. The number refers to the thickness in mm.

3.- RESULTS

Table II shows the mean values obtained on the composite in the bending and compression tests in each load-applying direction, as well as the standard deviation derived from the series of tests. Failure of this material occurred without plastic deformation. The values are low and only allow the use of this material for load-bearing purposes in 1- or 2-storey housing.

Table II. Tensile strength

MPa	Tensile strength			Modulus of elasticity		
	X	Y	Z	X	Y	Z
Bending	0.015	0.205	0.474	0.853	3.831	17.514
std. dev.	0.003	0.026	0.070	0.10	1.80	4.48
Compression	0.135	0.360	0.296	5.078	21.924	31.125
std. dev.	0.001	0.009	0.004	1.02	3.54	4.07

Figure 4 shows the thermal transmittance results as a function of moisture in the hot box test. The former variable can be seen to increase with increasing relative humidity.

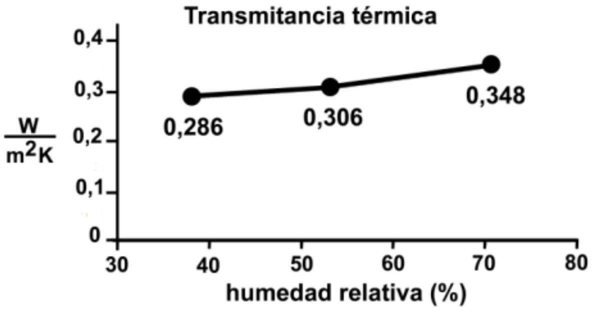


Figure 4. Thermal transmittance versus relative humidity

Table IV shows the tensile stresses at the time of fracture produced in the “interface” between the rod-adhesive-composite joint. Adhesive 4 is the adhesive that provides the fixing system with the greatest strength, exceeding 100 kp/fixing. Taking the Basic Document on Structural Safety and Actions in Building (Spanish acronym, DB-SE-AE) of the Technical Building Code in force in Spain [9] as the reference document, the number of fixings per m^2 could be limited to 3 when considering the most adverse climate conditions in the aforementioned document.

Table IV. Tensile stress on the fixings. Angles of 0 and 90º between the rod and the wood fibres.

Adhesive	kp (0º)	kp (90º)
Adhesive 1	96.1	78.4
Adhesive 2	94.8	120.5
Adhesive 3	133.2	82
Adhesive 4	118	138

Figures 5 to 7 show the micrographs obtained under a scanning electron microscope (SEM) on “metallized” samples. The distributions of the main chemical elements were analysed by energy dispersive X-ray (EDAX) spectroscopy. Figure 5 shows a general view of one of the samples, in which one of the wood fibres can be observed together with small “clumps of cement” which act as binders for the wood fibres. Table V shows the weight distribution of the main chemical elements located on this fibre. The elements Ca, Si, and Al are associated with the cement.

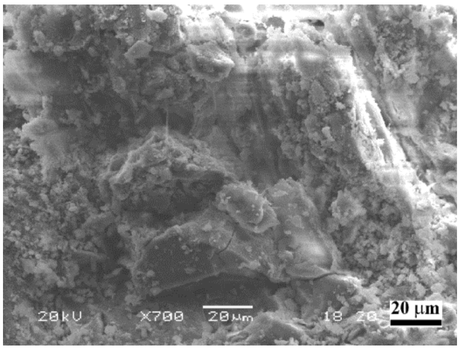
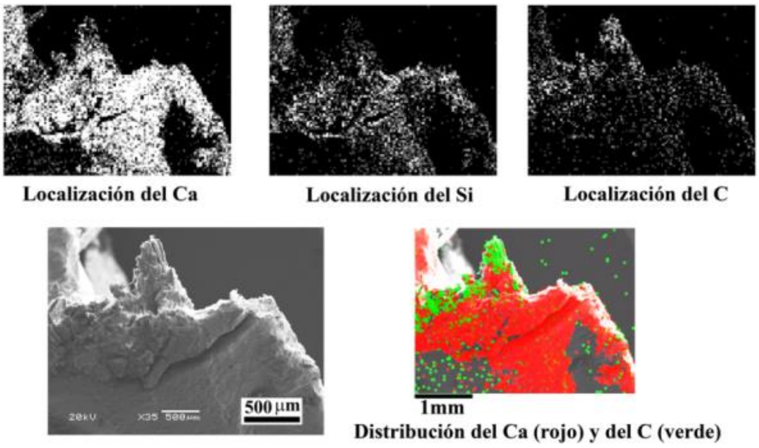


Figure 5. General view

Table V. Weight distribution of the main chemical elements found

Element	% in weight
C	12.54
O	50.06
Al	0.93
Si	4.99
Ca	30.36
Fe	1.11

Figure 6 shows the fractured end of one of the fibres. The distribution of Si and Ca was analysed at this fractured end, allowing the location of the position of the cement at this end. C is associated with the fibre itself and indicates the areas not bonded by cement. In this particular case, the fractured end appears to lack this binder. It appears that the proportion of cement is the minimum necessary to fulfil the function of binder and that its distribution is heterogeneous among the fibres, forming small "clumps" (ranging from about 100 microns to a few millimeters) separated several mm from one another, thus providing the material with high porosity. This leads to a high level of thermal insulation and high water vapor permeability, thus reducing the risks of interstitial condensation [12]. Figure 7 shows a number of transversal plies of the wood fibres, from which their thickness can be observed to be around 300 microns.


Localización del Ca

Localización del Si

Localización del C

Distribución del Ca (rojo) y del C (verde)

Figure 6. Location of Ca, as a representative component of cement (in red)

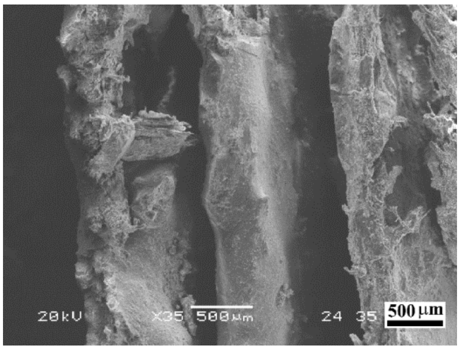


Figure 7. Cross-sectional view of the wood fibres

As a complementary study, it was decided to add an inner layer of mineral wool to the enclosure formed by the composite material to improve the insulation level of the building system and evaluate its compliance with the Passivhaus standard by means of this improvement. Table I and Figure 4 show the elements comprising this building system. The overall thermal conductivity of the enclosure reached 0.06 W/mK. The overall thermal transmittance of this system is less than 0.2 W/m^2K, which means a reduction of more than 70% for climate zones C and of more than 65% for climate zones D in terms of the heating demand required by the Technical Building Code for façades [13]. The "joints" between the enclosure wall and the eaves of the sloping roof were assessed using Energy Flixo hygro-thermal software to ensure the level of insulation was maintained and the absence of thermal bridges [14] or any possible condensation, as these "joints" are the weakest points from the thermal point of view. Figure 8 shows the results thus obtained. Under outdoor temperature conditions of 0 °C and indoor temperature conditions of 20 °C, the lowest temperature reached on the inner surface of the thermal envelope would be 16.84 °C, which is higher than the dew point temperature at an average relative humidity of 60%.

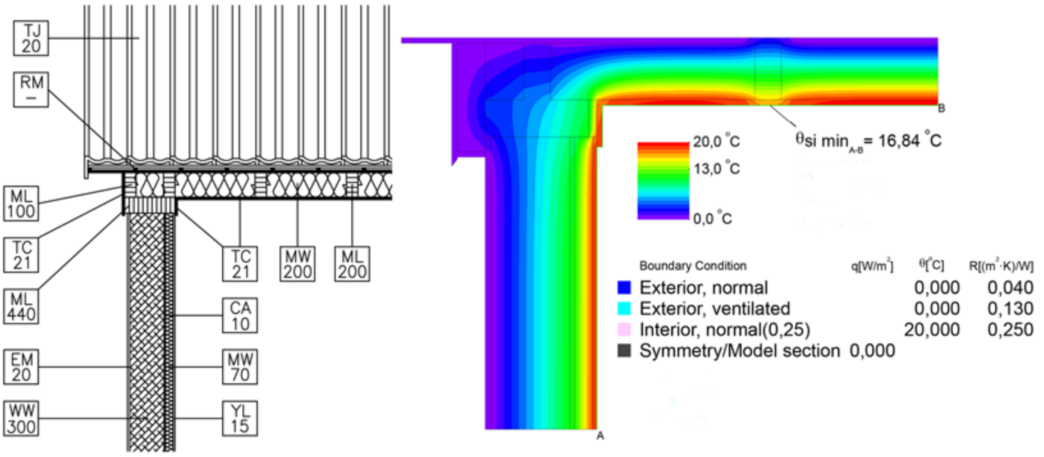


Figure 8. Results from the analysis carried out using Flixo-Energy hygro-thermal software on the "joint" between the enclosure wall and the sloping roof. Same nomenclature as in Figure 4.

4. CONCLUSIONS

Having conducted the structural and functional tests for the characterization of a composite consisting of cement-bonded wood fibres with a density of 400 kg/m^3, it can be concluded that:

1. The flexural strength until failure in the in-service load-bearing direction is higher than that obtained by compression; this may be due to the resistive effect of the fibres, which are located mainly in a direction perpendicular to the applied load.

2. The compressive strength in the in-service load-bearing direction is around 0.3 MPa. The flexural strength in this same load-bearing direction would exceed 0.45 MPa. These values only allow the use of this material for load-bearing purposes in 1- or 2-storey housing.
3. The overall thermal conductivity at 60% relative humidity is 0.06 W/mK.
4. For the design of a modular building system, it is advisable to use fixing systems that act as an adhesive bond between the metal rods and the material itself composed of fast-setting silicon-carbonate mortar with an apparent density of around 2250 kg/m^3. Under this assumption, the tensile strength of each fixing would exceed 100 kp.
5. The distribution of cement, which acts as a binder of the wood fibres, is heterogeneous, evidencing the appearance of small “clumps” of different sizes ranging from around 100 microns to less than 2 mm, isolated from one another, thus providing the material with a high level of porosity and hence a high level of thermal insulation.

The modular building system consisting of 30 cm of this material and 7 cm mineral wool would meet Passivhaus building standards, ensuring the absence of thermal bridges and a reduction in the heating demand required by the Spanish Technical Building Code for façades of more 70% for climate zones C and more than 65% for climate zones D. Furthermore, this modular building system shortens building time and hence labour costs, equipment and cranes rental, etc. It would also be an attractive and economical solution for the construction of houses that aspire to meet the Passivhaus manufacturing standard. Complementarily, building time and costs could be further reduced if the building system dispenses with the supplementary use of a 7-cm layer of mineral wool. In this case, it would not meet the Passivhaus standard, but a reduction would be achieved in the heating demand required by the Spanish Technical Building Code for façades of more than 40% in climate zones C and of more than 28% in climate zones D, making this material and building system very economical, environmentally friendly and efficient from the thermal point of view.

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