Characterization of thermal insulation materials developed with crop wastes and natural binders

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Abstract:

This paper seeks to discuss the possibility of developing insulation materials for the construction sector made of non-industrial crop wastes and natural binders. Three different crop wastes widely available in Spain, namely barley straw, corn pith and rice husk, are used in the production of experimental insulation panels. Their thermal behaviour, equilibrium moisture content and water vapour permeability are assessed in order to determine their suitability as a construction insulation material. Results show that crop wastes can perform adequately as insulation materials with any or little manipulation. They also reflect how the choice of the crop waste affects the characteristics of the final products.

Sustainable construction materials, natural fibres insulations, crop wastes, hygrothermal behaviour

1. Introduction

The intervention on the existing building stock is a vital tool to face the challenge of reducing CO2 emissions established by the European Commission for 2020 and 2050. Existing buildings consume about 40% of EU's total annual energy consumption, mainly for heating and air conditioning and the implementation of optimized thermal insulation systems on these buildings is regarded as one of the main strategies to improve their energy efficiency [1,2].

By 2050, in line with European GHG reduction scenario, about 10 million houses in Spain need to be insulated. [3]. Therefore, the energy as well as the depletion of non-renewable natural resources associated to their production are important factors to take into account. [2]

Actually, the increasing consciousness on the hazardous effects that certain insulation building materials have both to human health and to the environment has inspired a rich research on healthier and renewable options. Recent developments support the use of biomass from industrial crops (mainly hemp, kenaf or flax) as an alternative to petrol based products. Nowadays, these developments have allowed the insertion in the mainstream market of some natural insulation materials such as hemp wools or wood fibres.

Some research has been done as well on the use of non-industrial crop wastes such as straw, stalk cores or husks of cereals [4]. Although many of such research have been focused on the reinforcement in composites [5], the development of high and medium density boards [6] or the straw bale wall systems [7], there is an increasing interest in their use in natural thermal insulation materials.

Since some pioneering patents from the twenties [8] to the present, many attempts have been done to produce insulation boards. Pinto et al. [9,10] found that exist similitudes between corn cob and EPS regarding their microstructure, but that the thermal conductivity of experimental panels developed with corn cobs presented a higher thermal conductivity than EPS. Similar results were obtained by Dowling et al. [11]. Wang D et al. [12] made experimental low density boards with a mixture of wheat straw and corn pith. Their results show that the equilibrium moisture content is not affected by the density of the sample. They also found that thickness swell is larger than linear expansion due to the orientation of the fibres, parallel to the faces of the board.

Concrete, lime and other inorganic materials are commonly used as binders, dramatically increasing the thermal conductivity of the final product [13]. Organic resins are also generally used, but have negative side effects caused by the emission of volatile organic compounds. Besides, all these binders may increase the embodied energy and prevent the biodegradability of the final product, causing problems of waste disposal or recycling. Binderless panels have been developed, but their production need high pressure, which increases their thermal conductivity. The use of natural binders, e.g. starch or casein, may be an alternative to overcome all these difficulties: the resulting panels are light, formaldehyde free and completely biodegradable.

Vejelienė et al. [14] tested insulation specimens of binderless -tied- wheat straw boards in different configurations and found that boards made of chopped straw (2-4cm long) presented a lower thermal conductivity than those made with the entire stalk. Furthermore, density seemed not to have any impact on thermal conductivity when straw was chopped, but had a significant effect on entire straw. Entire straw at 50kg/m3 had similar conductivity than chopped straw (about 0,041 W/mK)

Cadena [15] developed insulation boards based on rice husks and yuca starch. They concluded that starch was a suitable binder as it didn't increased the thermal conductivity of the samples as PVA did. The best mixture presented a thermal conductivity of 0.065 W/mK and a density of 194.96 kg/m3. Nevertheless, the resistance in front of water had to be improved. No study was found that used alginate as a binder in insulation materials, although it has been used traditionally in earth renders [16] and was used in unfired bricks to increase their compression strength [17].

A significant aspect of natural thermal insulations is their hygroscopicity, that is, their capacity to accumulate moisture by adsorption from the air [18,19,20]. As the adsorption is higher when relative humidity is increased and the excess of moisture is released when humidity is decreased, this behaviour can contribute to regulate the indoor humidity conditions [19]. From the point of view of the performance of building envelope that incorporates a natural insulation, the knowledge of the material properties is of main importance for a correct evaluation of the whole hygrothermic behaviour. Thermal conductivity, equilibrium moisture content and water vapour permeability are the three main characteristics that, once evaluated, can be incorporated as an input data for simulation programs [19].

In this paper, different crop wastes are considered to analyse their viability to be used as thermal insulators. They have been selected taking into account their availability in Spain. Previous studies showed that barley, wheat, corn and rice waste products are produced in a larger quantity yearly [21]. The vegetal raw materials have been linked by natural organic binders: corn starch, alginate and casein.

2. Materials and methods

2.1. Vegetable raw materials

Among the available raw materials, three were chosen that presented remarkable morphological differences: barley straw, corn pith and rice husks. Corn stalks contain an interior tissue -the pith- predominantly formed by relatively big parenchyma cellules (diameter about 100-140 μm) that present a thin cellular wall. Barley straw is hollow and its parenchyma cellules are smaller (diameter from 20 to 40 μm approximately). Figure 1 shows SEM images of the two raw materials. The factors mentioned above would explain the significant lower density of the corn pith (about 13,44kg/m3) when compared with the barley straw (estimated at 24,66kg/m3). Rice husk is a by-product with little applications at the present. It degrades slowly which makes it very difficult to reintroduce in fields. Lately it’s being revalorised for energy production. Rice husk is the densest among the chosen crop wastes: 64,27kg/m3 and present an important amount of silica [15] [22].

2.2. Binder materials

Three different biopolymers were used as binders to produce the panels, two polysaccharide i.g. corn starch and sodium alginate, and a protein: casein.

Corn starch is commonly used in binders and adhesives and thus, it has been widely used in construction, as well as in other industries as packaging and paper making [23]. Alginate is mainly used in cosmetics and food industry, even if a reference was found where it was added to clay bricks [17]. Finally, casein has been used traditionally in construction, it has been widely used as a binder and romans mixed it with mortar to confer consistency and a certain hydrophobicity to the mixture [24].

Corn starch and sodium alginate were provided by Cargill, both presented in the form of a white powder, while casein was provided by the research group Patrimoni-UB (University of Barcelona) in the form of a yellow powder with a strong odour.

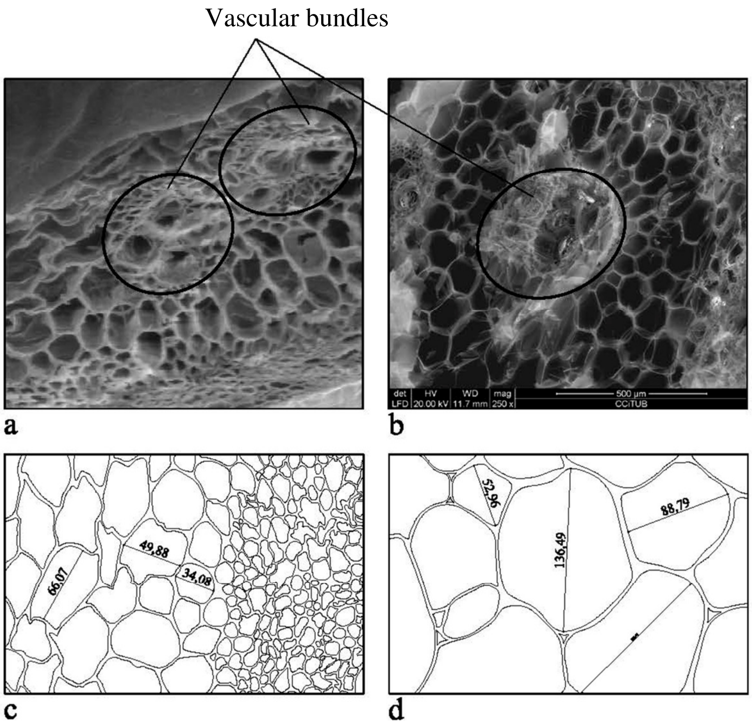

Figure 1. SEM images of barley straw (a) and corn pith (b). Image (a) is scaled four times more than (b). Drawings undernith show both tissues at the same scale, (c) for barley and (d) for corn.

2.3. Sample preparation

The external peel of entire corn stalks was manually removed, as well as nots, to separate the internal pith. Then the pith and the barley straw were chopped separately with a lawnmower and sieved. Rice husk was directly sieved. Particles of 2, 0.5, 1 mm diameter respectively were used in the production of samples. Particle sizes were previously determined taking into account workability and thermal conductivity of the mixtures.

Starch and alginate were mixed with water and a small amount of vinegar (6% acidity) to form a gel. Vinegar and sodium bicarbonate were added to the mixture of water and casein to activate the latter, instead of NaOH and lime usually used.

Samples of two different sizes were prepared for each formulation: 40 x 40 x 2 mm and 150 x 150 x 30 mm. The chosen formulations were obtained from literature and previous work [25]. The aim of this previous work was (1) select the raw materials of study among a wider range of available materials, (2) determine the particle size used in each formulation and (3) reduce the use of binders and other additives to the minimum necessary to agglomerate the mixture. Table 1 shows the final formulations chosen after this previous work.

	Binder	Water	Vinegar	Sodium bicarbonate
S-Barley (0.5 mm)	0.23	2.28	1.20	
S-Corn (2.0 mm)	0.18	3.02	0.60	
S-Rice (1.0 mm)	1.0	1.17	0.40	
A-Barley (0.5 mm)	0.04	2.76	0.50	
A-Corn (2.0 mm)	0.13	7.87	0.50	
A-Rice (1.0 mm)	0.05	2.21	0.42	
C-Barley (0.5 mm)	0.36	1.64	0.40	0.40
C-Corn	0.11	0.49	0.80	0.40
C-Rice	0.11	0.48	0.33	0.17

Table 1: Formulations of the experimental natural insulation materials. Values are expressed in grams for 1g of crop waste material

2.4. Hygroscopic characterization: equilibrium moisture content (EMC) and water vapour diffusivity resistance factor (μ)

EMC was experimentally determined by means of the salt solution method for three different RH (36%, 67% and 94%).

Water vapour diffusivity resistance factor (μ) was determined following the standard UNE-EN 12088. A saturated solution of NaOH (18% RH) and Na_2SO_4 (95% RH) were used for the dry and wet cups respectively. Samples were weighed regularly for a week or until a linear progression in weigh change was observed.

2.5. Thermal characterization: thermal conductivity and dynamic thermal performance

Thermal conductivity (λ) and thermal diffusivity (α) were measured on the big samples with the electronic thermal analyser, QuicklineTM-30, based on the ASTM D5930 standard, at room conditions. Three measurements were done for each sample.

Dynamic thermal behaviour was also analysed. For this purpose, two thermocouples were used: one of them introduced 15 mm below the surface and the second placed on their surface. Samples were conditioned at 12ºC in a fridge until equilibrium was reached. They were then placed in an oven pre-set at 50ºC. They were left there for 1.5 hours and then placed again in the fridge for other 1.5 hours.

3. Results and discussion

3.1. Hygroscopic characterization

Table 2 show the equilibrium moisture content in weigh percentage (EMC%) of the different samples for the three RH studied. The results obtained for the samples with starch and alginate are similar between them and also similar with those obtained by Collet et al [18] for hemp wools. EMC% in these cases is about ten times higher to those that correspond to a mineral wool [26]. Mixtures containing casein have a remarkable higher EMC% in all RH. Further work has to be accomplished in order to elucidate the reason of these extremely high values.

	EMC%			μ	
HR	36%	67%	94%	Dry cup	Wet cup
S-Barley	2.96	10.13	18.27	11.60	3.80
S-Corn	2.48	9.38	20.62	11.18	3.00
S-Rice	3.21	8.73	14.21	12.71	4.56
A-Barley	2.77	10.37	21.72	10.40	4.00
A-Corn	2.26	13.29	28.96	12.80	2.94
A-Rice	2,74	8.86	16.5	9.87	5.31
C-Barley	5.57	24.64	75.69	11.36	4.19
C-Corn	9.11	38.82	94.15	7.80	3.18
C-Rice	6.34	23.85	67.39	12.05	3.51

Table 2. EMC and μ results for the nine specimens analysed

The kind of vegetal waste also has a remarkable effect on EMC%. Samples containing rice are the ones that absorb less moisture followed by barley and corn pith. Nevertheless, this trend is inverted when the moisture content is expressed per volume ratio instead of mass ratio. This is due to the lowest density of corn mixtures as is shown in Table 3.

Values for water vapour diffusivity resistance factor are also shown in Table 2. As expected, the results obtained by the two methods are different, the wet-cup method producing the higher value [27]. Vapour permeability increases as higher humidities are reached. Results are similar to other natural fibre insulation (NFI) materials such as wood fibres and cork insulation boards which present a μ value between 5 and 10 [28]. Nevertheless, hemp fibre usually present a slightly lower μ value, between 1 and 3 [18,28], which is more similar to mineral wools.

3.2. Thermal characterization

Table 3 shows densities and thermal conductivity and diffusivity of the nine specimens analysed. Mixtures containing rice husks present the highest thermal conductivity and the ones containing corn pith the lowest, regardless to the binder used. This result is correlated with the density of the formulations, as rice products are two times denser than corn ones. Regarding the binders, alginate mixtures are less dense and thus present a lower thermal conductivity, while casein seems to increase the thermal conductivity of the mixtures. The best result was for corn and alginate (0.052 W/mK). Results are comparable to wood fibre boards, even if they are higher than other commercially available insulation materials (see Table 3).

As thermal diffusivity is proportional to conductivity and inversely proportional to density, results are similar for all the mixtures.

	δ (kg/m3)	λ (W/mk)	α 10^{-6} (m^2/s)
S-Barley	220	0.075	0.202
S-Corn	160	0.060	0.347
S-Rice	290	0.077	0.330
A-Barley	170	0.066	0.279
A-Corn	80	0.052	0.357
A-Rice	210	0.073	0.332
C-Barley	210	0.074	0.272
C-Corn	140	0.067	0.276
C-Rice	270	0.098	0.377
Mineral wool	20-200	0.035-0.045	-
Expanded polyestirene	15-30	0.035-0.040	-
Extruded polyestirene	25-45	0.030-0.040	-
Wood fibre	30-270	0.040-0.090	-
Hemp wool	20-68	0.040-0.050	-
Cork board	100-220	0.045-0.060	-

Evaluation of the dynamic thermal performance of the materials was also done following the method described in section 2.5. Together with the formulations developed, a sample of rock wool insulation was tested. In general, the temperature inside the sample has a certain delay compared with the temperature of the surface when the sample is changed from the cool camber to the hot one and vice versa.

All samples containing crop wastes experience a similar behaviour. As an example, Figure 2 shows the change in internal temperature against time for corn alginate, and compares it with a mineral wool. As expected, the lower diffusivity of the mineral wool ($0.34\cdot10^{-6}$ m^2/s) with respect to that of the A-corn ($0.36\cdot10^{-6}$ m^2/s) results in a lower slope in temperature change. Nevertheless, at about 40ºC, this tendency is inverted as the A-corn sample needs much more time to reach the temperature of the hot chamber. A similar behaviour is observed when the samples are moved from the hot to the cool chamber. This slowing down in the dynamics is due to the adsorbed-desorbed water vapour in the interior of the fibre matrix and the heating involved in such a process.

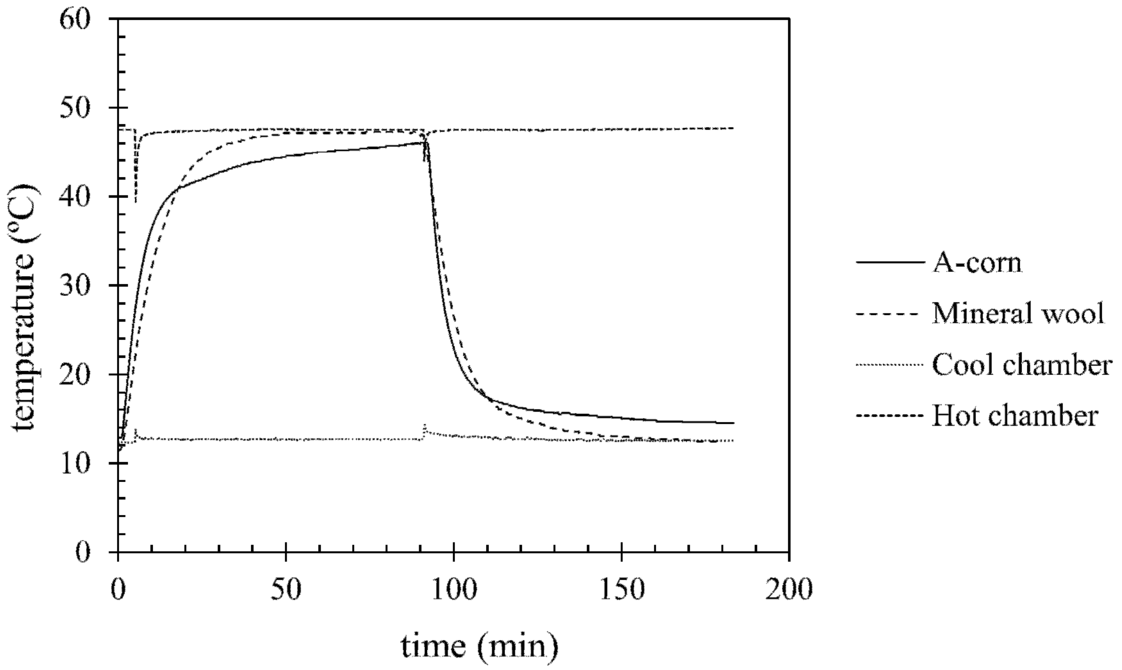

Figure 2: Dynamic thermal behaviour. Internal temperature for A-corn sample is compared with a mineral wool.

4. Conclusions

Different thermal insulation materials based on crop wastes and natural binders where characterised. Their thermal behaviour (both steady state and dynamic), equilibrium moisture content and water vapour permeability were analysed.

The hygroscopicity of the mixtures, measured by the equilibrium moisture content, depend on the specific crop waste used, being mixtures with corn pith the ones with higher values. Mixtures bonded with alginate and starch show similar results while casein seems to substantially increase the moisture sorption of the samples. Water vapour permeability is similar for all the cases and is in agreement with the values found in literature for other fibre insulation materials.

Results for thermal conductivity are acceptable for insulation materials as they are comparable to wood fibre boards, even if they are higher than other commercially available insulation materials such as mineral wools or EPS. The lower value was measured on corn pith bonded with alginate.

The intrinsic hygroscopicity of the natural fibres results on a remarkably different dynamic thermal behaviour when compared with mineral fibres. When environmental temperature increases part of the internal moisture is desorbed. This process involves heat absorption and therefore the increment in sample temperature is lower than expected regarding its thermal diffusivity. The opposite occurs when temperature decreases and moisture is adsorbed. In both cases the thermal inertia of the material is increased.

In conclusion, results show that crop wastes can perform adequately as insulation materials with any or little manipulation. The fabrication process should be improved in order to reduce the density of the mixtures and therefore their thermal conductivity.

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