Study of the Hygric Behaviour and Moisture Buffering Performance of a Hemp–Starch Composite Panel for Buildings

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This paper presents the results of a laboratory investigation into the hygric properties and moisture buffering performance of hemp-starch composite panels designed for building applications. Composite panels were produced by bonding hemp shiv with wheat starch as a binder. Two types of hemp shiv were tested: chemically processed shiv with enhanced adhesion between fibers and starch matrix, and non-treated shiv. The panels were then characterised in terms of their hygroscopic properties (sorption curve and vapour diffusion resistance factor) and their moisture buffering performance (moisture buffering value, MBV). The determination of theoretical MBV was based on the effusivity of the material, which is obtained from its basic hygroscopic characterisation. The results show that both panels are excellent hydric regulators that can be used to improve indoor hygrothermal comfort by buffering indoor relative humidity variations.

Keywords: Hemp; Starch; Green materials; Hydric properties; Moisture buffering

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INTRODUCTION

To control energy consumption, several European countries have adopted regulations to increase building envelope performance with respect to heat loss and air permeability reductions. Because of these changes, there has been an increase in indoor relative humidity levels in occupied buildings, which can lead to health problems and material deterioration if not controlled (Bornehag *et al.* 2001). The use of hygroscopic materials that can buffer indoor moisture levels might bring considerable energy savings and maintain high indoor comfort (Osanyintola and Simonson 2006; Cerolini *et al.* 2009). Among these materials, vegetal fiber materials such as hemp-based materials are a promising solution for the future because they are eco-friendly and are low in embodied energy and carbon-negative materials (Zampori *et al.* 2013). Although many studies have focused on the characterisation of hemp-lime mixtures (Elfordy *et al.* 2008; Evrard and De Herde 2010; Arnaud and Gourlay 2012; Collet and Pretot 2012; Collet *et al.* 2013; De Bruijn and Johansson 2013; Walker and Pavia 2014) and highlighted their high moisture buffering capacity, there have been few studies concerning the use of hemp with other binders with a reduced environmental impact such as corn starch (Balčiūnas *et al.* 2013), wheat starch (Le *et al.* 2014), or hybrid organic-inorganic binders (Sassoni *et al.* 2014). These latter works have focused on the thermal and mechanical properties of the material and good thermal conductivity values have been found within the range from 0.07 to 0.13 $W \cdot m^{-1} \cdot K^{-1}$ depending on hemp hurds size. This paper presents a vegetal fiber composite

material made of hemp shiv and wheat starch as binder, and the preliminary results of hydric property measurements and moisture buffering performance evaluation are reported and discussed. This material is intended to be used as 2.5-cm-thick panels within or on the interior side of a wall. Two types of hemp shiv were tested: chemically treated shiv (TS), with enhanced adhesion between fibers and starch matrix (Umurigirwa *et al.* 2013), and non-treated shiv (NTS).

The primary purpose of our study was to characterise the hygric properties of the panels and assess their moisture buffering performance. Experiments were carried out to determine the sorption isotherm curve and vapour diffusion resistance factor under steady state conditions for each panel. Moisture buffering performance was evaluated in terms of the moisture buffering value (MBV) of the panels, which was also compared to the theoretical value (MBV_{Ideal}) computed from analytical calculations.

EXPERIMENTAL

Materials

Among biopolymers, starch is one of the most promising renewable bio-resources because of its competitive price and applicability to various industries. The native wheat starch NATILOR was provided by the Chamtor Company (France). Starch was extracted from wheat seeds and stored at 50% relative humidity prior to use. Chemically, starch is a mixture of two classes of glucose-based polysaccharides, namely amylose and amylopectin, each of which is linked by glycoside bonds. The heating of starch granules in water or aqueous plasticiser results in a gelatinisation caused by irreversible swelling of the granules, and this mixture forms the binder, which holds fibres together and stabilises the composite structure to ensure shear transmission in the composite (Le *et al.* 2014).

The aggregates are industrial hemp hurds, KANABAT, with a size range from 5 to 20 mm and produced by la Chanvrière de l'Aube (France). Hemp hurds were mixed with wheat starch binder at a hemp/starch ratio of 3.3 by weight. The specimens were compacted at 0.25 MPa using a press. Two compositions were studied, differing in hemp hurd properties: specimens without surface treatment (NTS), and specimens with treated surface (TS), in which hurds were subjected to surface treatment by alkalisation (with 1% NaOH treatment) and then treated with a silane coupling agent (Si) to enhance the adhesion between shives and the polymer matrix (Umurigirwa *et al.* 2013). The final panels for this study have a nominal thickness of 25 mm and densities of 170 and 210 $kg \cdot m^{-3}$ for NTS and TS, respectively.

Methods

Sorption isotherm

The adsorption isotherm was determined according to the European standard EN NF ISO 12571 (2000) using the desiccator method. Four samples of each composition, with dimensions of 10 cm × 10 cm × 2.5 cm, were tested. The hygroscopic salts used were $MgCl_2$, $Mg(NO_3)_2$, NaCl, and KNO_3, giving relative humidities of 33%, 53%, 75%, and 94%, respectively. The desiccators were placed in a climatic chamber at 23 ± 0.5 °C and 50 ± 2% of relative humidity. The moisture content by mass *u* (kg/kg) was calculated according to the following equation:

$$u = \frac{m - m_o}{m_o} = \frac{m_w}{m_o} \quad (1)$$

where m (kg) is the mass of the wet specimen, m_0 (kg) is the mass of the dry specimen at 0% relative humidity, and m_w is the mass of water. The mass was determined with a 10 mg accuracy scale. Initially, specimens were dried for two weeks in a vacuum desiccator containing anhydrous calcium chloride lumps with diameters less than 2 mm. The anhydrous desiccant was dried for 2 h at 250 °C before use. The desorption isotherm was determined from the 94% state.

Vapour permeability

The material's vapour permeability was measured according to the European standard NF EN ISO12572 (2001). The dry cup method and the wet cup method prescribe two standardised procedures for this purpose. The test involved sealing the sample, of a set thickness (d), above a test cup containing saline solution so as to have either a dry cup or a wet cup. The whole system was placed in the climatic chamber with a different vapour partial pressure than that within the cup. Because of the partial vapour pressure gradient between the inner part of the cup and the climatic chamber, the mass of the cup varied. The rate of vapour flow across the specimen under steady state conditions was determined gravimetrically. Before testing, the specimens were stored at 23 °C and 50% relative humidity until they reached a constant weight. After this, they were sealed on the open side of the cup containing anhydrous calcium chloride flocks (Fig. 1a) or saturated potassium nitrate solution (Fig. 1b). The assembly was placed in a climatic chamber at 23 °C and 50% relative humidity (Fig. 1c). Five samples for each composition with diameters of 10 cm and thicknesses of 2.5 cm were tested and weighed periodically. The results are expressed as water vapour permeability δ and the vapour resistance factor μ,

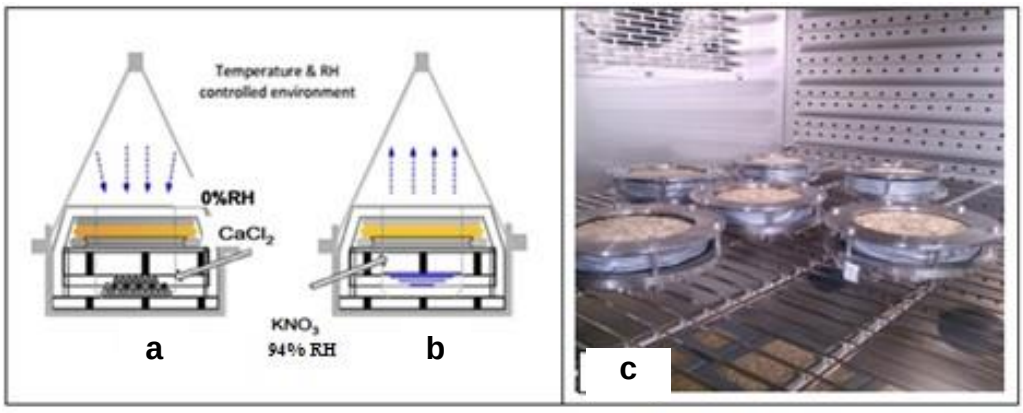

Fig. 1. Experimental apparatus for water vapour permeability measurements: (a) dry-cup method; (b) wet-cup method; and (c) samples placed in the climatic chamber

$$\delta = W_c \cdot d \quad (2)$$

$$\mu = \frac{\delta_a}{\delta} \quad (3)$$

where W_c is the water vapour permeance ($kg \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$), which as corrected to take into account the air layer resistance in the cup according to NF EN ISO 12572 (2001), d is the test specimen thickness (m), and δ_a ($kg \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}$) is the water vapour permeability in air.

Moisture buffer value

The moisture buffer value was measured according to the method defined in the NORDTEST Project (Rode 2005). For this test, the edges and the back-sides of samples were sealed to obtain a one-dimensional moisture flow. Samples were stabilised at 23 ± 0.5 °C and 50 ± 2% RH in a climatic chamber and weighed until the attainment of equilibrium was determined. After stabilisation, the protocol defines cyclic step-changes in relative humidity between high (75%) and low (33%) values for 8 and 16 h, respectively, until the change in mass is less than 5% between the three last cycles. The step changes in relative humidity were achieved within 10 min from low to high RH and within 30 min from high to low RH. The change in mass (Δm) of the sample during the uptake period gives the practical MBV in $g \cdot m^{-2} \cdot \%RH^{-1}$. Samples were weighed during the adsorption and desorption period with five measurements at high relative humidity and two measurements at low relative humidity. The practical MBV was calculated by,

$$MBV_{practical} = \frac{\Delta m}{A \cdot \left(RH_{high} - RH_{low}\right)} \quad (4)$$

where A is the area of the specimen, RH_{high} is the highest relative humidity, and RH_{low} is the lowest.

The $MBV_{practical}$ value can be compared to an ideal value, called MBV_{ideal}, which is the theoretical buffer capacity computed using semi-infinite solid theory and a Fourier series without transfer resistance at the exchange surface (Rode 2005; Rode *et al.* 2007),

$$MBV_{Ideal} \approx 0.00568\, p_{sat} b_m \sqrt{\tau} \quad (5)$$

where b_m ($kg \cdot m^{-2} \cdot Pa^{-1} \cdot s^{-0.5}$) is the moisture effusivity of the material, p_{sat} (Pa) is the pressure of saturation (2816 Pa at 23 °C), and τ is the time period of the stepwise relative humidity variation (24 h = 86,400 s.) The moisture effusivity describes the capacity of the material to adsorb and release moisture on its surface. It is given by:

$$b_m = \sqrt{\frac{\delta \cdot \rho_0 \cdot \xi}{p_{sat}}} \quad (6)$$

where ρ_0 is the density of the dry material ($kg \cdot m^{-3}$). The quantity ξ is the moisture capacity ($kg \cdot kg^{-1}$).

According to the NORDTEST protocol, the total exposed surface area should be greater than 300 cm^2. For material thickness, the test protocol permits two options: the thickness as in the intended practical application, or a thickness larger than the 1% penetration depth for daily humidity variations. The latter is defined as the depth at which

moisture amplitude variation within the material falls to 1% of its original value at the surface. For sinusoidal variations, it is given by Arfvidsson (1999),

$$d_{p,1\%}=4.61\sqrt{\frac{D_m\cdot\tau}{\delta}} \quad (7)$$

$$D_m=\frac{\delta\cdot p_{sat}}{\rho_0\cdot\xi} \quad (8)$$

where D_m is the moisture diffusivity of the material ($m^2\cdot s^{-1}$), δ is the material vapour permeability, and τ is the time period (s). For both TS and NTS specimens, two thicknesses (2.5 and 5 cm) were tested and compared, as shown in Table 1 and Fig. 2a and Fig. 2b.

Table 1. Thickness and Dimensions of Specimens for MBV Determination

	Thickness (cm)	Dimensions (cm × cm)	Number of specimens
NTS	2.5 5.0	20 × 20 20 × 20	2 2
TS	2.5 5.0	20 × 20 10 cm diameter	1 4

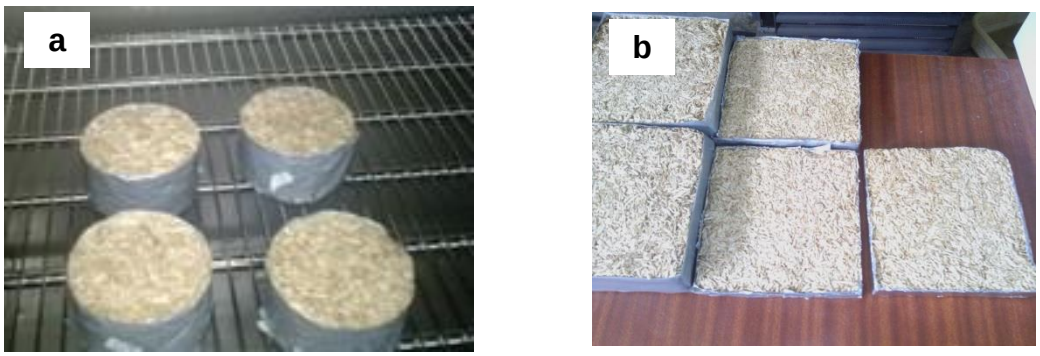

Fig. 2. Specimens after sealing for the MBV test: (a) the TS with 5 cm thickness (b) remaining specimens.

RESULTS AND DISCUSSION

Sorption Isotherms

Figure 3 shows the experimental values for the sorption test measurement for NTS (Fig. 3a) and TS (Fig. 3b). These curves have a sigmoid or S-shape profile and correspond to type II of the classification of BET sorption modes, which is typical for cellulosic materials (Nilsson *et al.* 2005; Alix *et al.* 2009; Célino *et al.* 2014).

The relationship between mass content and relative humidity is an increasing nonlinear function. As the hemp/binder ratio is the same for both shiv types, their sorption curves show the same behaviour. For low and medium relative humidities, the gravimetric water content increases slightly *versus* relative humidity to reach about 5.6% at 53% RH

for the adsorption branch for TS specimens and 5.5% for NTS. For higher relative humidities, the water content strongly increases and reaches about 18.5% at 94% RH for TS and 17.2% for NTS. It can be observed that (Si) treatment did not reduce the water sorption, in accordance with results obtained for flax fibers (Alix *et al.* 2009). Within the studied domain, a hysteresis loop can be seen that is increasing with relative humidity. It is possible to calculate a hysteresis value by subtracting the water content during the drying isotherm from that during the wetting isotherm. This value is 2% at 75% RH and 1% at 33% RH for TS and 1.5% and 0.2%, respectively, for NTS. This hysteresis is commonly explained by capillary condensation hysteresis, contact angle hysteresis, and the inkbottle effect (Derluyn *et al.* 2012). The difference between TS and NTS is explained by the fact that treating fibers with NaOH and adding (Si) effectively changed the surface topography of the fibers and their crystallographic structure (Mwaikambo and Ansell 1999), enhancing hysteresis phenomena (Bilba and Arsene 2008).

There are various models to adjust the sorption isotherms obtained from the hygroscopic sorption test. In this study, the one based on the following analytical expression (Merakeb *et al.* 2008) was used,

$$\ln\left(\frac{u}{u_s}\right) = a\,\ln(\phi)\exp(b\cdot\phi) \qquad (9)$$

where u is the moisture content (kg·kg^{-1}), u_s is the saturation moisture content (kg·kg^{-1}), ϕ is the relative humidity, and a and b are fitting parameters. The values of such parameters are shown in Table 2 for both TS and NTS and for the mean sorption curve (average between adsorption and desorption); the adjustment curve is shown in Fig. 3.

Table 2. Sorption Isotherm Parameters

	u_s	a	b
TS	0.222	1.113	1.055
NTS	0.211	1.145	1.126

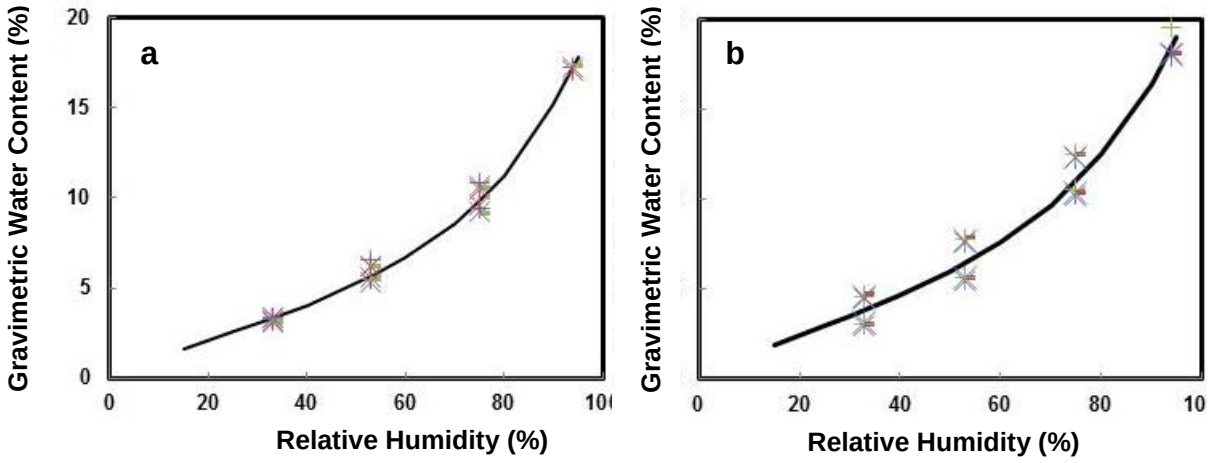

Fig. 3. Sorption isotherms for the hemp-starch composite: (a) non-treated specimens and (b) treated specimens

Vapour Resistance Factor

The vapour resistance factor was adjusted according to the analytical form proposed by Roels *et al.* (2010),

$$\mu = \frac{1}{a + b\, e^{c\phi}} \tag{10}$$

where *a*, *b*, and *c* are fitting parameters. An additional permeability test was added at (0/25%) to compute the analytical form coefficients. The values of these parameters are shown in Table 3, and the adjusted curve is shown in Fig. 4a for NTS and Fig. 4b for TS.

Table 3. Water Vapour Resistance Factor Parameters

	a	*b*	*c*
TS	0.192	0.0107	3.03
NTS	0.177	0.00515	3.4

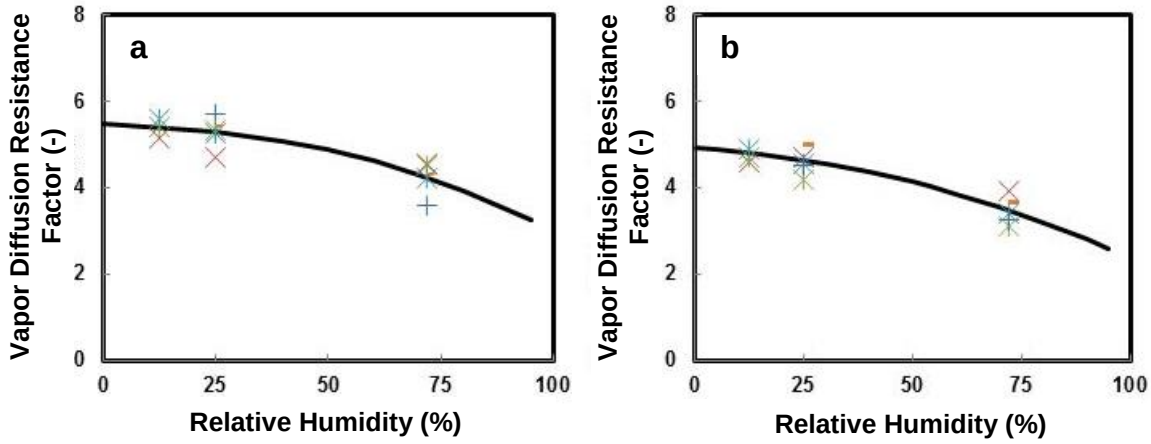

Fig. 4. Vapour resistance factors for the hemp-starch composite: (a) NTS and (b) TS

With the dry cup test, the value of the vapour resistance factor of NTS was 5.28 ± 0.35, which is comparable to the values of hemp-lime mixtures. This value is higher than that obtained by Evrard and De Herde (2010), lower than that recorded by Collet *et al.* (2013), and similar to that of Walker and Pavia (2014). For the TS, the average value of the dry cup test was 4.58 ± 0.3, which is lower than that of NTS. These results suggest that the spaces between hemp particles strongly contribute to the permeability. For higher relative humidities (wet cup test method), the vapour resistance factor decreases, as indicated by other authors using the same test method (Roels *et al.* 2004; Sonderegger and Niemz 2009). For NTS, the vapour resistance factor is 4.22 ± 0.38; for TS, it is 3.47 ± 0.33.

Table 4. Moisture Buffering Properties at 54% RH

	μ	ξ (kg·kg^{-1})	D_m (m^2·s^{-1})	b_m (kg·m^{-2}·Pa^{-1}·s$^{-0.5}$)	$d_{p,1\%}$ (cm)	MBV_{Ideal} (g·m^{-2}·%RH^{-1})
NTS	4.77	0.14	4.93×10^{-9}	5.97×10^{-7}	3.1	2.8
TS	4.03	0.156	4.26×10^{-9}	7.6×10^{-7}	2.9	3.6

Moisture Buffer Value

Table 4 shows moisture buffering properties of both TS and NTS as computed from Eqs. 5 through 10 for an average relative humidity of 54%. Both materials have high moisture capacity and high vapour permeability. They belong to group C, according to the material categorisation of Ge *et al.* (2014), and thus are expected to show a high moisture buffering potential under long and short moisture loads. The TS specimens perform better than the NTS because they have higher moisture sorption effusivity and lower vapour diffusion resistance. The ideal MBV of the NTS is 2.8 $g \cdot m^{-2} \cdot \%RH^{-1}$, and that of TS is 3.6 $g \cdot m^{-2} \cdot \%RH^{-1}$.

Table 5. Practical Moisture Buffer Value ($g \cdot m^{-2} \cdot \%\ RH^{-1}$) for 5-cm-thick Hemp-Starch Specimens (both TS and NTS): Last Three Cycles

Specimen	T1	T2	T3	T4	NT1	NT2
Average MBV ($g/(m^2\ \%RH)$)	3.36	3.36	3.41	3.45	2.46	2.41
Standard deviation ($g/(m^2\ \%RH)$)	0.05	0.05	0.02	0.03	0.05	0.03

Table 5 shows the average value of the practical MBV for TS and NTS (5 cm) for the last three cycles, and Fig. 5 shows the MBV *versus* cycle number for the treated and untreated specimens. The steady state was reached by cycle 4 for TS and by cycle 3 for NTS specimens (mass variation was less than 5% within each cycle). For TS, the values obtained were in the range of 3.36 to 3.45 $g \cdot m^{-2} \cdot \%RH^{-1}$, with an average value of 3.39. The average value of the NTS specimen was 2.43 $g \cdot m^{-2} \cdot \%RH^{-1}$.

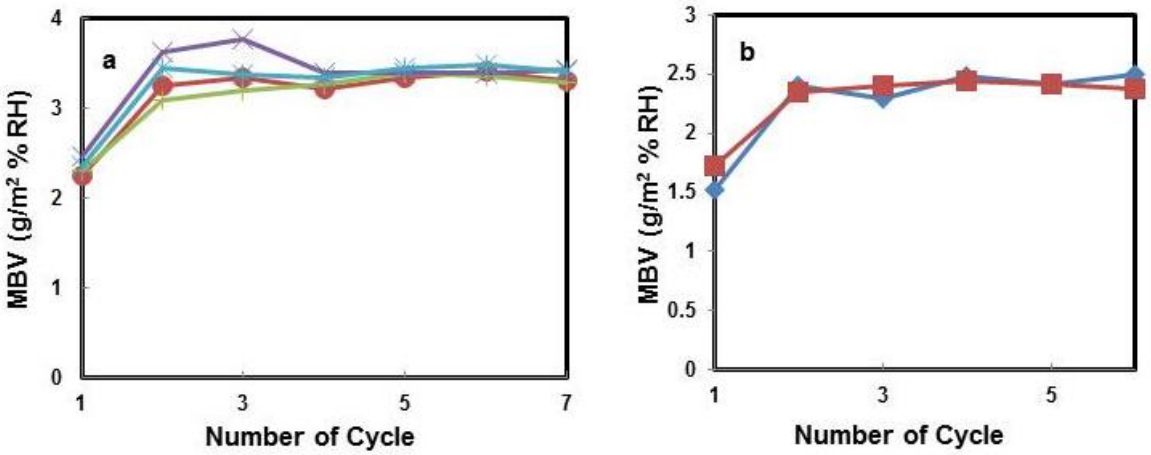

Fig. 5. The moisture buffer value *versus* cycle number: a) for treated specimens b) for untreated specimens

Table 6. Practical Moisture Buffer Value ($g \cdot m^{-2} \cdot \%\ RH^{-1}$) as a Function of Thickness

Thickness (cm)	TS	NTS
2.5	3.49	2.52
5	3.39	2.43

Table 6 compares values of the MBV as a function of thickness. The BMV values found for 2.5 cm and 5 cm thickness were too close and they were lower than the ideal MBV values computed in Table 4. These results are in accordance with those of Roels and Janssen (2006), who showed that the MBV value drops quickly for thicknesses less than a $1/e$ (about 37%) penetration depth; at higher thicknesses, the MBV varies slightly.

Compared to other materials, hemp-starch materials exhibit an excellent moisture buffering performance; they perform better than hemp-lime mixtures, whose practical MBV is around 2.15 $g \cdot m^{-2} \cdot \%RH^{-1}$ (Collet and Pretot 2012; Collet *et al.* 2013), and they have a similar behaviour to that of pure cellulosic materials, whose practical MBV is 3 $g \cdot m^{-2} \cdot \%RH^{-1}$ (Cerolini *et al.* 2009). Treatment of the fibres increases the MBV value by approximately 39%. For both cases, the panels can be classified as "excellent" in concordance with the classification established by the NORDTEST protocol (Rode 2005). Thus, when applied on internal wall surfaces, these panels can be used to increase the hygrothermal comfort level and buffer indoor RH variations. However, these values are valid only for uncoated panels. When a coating is applied in order to increase material durability, the MBV value is expected to decrease.

CONCLUSIONS

1. The hydric properties and moisture buffering capacity of an agro-composite panel made of hemp hurds and wheat starch as a binder were studied with and without fibre chemical treatment. The adsorption isotherm curves show that fibre treatment enhances hysteresis phenomena and increases the material moisture capacity.
2. In relation to practical moisture buffering value, the uncoated panels exhibited an excellent performance and can be used to regulate indoor relative humidity. This practical value is expected to decrease when a coating is applied in order to enhance material durability, especially for the untreated specimens.
3. The present study provides an experimental data set that can be used in models *via* hygrothermal software to explore the suitability of these materials for different wall types and weather conditions. Further tests are in progress to evaluate additional physical properties as well as reaction to physical durability and biological degradation.

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