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Hygic Properties of Hemp Bio-Insulations with Differing Compositions

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Abstract

The paper presents the results of a laboratory investigation on the hygic properties of five hemp insulation materials commercially available in the UK. The hemp fibre content varies between 30-95% in the total fibre content of the insulation materials examined. The adsorption-desorption isotherm, moisture buffer value, vapour diffusion resistance factor and water absorption coefficient were determined for the insulation materials investigated. The results showed that the hygic properties of the hemp insulation materials could vary widely depending on the constituents and fibrous structure. The considerable differences noted in the hygic properties of the insulation materials examined could potentially influence their hygrothermal performance as part of a building thermal envelope.

Keywords: Hemp thermal insulation; Hygic properties; Hygrothermal properties; Thermal insulation materials; Moisture buffering; Adsorption isotherm.

1. Introduction

Use of sustainable materials is becoming an integral part of the construction process in response to the concerns over resource depletion and global warming. As such,

sustainability and efficiency are becoming key criteria for selecting thermal insulation materials [1]. Hemp insulation is a plant-based, renewable and carbon-negative thermal insulation material. Among the bio-based thermal insulation materials, hemp insulation is of particular importance in the UK. Hemp is a high yield and low input crop with the additional advantages of being a break crop in cereal rotations. Other benefits include weed control and less field operation. Compared to the conventional mineral and petrochemical based thermal insulation materials like stone wool, glass fibre and expanded polystyrene (EPS) insulations, hemp insulation is a relatively new product. Hence, limited information is available on the hygric and thermal properties of hemp insulations. The effects of hygric properties of insulation materials on the hygrothermal performance of building envelopes are manifold. Moisture can effect heat flux, heat capacity, condensation, mould growth and structural integrity [2]. If the key hygric and thermal properties of the insulations are known, the data can then be assessed individually or can be used in numerical simulation software to study the hygrothermal performance of the materials in building envelope for given hygrothermal boundary conditions. Thus, for example, it can be determined whether a vapour barrier is required in a thermal envelope or how long it will take for a wet insulation to dry out.

This paper characterises five types of hemp insulation materials available in the UK market in terms of the following key hygric properties: adsorption-desorption isotherm, moisture buffer value (MBV), vapour diffusion resistance factor (μ value) and water absorption coefficient (A value). The moisture buffer value represents the materials' relative humidity management capacity in adjacent spaces. The other three parameters (adsorption-desorption isotherm, vapour diffusion resistance factor and water absorption coefficient) can be used in hygrothermal and biohygrothermal

simulation software to study the hygrothermal performance and mould growth potential of the insulation materials in various building envelopes and climatic conditions.

2. Theory

2.1 Adsorption-desorption isotherm

Adsorption is the increase in the concentration of a dissolved substance at the interface of a condensed and a liquid or a gaseous phase due to the operation of surface forces [3]. An adsorption isotherm is the constant temperature relationship between the amounts of adsorbate accumulated by the unit quantity of adsorbent in equilibrium condition in a range of partial pressure [4]. An adsorption isotherm can be divided into three distinct regions in relation to water storage functions (Fig. 1).

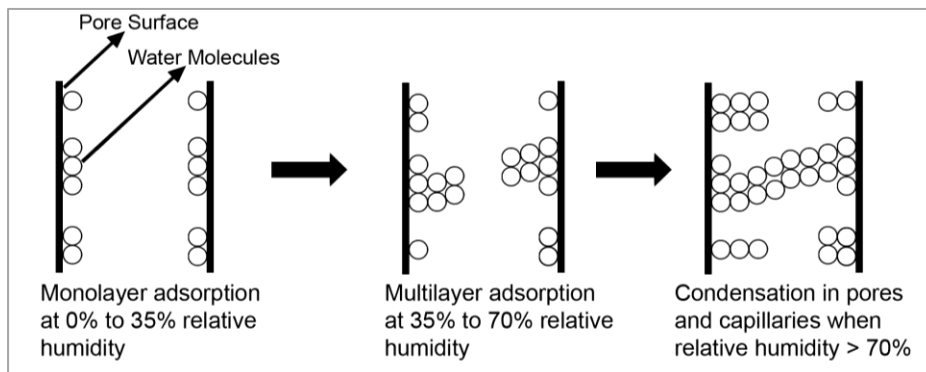


Fig.1. Physisorption, adopted from Osborne [5].

At lower relative humidity, 0-15% according to Hill, Norton and Newman [6] and 5-35% according to Collet et al [7], water molecules are adsorbed in a monolayer (solid solution) on to the internal surfaces of the cell wall. Multi-molecular layers of water are formed on the cell wall micro-capillaries at a relative humidity varying between 15% and 70%, while capillary condensation occurs at further higher relative humidity ranges. Area covered by 0% to 95-98% relative humidity is defined as hygroscopic region. Adsorption isotherms, in subcritical temperature, are classified by the

International Union of Pure and Applied Chemistry (IUPAC) into six distinct types [8], as shown in Fig. 2.

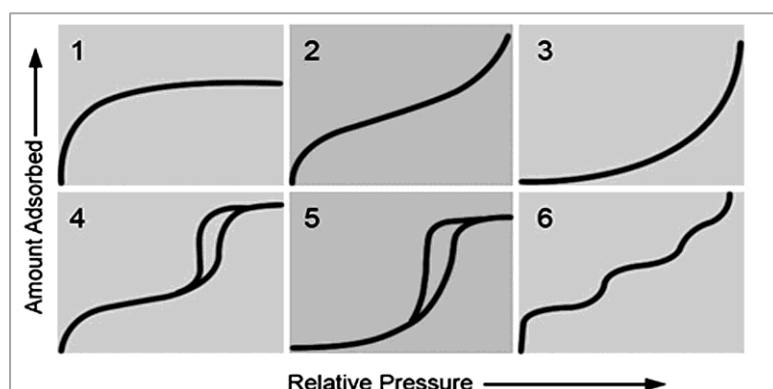


Fig. 2. IUPAC classification of adsorption isotherms.

Type 1 corresponds to Langmuir isotherm describing monolayer adsorption on microporous (pore widths below 2 nm) adsorbent. Type 2 describes adsorption on macroporous adsorbent with adsorbent-adsorbate interaction. There is initial formation of monolayer and subsequent formation of multilayer. Type 3 describes multilayer isotherm on macroporous adsorbent with weak adsorbent-adsorbate interaction. Type 4 and 5 represent adsorption isotherm with hysteresis. Capillary condensation occurs in mesopores (pore widths from 2 to 50 nm) in these two types. Type 6 includes steps that occur due to phase transition of adsorbed molecular layer or due to adsorption on different faces of crystalline solids.

2.2 Moisture buffering

Moisture buffer capacity is a property by which hygroscopic materials in touch with surrounding air adsorb and desorb moisture to create equilibrium with the relative humidity of the surrounding space. Moisture buffering capacity can be used for moderating the humidity fluctuations in internal spaces. Several quantitative methods are available to determine and represent moisture buffering capacity such as the method developed by the Organisation for Testing in the Nordic Countries (NORDTEST) [9], Japanese Standards [10], ISO standard [11] and the method

proposed by Padfield [12]. Among them, NORDTEST method is mostly used in the European context. The three ways of representing moisture buffering capacity described by NORDTEST method are explained in subsections 2.2.1- 2.2.3.

2.2.1 Moisture effusivity

Moisture effusivity (b_m) is the measure of the ability of the material to exchange moisture with its surroundings when the surface of the material is exposed to sudden change in humidity. The equation for moisture effusivity is:

$$b_m = \sqrt{\frac{\delta_p \cdot \rho_0 \cdot \left(\frac{\partial u}{\partial \varphi}\right)}{P_s}} \quad (1)$$

Where b_m is the moisture effusivity [$\text{kg}/(\text{m}^2 \cdot \text{Pa} \cdot \text{s}^{1/2})$], δ_p is the vapour permeability [$\text{kg}/(\text{m} \cdot \text{s} \cdot \text{Pa})$], ρ_0 is the dry density of the material (Kg/m^3), u is the moisture content (kg/kg), φ is the relative humidity (-), P_s is the saturation vapour pressure (Pa).

2.2.2 Ideal moisture buffer value

The most common step change function for moisture buffering is to expose the surface to 75% relative humidity for 8 hours and to 33% relative humidity for 16 hours in each testing cycle. The equation for the relationship between surface moisture flux and time is:

$$G(t) = \int_0^t g(t) dt = b_m \cdot \Delta P \cdot h(\alpha) \cdot \sqrt{\frac{t_p}{\pi}} \quad (2)$$

Where $G(t)$ is the accumulated moisture uptake (kg/m^2) and the corresponding moisture release during a time period t_p , $g(t)$ is the moisture flux over the surface at time t and $h(\alpha)$ can be expressed by the following equation:

$$h(\alpha) = \frac{2}{\pi} \sum_{n=1}^{\infty} \frac{\sin^2(n\pi\alpha)}{n^{3/2}} \approx 2.252[\alpha(1 - \alpha)]^{0.535} \quad (3)$$

where α is the fraction of the time period when moisture load is high. In this case the value of $\alpha = 1/3$ and $h(\alpha) = 1.007$ and therefore Eq. 2 becomes:

$$G(t) \approx 0.568 \cdot b_m \cdot P_s \cdot \sqrt{t_p} \quad (4)$$

The value (MBV_{ideal}) is determined by dividing Eq. 4 by the change in relative humidity, as follows:

$$MBV_{ideal} \approx \frac{G(t)}{\Delta RH} = 0.568 \cdot b_m \cdot P_s \cdot \sqrt{t_p} \quad (5)$$

Where ΔRH is the change of relative humidity (%). MBV_{ideal} is measured in $[\text{kg}/(\text{m}^2 \cdot \%RH)]$.

2.2.3 Practical moisture buffer value

Practical moisture buffer value $MBV_{practical}$ is the amount of moisture content that passes through the unit open surface of the material during a certain period of time when the material is exposed to variation in relative humidity of the surrounding air. The unit of $MBV_{practical}$ is $[\text{kg}/(\text{m}^2 \cdot \%RH)]$.

2.3 Vapour permeability and vapour diffusion resistance factor

Moisture transfer occurs through porous materials when there is vapour pressure differential between two opposite surfaces. Fick's law [13] expresses isothermal moisture transfer by the following equation:

$$g_v = -\delta \cdot \nabla \rho_v \quad (6)$$

Where g_v is the vapour/moisture flux $[\text{kg}/(\text{m}^2 \cdot \text{s})]$, δ is the vapour permeability of the porous system in the material $[\text{kg}/(\text{m} \cdot \text{s} \cdot \text{Pa})]$, ρ_v is the water vapour partial pressure (Pa).

Vapour diffusion resistance factor is introduced by Krischer [13] on the basis that vapour flow rate through a unit surface of air is always higher than that through a unit

surface of a porous material. The equation for the vapour diffusion resistance factor is expressed as:

$$\mu = \frac{\delta_a}{\delta} \quad (7)$$

Where μ is the vapour diffusion resistance factor (-), δ_a is the vapour permeability of air [kg/(m.s.Pa)].

The diffusion equation is expressed in terms of vapour diffusion resistance factor as follows:

$$g_v = \frac{\delta_a \cdot \nabla \rho_v}{\mu} \quad (8)$$

Vapour transmission property is also expressed in terms of the thickness of a motionless air layer which has the same water vapour resistance as the test specimen and expressed as the water vapour diffusion equivalent air-layer thickness (S_d value). S_d is expressed in meters (m) and is given by the following equation:

$$S_d = \mu \cdot d \quad (9)$$

Where d is the thickness of the sample (m).

2.4 Water absorption coefficient

When a porous material is in direct contact with liquid water, water will be absorbed by the free water surface into the material by capillary forces. When the contact is removed, water can be redistributed in the material. The amount of water absorbed is proportionate to the square root of time. The water absorption coefficient or 'A' value is thus expressed as the ratio of water flux through the free water surface and the square root of time and is determined by a one-directional free water intake test. Materials with higher water absorption coefficient can effectively manage liquid water in situations such as direct exposure to driving rain, surface diffusion, etc. Materials

are more susceptible to the exposure to water during the construction phase than in service conditions.

3. Material and method

3.1 Material

Five commercially available hemp insulation materials in the UK are selected for hygric characterisation. Their commercial names are replaced by the following names: Hemp-1, Hemp-2, Hemp-3, Hemp-4 and Hemp-5. The properties of the insulation materials investigated are summarised in Table1.

Table 1. Summary of the insulation properties.

Materials	Measured mean density (Kg/m ³)	Measured mean thickness (mm)	Constituents	Declared specific heat capacity (J/kg.K)	Declared dry thermal conductivity (W/m.K)
Hemp-1	55	48	30% hemp fibre, 60% wood fibre, 10% polyester.	1700	0.038
Hemp-2	50	55	85% hemp fibres, 10-12% bi-component fibres and 3-5% soda.	1600	0.038
Hemp-3	60	47	70% hemp fibres, 15% hemp shive, 8% ammonium phosphate, 7% polyolefin fibres	1700	0.043
Hemp-4	39	45	95% hemp fibres and 5% combination recycled adhesive binder.	1700	0.039
Hemp-5	45	57	35% hemp fibre, 35% recovered waste cotton fibre, 15% bi-component polyester fibre and 15% fire retardant.	1700	0.039

Figure 3 shows the scanning electron microscopy (SEM) images of the hemp insulations. The average diameter of hemp fibre bundles in hemp insulations are as follows: 43 µm for Hemp-1, 46 µm for Hemp-2, 24 µm for Hemp-3, 55 µm for Hemp-4, 40 µm for Hemp-5. Fast Fourier Transform (FFT) of the images shows that fibres are randomly oriented in all insulation materials analysed.

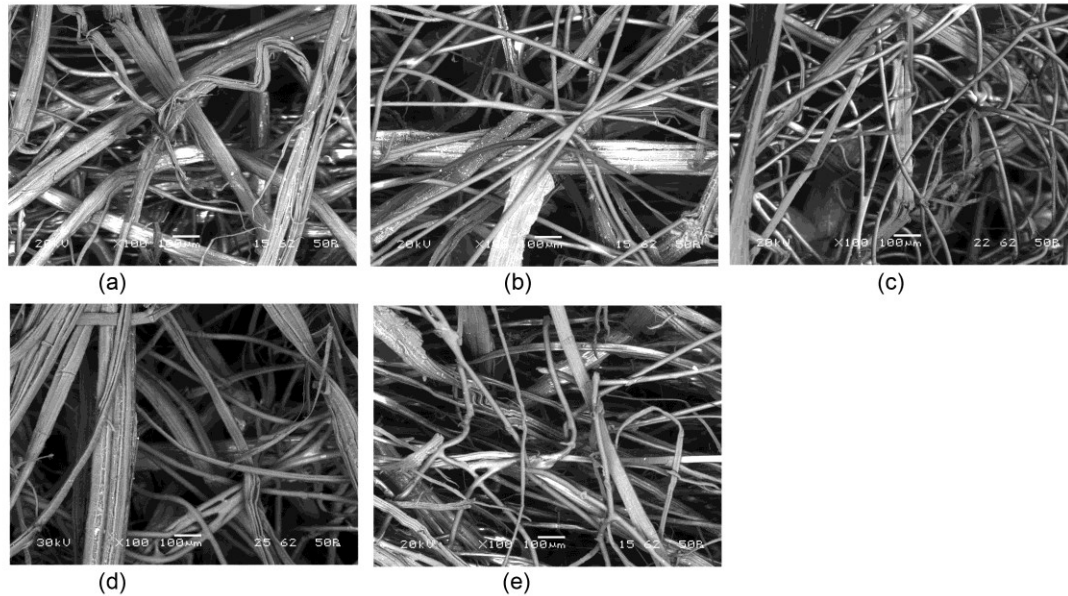


Fig. 3. SEM images of the hemp insulations at 100X magnification: (a) Hemp-1, (b) Hemp-2, (c) Hemp-3, (d) Hemp-4, (e) Hemp-5.

3.2 Method

3.2.1 Determination of adsorption-desorption isotherms

3.2.1.1 Method

The methods for experimentally determining the adsorption-desorption isotherms of thermal insulating materials are outlined in the British Standard BS EN ISO 12571 [14]. Three samples of a dimension of 200 mm X 200 mm with true thickness are initially dried in a ventilated oven at 40 ± 2 °C and less than 10% relative humidity to reach constant mass. Constant mass is considered to be reached when the change in the mass of the test specimens over a 24 hour period is less than 0.1 % of the total mass when weighed in a scale with an uncertainty not greater than 0.1 % . The precision scale that was used had both readability and repeatability of 0.001 grams (g). To determine the adsorption isotherm, the samples are consecutively exposed to minimum four evenly distributed increasing humidity conditions between 30% to 95% while keeping the temperature constant at $23 (\pm 0.5)$ °C in a climate chamber. For

determining the desorption isotherm, the process is carried out in reverse order. During each exposure, the samples have to reach equilibrium moisture content (EMC). For EMC, constant mass is reached if the change of mass between three consecutive weighings, each made at least 24 hours apart, is less than 0.1 % of the total mass. To study the kinetics of adsorption, the mass of the samples were measured at every 8 hours during the adsorption phase.

The adsorption/desorption of moisture content by weight U (kg/kg) is calculated as follows:

$$U = \frac{m - m_0}{m_0} \quad (10)$$

Where, m_0 is the mass of the material at dry condition (kg) and m is the mass of the material at the equilibrium moisture content at any relative humidity (kg).

3.2.1.2 Analysis of adsorption-desorption Isotherm

The ‘Guggenheim, Andersen and de Boer’ (GAB) equation [15] has been selected for the interpretation of the experimental adsorption data. The GAB isotherm is based on further modification of Brunauer, Emmett and Teller (BET) isotherm [15]. Like the BET formulation, the GAB formulation also assumes that adsorbate molecules beyond the first layer are similar. However, according to the GAB model, the states of the other adsorbate layers are different at pure liquid state. For this reason, the GAB equation introduces an additional parameter, namely K , that determines the state of the adsorbed molecules beyond the first layer [15]. The equation for the GAB isotherm is:

$$W(\varphi) = \frac{W_{mG} C_G K \varphi}{(1 - K \varphi)[1 + (C_G - 1)K \varphi]} \quad (11)$$

Where W is the moisture content of the material on a dry basis (-), C_G is the energy constant related to the difference of free enthalpy of water molecules in the liquid

state and in the monolayer and is defined as the ratio of the partition function of the first molecule adsorbed on a site and the partition function of the molecules adsorbed beyond the first molecule in the multilayer. W_{mG} is the temperature-dependent monolayer value in the same unit as W and it is the measure of the availability of active site for water sorption. K is a constant, characterizing the state of the adsorbed molecules beyond the first layer.

The linearized function of the GAB isotherm is:

$$F(\text{GAB}) \equiv \frac{\varphi}{(1 - K\varphi)W(\varphi)} = \frac{1}{C_G K W_{mG}} + \frac{C_G - 1}{C_G W_{mG}} \varphi \quad (12)$$

The GAB equation has been chosen for its higher coverage of activity range for monolayer sorption values ($0.05 < \varphi < 0.8-0.9$) [7] compared to that of BET equation ($0.05 < \varphi < 0.3$). K value is determined from the best linearization plot of $F(\text{GAB})$ versus φ . The other two constants, W_{mG} and C_G , are then determined from two linear regression coefficients.

3.2.2 Determination of moisture buffer value

The moisture buffering experiment was carried out according to the NORDTEST protocol [9]. Three samples of insulation materials were used in the experiment. Each sample had an exposed surface area of 100 mm X 100 mm. The other five surfaces of each sample were sealed with aluminium foil tape, as shown in Fig. 4.

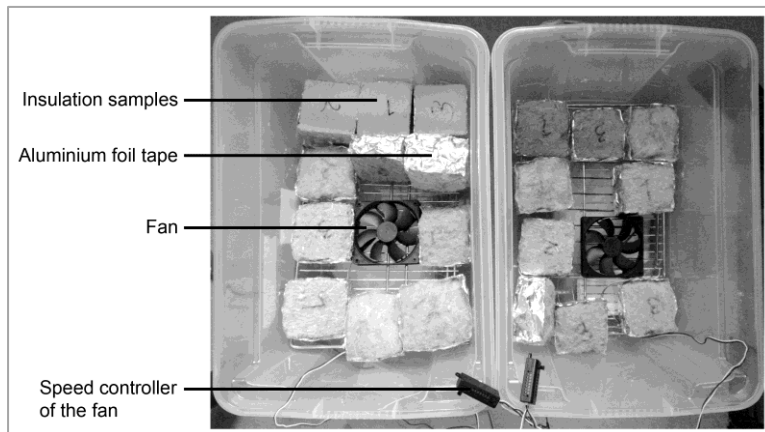


Fig.4. Moisture buffering test setup.

The thickness of each sample was the actual product thickness. The test conditions are shown in Table 2. The materials are exposed to cyclic relative humidity conditions. Each 24-hour cycle is a combination of 8-hour exposure to 75% relative humidity and 16-hour exposure to 33% relative humidity at 23 °C temperature. As suggested by the NORDTEST method, air velocity of 0.1 ± 0.05 m/s is maintained by two fans with controllers, as shown in Fig. 4.

Table 2. The test conditions of moisture buffering for all the insulation samples.

Temperature (°C)	Relative Humidity (%)	Exposure (Hours)	Time	Salt Used
23 ± 0.5	33 ± 3	$16 \pm (10 \text{ minutes})$		MgCl ₂
23 ± 0.5	75 ± 3	$8 \pm (10 \text{ minutes})$		NaCl

At each of the cycles, the change of mass of the insulation samples Δm (g) is calculated as the average of the mass gain during adsorption and mass loss during desorption. The measurement of mass was performed by a precision scale with readability and repeatability of 0.001grams (g). The experiment is continued until there is not more than 5% variation in 3 consecutive determinations of Δm . Kinetics of mass was measured during the final cycle. $MBV_{practical}$ is expressed as weight change per m² per ΔRH and is measured in g/(m².%RH).

In loft applications, insulations are directly exposed to the ambient conditions of the loft space and in wall applications, insulations are usually covered with a 12.5 mm layer of plasterboard. Moisture buffer tests were carried out to simulate both situations.

3.2.3 Determination of vapour diffusion resistance factor

The vapour diffusion resistance factor of thermal insulating materials can be determined following the British Standard BS EN 12086 [16]. Five samples of a dimension of 100 cm² and thickness of 40 mm-100 mm are initially conditioned for at

least 6 hours at $(23 \pm 2)^{\circ}\text{C}$ temperature and $(50 \pm 5)\%$ relative humidity to reach constant mass. The insulation specimens are placed on glass dishes containing salt solutions or dessicants, depending on the test type (dry cup or wet cup). The sides of the insulations are adequately sealed to achieve one directional moisture flow. For the dry cup test, the relative humidity inside the dishes is 0% and outside the dishes is $50 (\pm 3)\%$. For wet cup test, the relative humidity inside the dishes is $50 (\pm 3)\%$ and outside the dishes is $93 (\pm 3)\%$. The test assembly is then conditioned in the climate chamber for 1 to 24 hours. The differential of partial vapour pressure between 'in the atmosphere' and 'in the test assembly' drives the vapour through the specimen. The assembly is weighed at every 24 hours until five successive determinations of change in mass per unit time for each specimen in $\pm 5\%$ of the mean value.

The rate of change in mass is calculated from the following equation:

$$G_{1,2} = \frac{(m_2 - m_1)}{(t_2 - t_1)} \quad (13)$$

Where m_1 (mg) is the mass of the test assembly at time t_1 , m_2 is the mass of the test assembly at time t_2 . The times t_1 and t_2 are successive times of weighing (hour), G is the mean of five successive determinations of $G_{1,2}$ (mg/h), and $G_{1,2}$ is within $\pm 5\%$ of G . The vapour diffusion resistance factor, μ , is calculated using Eq. 7. Vapour permeability δ is calculated from the following expression:

$$\delta = W \cdot d \quad (14)$$

Where W is the water vapour permeance [$\text{mg}/(\text{m}^2 \cdot \text{h} \cdot \text{Pa})$] and d is the test specimen thickness (m). W is determined from the following expression:

$$W = \frac{G}{A \cdot \Delta p} \quad (15)$$

Where A is the surface area of the specimen (m^2) and Δp is the pressure difference (Pa) as set in BS EN 12086. The vapour diffusion equivalent air-layer thickness (S_d value) is calculated using Eq. 9.

The aforementioned method of measuring vapour diffusion resistance factor did not take into account the surface vapour resistance of materials. The vapour diffusion resistance factors are, therefore, carried out with this limitation.

3.2.4 Determination of A value

The methods for experimentally determining water absorption coefficient (A value) of the building materials by partial immersion are outlined in the British Standard BS EN 15148 [17]. The test specimens are conditioned to the temperature of $18\text{ }^{\circ}\text{C}$ to $28\text{ }^{\circ}\text{C}$ with allowed temperature variation during the tests of $\pm 2\text{ }^{\circ}\text{C}$ and relative humidity of 40% to 60% with allowed relative humidity variation during tests of $\pm 5\%$. The insulation samples are conditioned to the test condition so that the change of mass is 0.1% of total mass when measured over 24-hour intervals. Samples are placed in a tank, resting on point supports so that the bases of the samples do not touch the tank surfaces, as shown in Fig. 5.

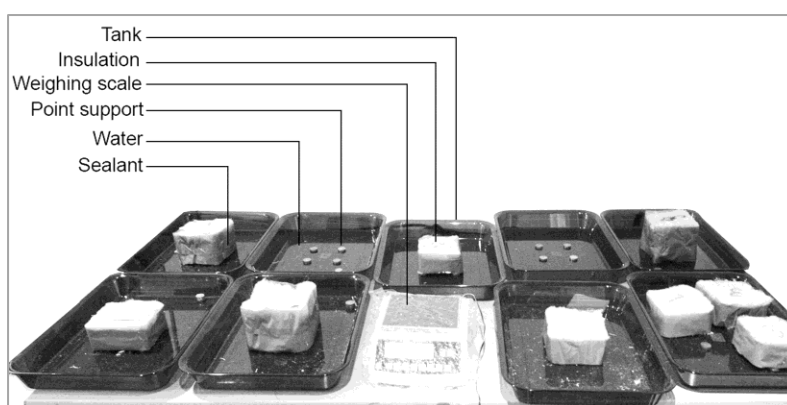


Fig. 5. Setup for assessing water absorption coefficient (A value).

The tanks are filled with water so that the water level is (5 ± 2) mm above the highest point of the base of the specimen. The sides of the samples are sealed with water and vapour tight sealant. All samples are weighed at the following times from the

beginning of the experimental work: 5 minutes, 20 minutes, 1 hour, 2 hours, 4 hours, 8 hours, 16 hours and 24 hours. The difference of mass per area (W) between each weighing and the initial weighing is measured using the following equations:

$$W = \frac{m_t - m_i}{a} \quad (16)$$

Where m_t is the mass at any time of weighing (kg), m_i is the mass at initial weighing (kg) and a is the surface area of the sample in contact with water (m^2).

According to the British Standard BS EN 15148, the A value can be expressed as A_w , W_w , $A_{w,24}$ or $W_{w,24}$. To determine the A value, $\Delta m_t = m_t - m_i$ is plotted against the square root of the weighing times. When a straight line can be drawn through the values of Δm_t , the line is extrapolated back to zero time where the value of the intercept is $\Delta m'_0$. In this case, the water absorption coefficient is denoted by A_w or W_w and it can be determined by using either Eq. 17 or Eq. 18.

$$A_w = \frac{\Delta m'_{tf} - \Delta m'_0}{\sqrt{tf}} \quad (17)$$

$$W_w = \frac{\Delta m'_{tf} - \Delta m'_0}{\sqrt{tf}} \quad (18)$$

Where $\Delta m'_{tf}$ (kg/ m^2) is the value of Δm at ' tf ' time. The time ' tf ' is 1 day expressed in seconds in Eq. 17 and 1 day expressed in hours in Eq. 18.

When the plot of Δm_t against square root of the time does not give a straight line, the water absorption coefficient is denoted by $A_{w,24}$ or $W_{w,24}$ and it can be expressed by using either Eq. 19 or Eq. 20.

$$A_{w,24} = \frac{\Delta m'_{tf}}{\sqrt{tf}} \quad (19)$$

$$W_{w,24} = \frac{\Delta m'_{tf}}{\sqrt{tf}} \quad (20)$$

Where $\Delta m'_{tf}$ (kg/m²) is the value of Δm at ' tf ' time. The time ' tf ' is 1 day expressed in seconds in Eq. 19 and 1 day expressed in hours in Eq. 20.

4. Results and discussion

4.1 Adsorption-desorption isotherm

The adsorption and desorption isotherm of the insulation samples are shown in Fig. 6 in terms of average percentage mass gain per unit dry mass (AMCw).

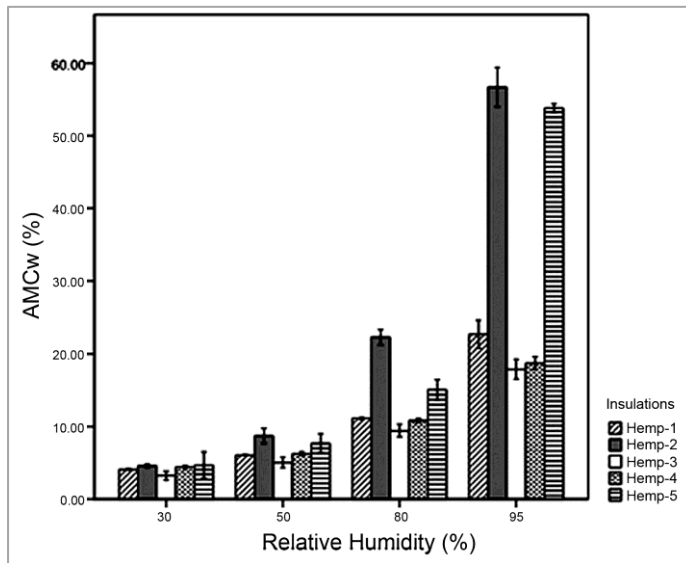


Fig. 6. Average moisture content by percentage mass gain per unit dry mass (AMCw) with 1 standard deviation.

Hemp-2 and Hemp-5 are the most hygroscopic materials while the other insulations are in the middle range in terms of moisture adsorption. This middle range, about 15% to 25% moisture gain, can be assumed as the typical range for most of the hemp fibres, as this is the range reported by most of the experimental determinations of adsorption isotherms [7],[18]. The high adsorption capacity of Hemp-2 and Hemp-5 can be advantageous in terms of controlling internal relative humidity and minimising interstitial condensation in an environment with cyclic variations of relative humidity. It can also be observed that in both Hemp-2 and Hemp-5 insulations the respective adsorption capacities are rapidly increasing at higher water activity ranges, especially between 80% to 95% relative humidity. At higher water

activity (starting from 70% relative humidity), transient micro capillary network is developed in the cellulose and lignocellulosic fibres and capillary condensation becomes increasingly dominant [6]. At the same time, more adsorption sites open up due to the swelling of the cells. The observed difference in moisture uptake behaviour of different fibres at higher water activity may be due to the fibrous structure of the insulations, porosity and different methods of processing of the fibres, resulting in different mechanical and sorption properties.

The adsorption-desorption isotherms of selected insulation materials based on the GAB regression together with the experimental data of average moisture content by weight (AMCw) are shown in Figs. 7-11. It can be noticed that the experimental data fits well with the GAB model in most of the cases up to 80% relative humidity.

Hysteresis is observed in Hemp-1, Hemp-2 and Hemp-3. Hysteresis is more pronounced in Hemp-1 and Hemp-3 insulation materials which contained wood and hemp shivs, respectively.

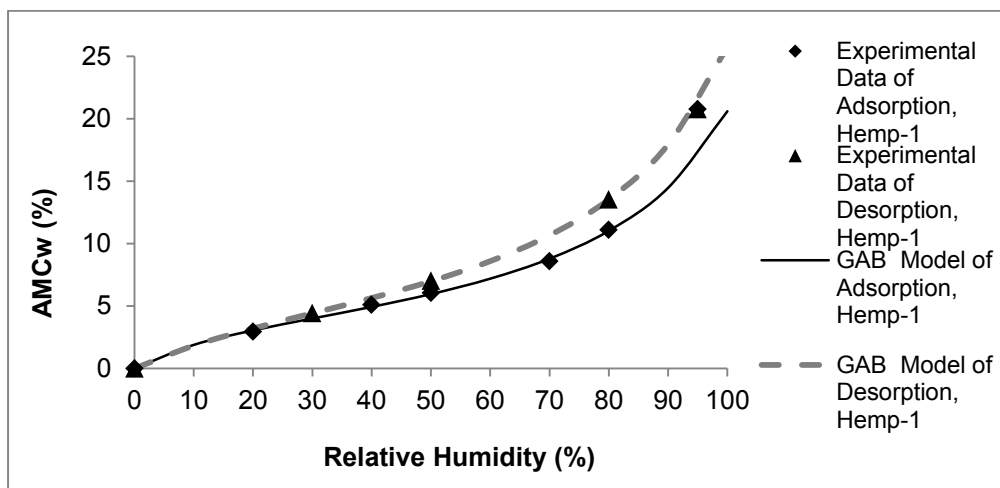


Fig. 7. Adsorption-desorption isotherm (AMCw) of Hemp-1 with GAB fit.

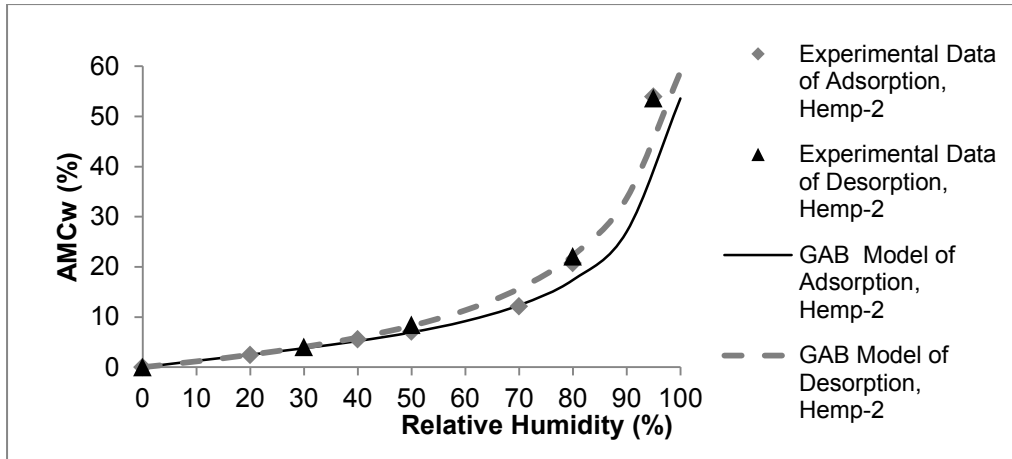


Fig. 8. Adsorption-desorption isotherm (AMCw) of Hemp-2 with GAB fit.

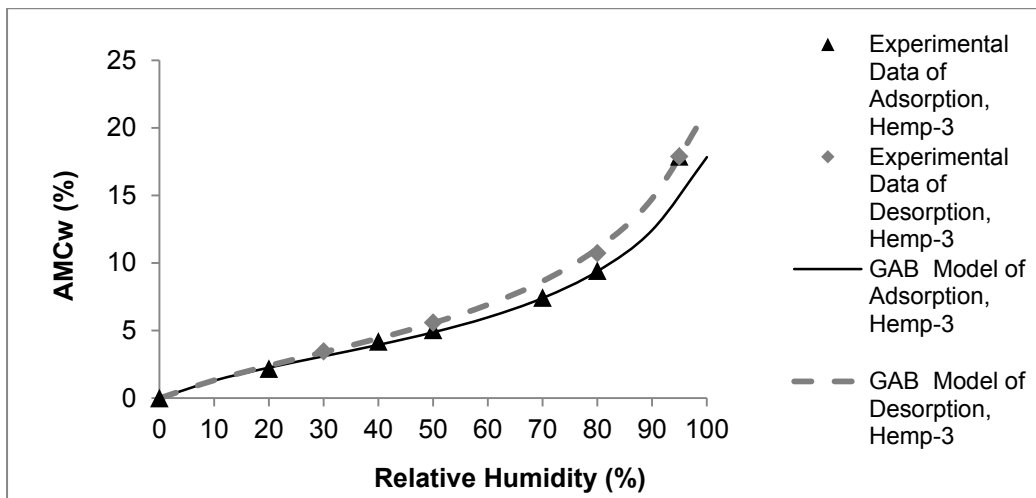


Fig. 9. Adsorption-desorption isotherm (AMCw) of Hemp-3 with GAB fit.

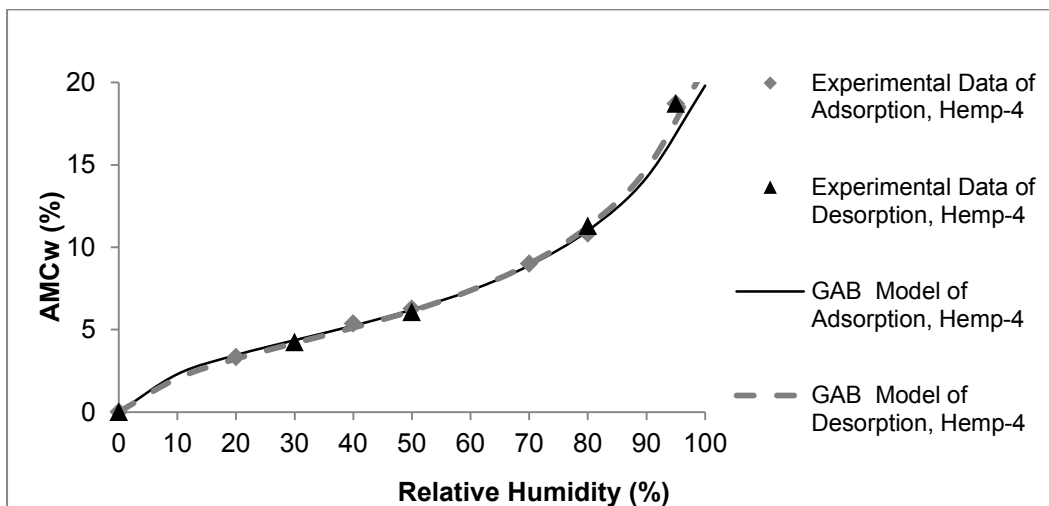


Fig. 10. Adsorption-desorption isotherm (AMCw) of Hemp-4 with GAB fit

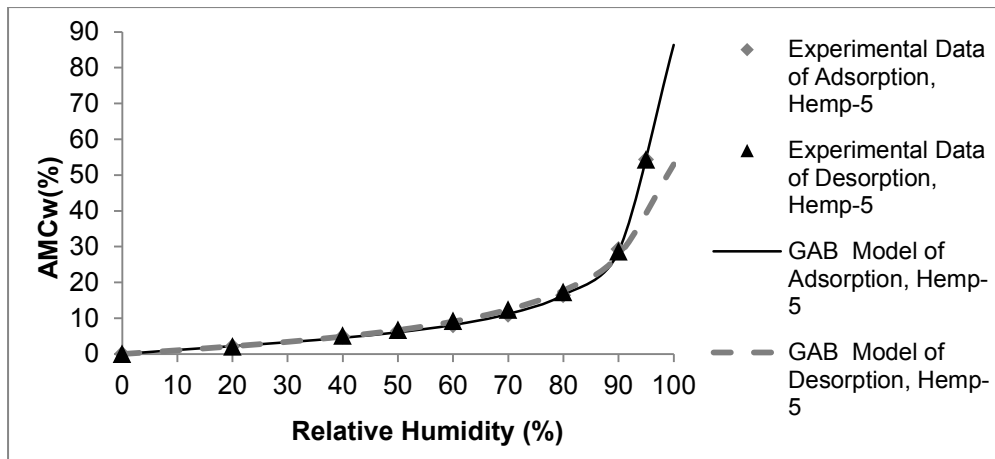


Fig. 11. Adsorption-desorption isotherm (AMCw) of Hemp-5 with GAB fit.

The GAB parameters for adsorption isotherms of the hemp insulations are provided in Table 3 . It can be noted that more active sites for monolayer water sorption, as represented by higher value of W_{mg} , are available in Hemp-2 and Hemp-5 insulations. It can also be noted that higher entropy and liquid state, as represented by higher K value, are also present in Hemp-2 and Hemp-5 insulations.

Table 3. GAB parameters for the insulation materials.

Material	GAB parameters			
	Temp (°C)	C_g	K	W_{mg}
Hemp-1	23	7.9	0.8	0.042
Hemp-2	23	2.65	0.9	0.056
Hemp-3	23	5.45	0.8	0.037
Hemp-4	23	11.54	0.79	0.042
Hemp-5	23	2.91	0.95	0.044

The GAB models of isotherms of products of biological origin are commonly represented by sigmoidal (IPAC type 2) shapes [6, 18]. However, it can be observed that while the sorption curves of Hemp-2 and Hemp-5 are not truly sigmoidal, they can be expressed in terms of the modified classification (Type IIa) of GAB-like sorption isotherms (Fig. 12), as observed by Blahovec and Yanniotis [19]. Similar sigmoidal and non-sigmoidal regression lines (Type IIa and Type IIb) were also

presented by Collet et al [7] while comparing two hemp insulations using the BET and GAB models.

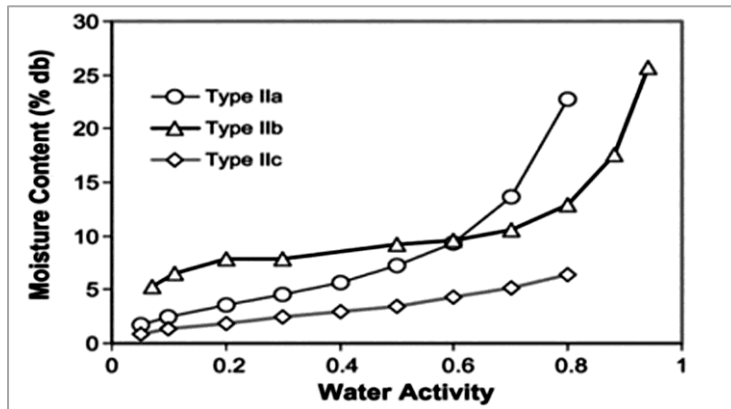


Fig. 12. Modified classification of type II isotherms [20].

Fig. 13 shows the adsorption kinetics of the hemp insulation materials for the period of 44.6 days. It can be noted that moisture content of Hemp-2 and Hemp-5 increases by 2.4 and 3.4 times, respectively, in response to the rise of relative humidity from 80% to 95%.

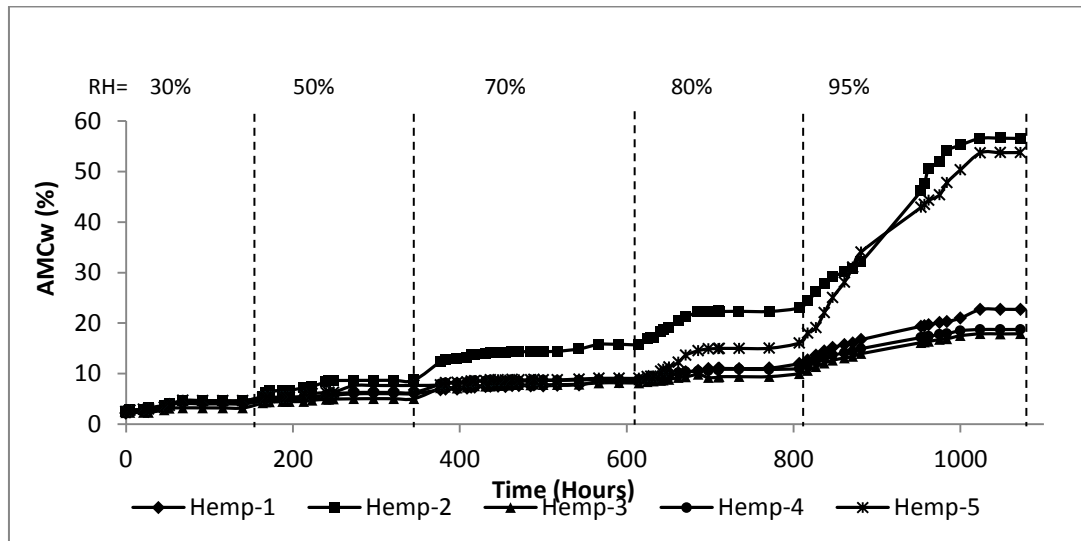


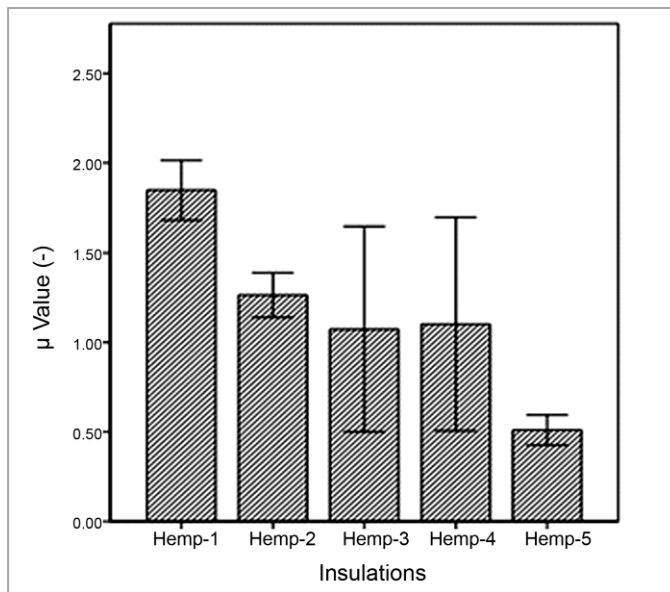
Fig. 13. Adsorption kinetics of the hemp insulations.

4.2 Vapour diffusion resistance factor (μ value)

The test for determining vapour diffusion resistance factor were carried out for 10 days. The μ value and S_d value of the insulation samples are shown in Table 4 and Fig. 14.

Table 4. μ value and S_d value of the insulation materials.

	μ value (-)		S_d value (m)	
	Dry Cup Test	Wet Cup Tets	Dry Cup Test	Wet Cup Tets
Hemp-1	1.89	1.85	0.091	0.089
Hemp-2	1.57	1.29	0.086	0.075
Hemp-3	2.63	1.11	0.124	0.052
Hemp-4	2.74	1.10	0.123	0.049
Hemp-5	-	0.51	-	0.029

**Fig. 14. Vapour diffusion resistance (μ value) factor of the hemp insulation materials during the wet cup test with 1 standard deviation.**

Hemp-5 shows the lowest μ value during the wet cup test whilst Hemp-1 shows the highest μ value. Only the wet cup test is performed for Hemp-5 due to the lack of required number of samples. The vapour diffusion resistance factor of Hemp-5 requires further investigation as this value was less than the value of the vapour diffusion resistance factor of air.

During the dry cup test, Hemp-4 exhibits the highest μ value whilst Hemp-2 exhibits the lowest μ value. There are considerable deviations from the mean μ value in Hemp-3 and Hemp-4 samples during the wet cup and dry cup tests, respectively. It can be observed in Table 4 that the μ value of insulation materials obtained by dry

cup tests are always higher than the corresponding μ values obtained by the wet cup tests. This is expected since vapour permeability is moisture dependent and the value of vapour permeability rises with the increase of moisture content of insulation materials.

It is plausible that the observed variations in the μ value of the insulation samples are due to the possible variations in porosity and tortuosity of these materials.

The non-homogeneity of some of the hemp insulations, as reflected by the high standard deviation from the mean μ value, may make it difficult to predict the actual performance of the insulation materials in terms of their vapour transmission.

4.3 Water absorption coefficient or A-value

Fig. 15 shows the Δm_t versus square root of time (\sqrt{s} , where s is seconds) plots for Hemp-1, Hemp-2, Hemp-3, Hemp-4 and Hemp-5 insulation materials, respectively.

In all the cases, the graph of Δm_t against \sqrt{s} does not give a straight line, but curves. In these cases, the A value can be determined by applying either Eq. 19 or Eq. 20. For the tests carried out, Eq. 19 was applied and the A values were determined in terms of $A_{w,24}$.

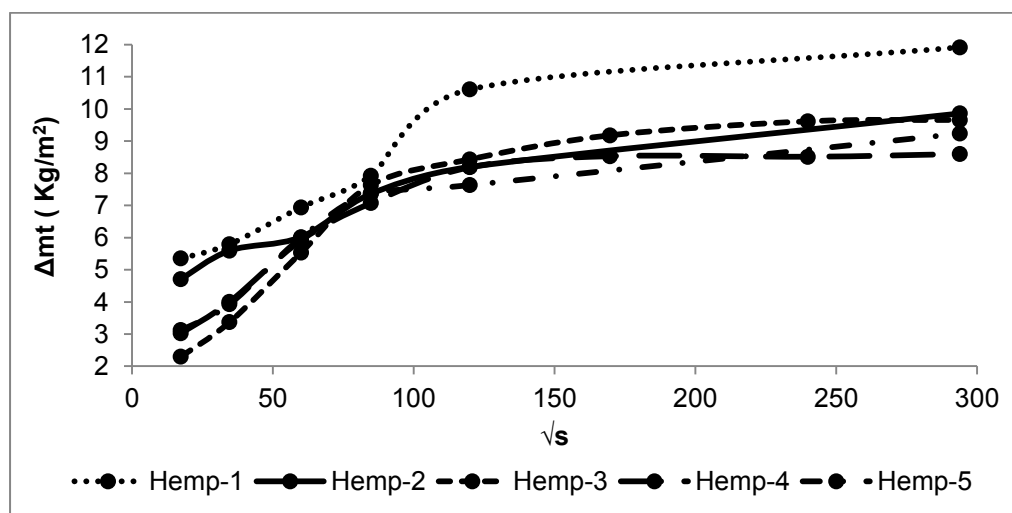


Fig. 15. Δm_t versus \sqrt{s} plot for Hemp-1, Hemp-2, Hemp-3, Hemp-4 and Hemp-5 insulations (average values of 3 samples).

Fig. 16 and Table 5 show the $A_{w,24}$ values of Hemp-1, Hemp-2, Hemp-3, Hemp-4 and Hemp-5. Except Hemp-1 insulation, all the hemp insulation materials exhibit similar $A_{w,24}$ values.

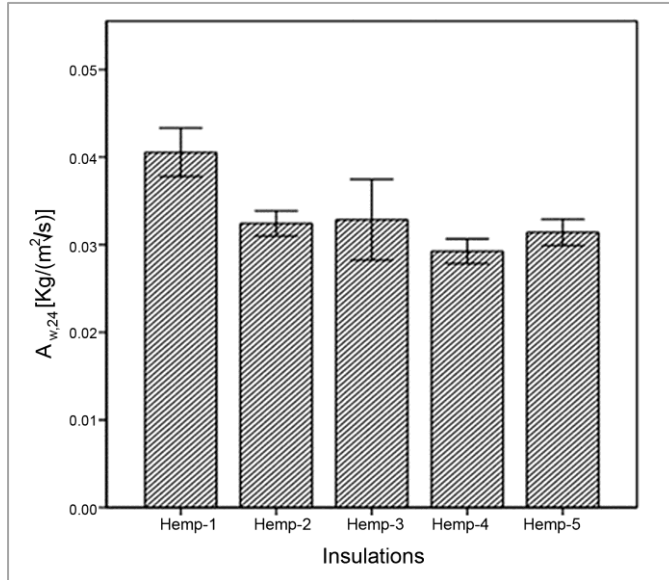


Fig. 16. The A value of hemp insulations with 1 standard deviation.

During the determination of the A values, it is observed that the long-term contact with liquid water can change the structure of the insulation surface that is in contact with water. Fibres are hardened and compacted near the surface and the density near the surface seems to increase as a result. The implication of these changes on the thermal conductivity and vapour diffusion may need further studies.

Table 5. Mean $A_{w,24}$ value of the hemp insulation materials.

Insulations	A value ($\text{Kg/m}^2 \sqrt{s}$)
Hemp-1	0.041
Hemp-2	0.034
Hemp-3	0.033
Hemp-4	0.029
Hemp-5	0.031

4.4 Practical moisture buffer value ($MBV_{\text{practical}}$)

The highest $MBV_{\text{practical}}$ was achieved for Hemp-2 followed by Hemp-5 (Fig. 17).

Hemp-4 showed the lowest value for $MBV_{\text{practical}}$.

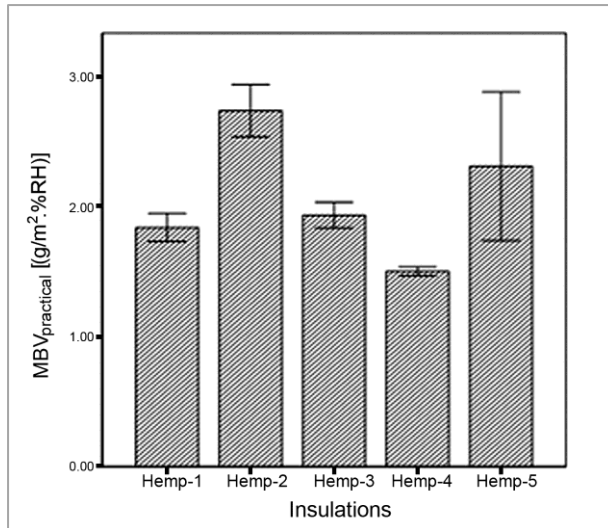


Fig. 17. Practical moisture buffer value of the insulations with 1 standard deviation.

The kinetics of moisture buffer the actual performance of the insulation materials is shown in Fig.18.

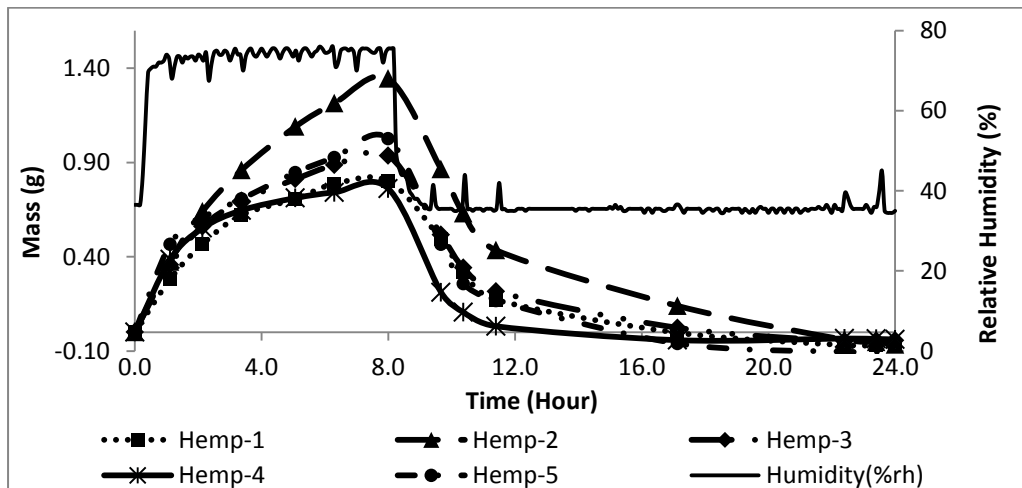


Fig. 18. Kinetics of moisture buffer of hemp insulations during the final cycle.

If the experimental results are explored in terms of adsorption isotherm, it can be observed that Hemp-2 and Hemp-5 show high moisture adsorption capacity and this is also reflected in their corresponding MBV_{practical} values. Hemp-1, Hemp-3 and Hemp-4 are in the mid-range in hygroscopic capacity, which is also their behaviour in terms of their corresponding MBV_{practical} values. In terms of practical moisture buffer value classes (Table 6), Hemp-2 and Hemp-5 can be classified as ‘Excellent’ and Hemp-1, Hemp-3 and Hemp-4 can be classified as ‘Good’. Hence, all the hemp

insulation materials belong to the two upper most classes in terms of moisture buffering efficiency.

Table 6. Ranges for practical Moisture Buffer Value classes [8]

MBVpractical class	Minimum MBV level [g/(m ² .%RH)]	Maximum MBV level [g/(m ² .%RH)]
Negligible	0	0.2
Limited	0.2	0.5
Moderate	0.5	1.0
Good	1.0	2.0
Excellent	2.0	-

Moisture buffer value reduces when 12.5 mm paper backed gypsum plasterboards of same length and width of the corresponding samples are installed on the upper surfaces of the hemp insulation materials. The comparative moisture buffer values are shown in Figure 19 where '(PB)' denotes the corresponding insulation samples with plasterboard (hemp-plasterboard system). It can be noted that the application of plasterboard reduces the mean moisture buffer values of Hemp-1, Hemp-2, Hemp-3, Hemp-4 and Hemp-5 insulations by 6.6%, 31.5%, 4.5%, 7.0% and 17.8%, respectively. The difference in the percentage of reduction of the moisture buffer value of the samples may be due to the porosity of the corresponding insulation samples.

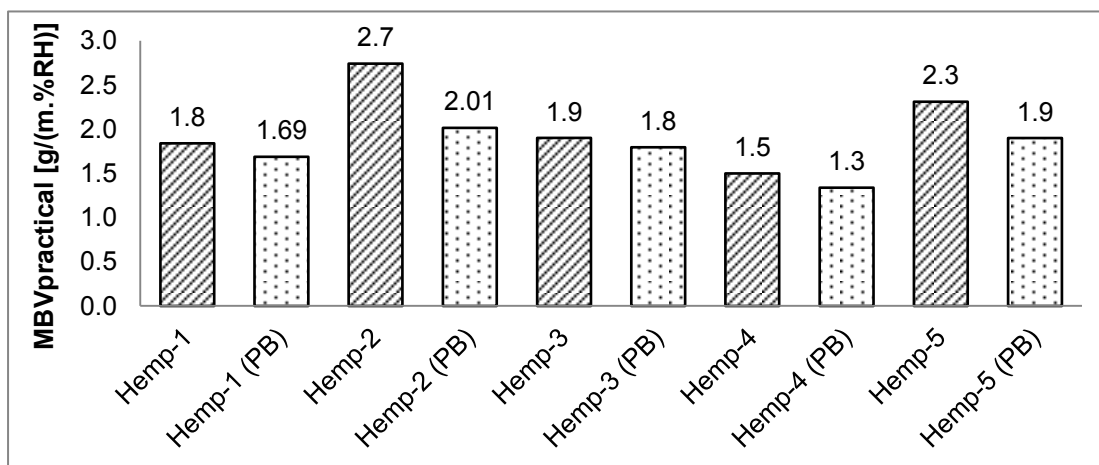


Fig. 19. Moisture buffer values of hemp insulation and hemp-plasterboard system.

It can also be noticed that, despite the reduction of moisture buffer values, the moisture buffer classes of the insulation-plasterboard system are same as the moisture buffer classes of the corresponding insulation materials.

5. Conclusions

Five hemp insulation materials available in the UK market are characterised in terms of their key hygric properties, namely adsorption-desorption isotherm, moisture buffer value, vapour diffusion resistance factor and water absorption coefficient. In relation to adsorption-desorption isotherm, hemp insulations exhibited varying moisture adsorption pattern and capacity. The insulation materials with more active area for monolayer water sorption also showed higher water adsorption capacity during high water activity. Hysteresis is more pronounced in insulations containing hemp shiv or wood fibre. The relatively dense hemp insulations showed less standard deviation in adsorption capacity, whereas hemp insulations of relatively lower density showed higher standard deviation in adsorption capacity. In relation to practical moisture buffer value, Hemp-2 and Hemp-5 exhibited 'Excellent' performance while Hemp-1, Hemp-3 and Hemp-4 showed 'Good' performance. The hemp insulations with higher moisture adsorption capacity showed higher $MBV_{practical}$ values. In terms of μ values, considerable variations among the insulation materials were observed. Hemp-5 showed the lowest μ value whilst Hemp-1 showed the highest μ value during the wet cup test. During the dry cup test, Hemp-4 exhibited the highest μ value whilst Hemp-2 exhibited the lowest μ value. There were considerable deviations from the mean μ value in Hemp-3 and Hemp-4 during the wet cup and dry cup tests, respectively. The μ value of insulation materials obtained by dry cup tests were always higher than those obtained by the wet cup tests. It is plausible that fibre processing, fibrous structure, tortuosity and porosity of the

insulations influence their moisture sorption and moisture diffusion properties. $A_{w,24}$ values of Hemp-2, Hemp-3, Hemp-4 and Hemp-5 insulation materials were equal up to the second decimal point. The $A_{w,24}$ value of Hemp-1 was 33% higher than the $A_{w,24}$ values of other hemp insulations. During the A value tests, it was observed that long-term contact with liquid water hardened the surface of the hemp insulations and increased the density of that surface. This change in the surface structure may influence the thermal conductivity and vapour diffusion resistance factor of hemp insulations. Performance of hemp insulation at high temperature was not explored as the focus of the present study was the building application of hemp thermal insulations.

Considerable differences in the hygric properties of the investigated hemp insulation materials were observed. Once their key hygric parameters are determined, numerical hygrothermal simulations can be performed to explore the suitability of these insulation materials for different wall types and weather conditions. Based on the initial performance, the insulation materials can be optimised for better performance.

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