

ON THE DEVELOPMENT OF SELF-CONTROLLED BIO-BASED PANELS FOR BUILDING'S THERMAL MANAGEMENT

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Abstract

EU is responsible for an annual generation of approximated 700 Mt of bio-based waste mass, of which only a small fraction is treated or exploited. At the same time, the demand for domestic energy consumption has never been greater. In the quest to save energy and reduce the effect of global warming, built environment research looks into the exploitation of bio-based by-products to tackle residential buildings' thermal efficiency. Recycled and recyclable bio-based materials are capable of natural moisture-management, maintaining indoor air quality and at the same time contributing to residential energy performance. Due to their hygroscopic properties, bio-based materials efficiently absorb and desorb moisture to their local surrounding environment. Within the framework of this paper, we present the preliminary work towards the development of a self-controlled bio-based panel system, for efficient moisture management. The proposed 'green' panels consist of bio-based fibres reinforcing bio-based matrices, to maximise hygrothermal behavior and through that feed the building management system. A comparison with the existing bio-based solutions is made in terms of moisture buffering behaviour and thermal conductivity. A review of the experimental methods to characterise dynamic water absorption and hygrothermal behavior is provided together with an analysis of the global warming potential and non-renewable energy fraction.

1. Introduction

Within the UK, the construction industry contributes over 55% of carbon dioxide emissions [1]. Bio-based materials not only boost thermal efficiency but also improve indoor air quality [2] and the

importance of indoor moisture management has been forthright in leading research in this area. Due to their hygroscopic properties, they both adsorb and desorb moisture to the local environment in an attempt to stabilise any relative humidity fluctuations, which affect comfort levels and energy usage within a building. Coupled with this, within the EU around 700 Mt of bio-based waste mass is produced annually of which at present, only a small percentage is reused for economic benefit. Many different basic bio-based insulation systems are currently available that are recycled from waste or decommissioned products/ elements.

The use of bio-based materials has become more and more prominent in the building rehabilitation sector since they meet energy and carbon reduction needs. Using hygroscopic materials to insulate i.e. a room can reduce energy usage by around 10% [3]. Bio-materials are superior to other materials (such as Fibreglass, Polyurethane Foam and Polystyrenes (EPS)) due to their relative simplicity, abundance and ability to mimic and if not better the equivalent fossil fuel based products [4] (see Figure 1) low embodied energy. Drawbacks of these materials are due to the lack of European legislation surrounding embodied energy [5]. In order to sufficiently understand the properties of these bio-based materials they have to be investigated to understand which materials possess the most case-specific characteristics.

In an attempt to reduce this by using naturally sourced materials, this paper presents a preliminary study for the development of a bio-based multifunctional insulation panel system for buildings. That said, experimentation on the Moisture Buffering Capacity (MBC) and Moisture Buffering Value (MBV) of 11 commercially available bio-based materials within the UK, is presented. In addition to the MBC and MBV, this study evaluates and classifies adsorption and desorption curves, in order to suggest insulation materials with inherent hygrothermal properties.

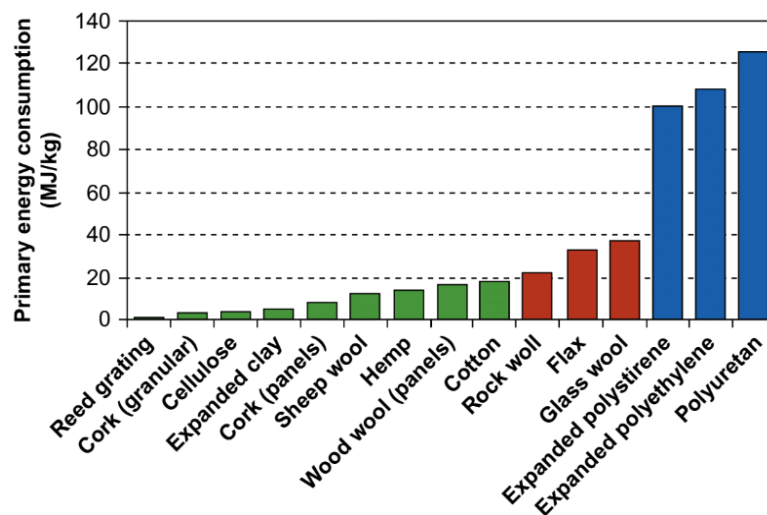


Figure 1. A graph to show the primary energy consumption of different insulating materials [4].

2. Materials

As aforementioned, 11 samples were tested as candidate insulation materials such as *cork*, *wool*, *saw mill residue*, *hemp*, *straw* and *woodfibre*. All samples tested herein were bio-based materials that are currently available in the UK's market. Insulation samples were modified according to NORDTEST/ISO [6, 7] standards, where samples were cut in order to meet exposed surface area requirements. The differing varieties of materials that have been tested are illustrated in Table 1 **Error! Reference source not found.**

Table 1. Sample Material Properties.

Sample Type	Sample Thickness (mm)	Density (kg/m ³)	Thermal Conductivity (W/mK)
Cork	65	120	0.04
Recycled (PET) Bottles	10	13	0.04
Wool 1	40	30	0.039
Wool 2	75	31	0.035
Wood Wool Board	15	8	0.065
Wool 3	65	18	0.039
Saw Mill Residue	55	50	0.038
Wool 4	50	45	0.04
Hemp	50	25	0.04
Straw	60	200	0.0397
Woodfibre	60	145	0.041

3. Methods

3.1 Preconditioning of the samples

Initially, samples were preconditioned at 23°C and 60% relative humidity for 24 hrs. In order to assess the ability for each material to adsorb and desorb water, they were exposed to cyclic step changes in relative humidity between 53% and 75% every 8 hrs and 16 hrs (respectively) at a constant temperature of 23°C. This test carried out in accordance with both NORDTEST protocol [6] and ISO 21353 [7].

Each sample was physically weighed every 2 hrs within the adsorption phase and then 3 times during the desorption phase and recorded on a balance to the nearest 0.01 g. Samples were placed horizontally within the climatic chamber and each had an exposed surface of 0.01 m². All other surfaces that were not exposed were covered in aluminium foil with a view to inhibiting moisture transfer. The materials change in weight will act as a direct index of their moisture buffering capacity.

3.2. Moisture Buffering Capacity (MBC)

In order to calculate the moisture buffering capacity, ρ of the samples, the following equation (Eq. 1) was used:

$$\rho = \frac{m_a - m_d}{A} \quad (1)$$

Where:

m_a = Mass of the sample at completion of moisture adsorption process (g)

m_d = Mass of the sample at the completion of moisture adsorption process (g)

A = Surface area of sample (m²)

3.3 Moisture Buffering Value (MBV)

In order to calculate moisture buffering value (MBV) of the samples the following equation (Eq. 2) was used:

$$MBV = \frac{m_a - m_d}{A\Delta\varphi} \quad (2)$$

Where:

m_a = Mass of sample at end of moisture adsorption stage (g)

m_d = Mass of sample at end of moisture desorption stage (g)

A = Exposed surface area of sample (m²)

$\Delta\varphi$ = Difference between relative humidity between adsorption and desorption stage (%)

All 11 samples were processed in the chamber, then once analysed, another experiment was conducted with the inherently optimal moisture buffering value and adsorption/desorption curve 6 samples. These six samples were then subjected to a third round of tests through which the final best performant 3 samples were selected.

4. Results and Discussion

Bio-based materials have been previously investigated by *Holcroft & Shea* [8], adopting the ISO 24353 which suggests 12 hrs adsorption/ desorption cycles as opposed to the presented herein 8 hrs & 16 hrs cycles, respectively. In addition, this work employed identical to [8] preconditioning environment, isothermal and relative humidity conditions.

For the 1st experiment, all 11 samples were subjected to MBV tests and after 7 cycles were compared to each other. The results exhibited that there are significant differences in MBV of the tested samples, which demonstrate four distinct ratings varying from ‘negligible’ to ‘good’. Results are presented in Table 2.

Table 2. Moisture Buffering Values obtained for the tested samples.

Sample Type	Moisture Buffering Value (MBV) (g/(m ² Δ%RH))	Qualitative MBV Classification [6]
Cork	0.626	Limited
Recycled Plastic Bottles (PET)	0.233	Negligible
Wool 1	1.241	Good
Wool 2	1.380	Good
Wood Wool Board	1.096	Good
Wool 3	0.092	Negligible
Saw Mill Residue	1.558	Good
Wool 4	0.069	Negligible
Hemp	0.699	Limited
Straw	1.853	Good
Woodfibre	1.929	Good

However, according to NORDTEST protocol, in order for moisture buffering value to be calculated, the samples should be in a quasi steady state. In order to align with this, 3 consecutive cycles have to

exhibit a mass variation of not higher than 5% [6]. That said, this initial experiment revealed that only 2 samples exhibited stabilization in mass (*Wool 2* and *Straw*) within 9 cycles. In all cycles, the variation in mass takes place during the adsorption stage (which would directly affect MBV). This can be attributed to the higher water activity within the climatic chamber (75% RH for 8 hrs). This water activity causes the development of a transient micro-capillary network within both the cellulose and lignocellulose fibres, where capillary condensation is therefore becoming increasingly dominant [9]. As these micro-capillary networks develop, for each individual sample this will occur at a differing rate and therefore require different time to stabilise due to the inherent nature as well as differing properties of bio-based materials [10]. A quicker stabilisation time would be ideal from the samples, as it would then begin to dynamically react to its localised hygrothermal conditions much quicker in comparison to a material with a longer stabilisation time.

The shape of the adsorption and desorption curves for the 11 original samples during this experiment can be categorised into 3 distinct groups. Group 1 (Fig. 2) includes the majority of the samples. Initially, all samples adsorb moisture with a high rate for approximately 8 hrs, during which, constantly increases. During the desorption phase, mass continuously decreases. This demonstrates a clear adsorption and desorption behaviour, with a peak 8 hrs that corresponds to the maximum amount of moisture uptaken by the sample. This behaviour indicates that bio-based materials react instantaneously to the differing hygrothermal behaviour, demonstrating the ability of water being able to penetrate and diffuse within the sample (hygroscopic property). With respect to Group 2 (Fig. 3), samples exhibit an initially high adsorption rate. As the experiment continues the gradient in adsorption curve changes with a decreasing tendency. This is mirrored in the desorption phase during which a high initial desorption rate is followed by a drop. Evidently, all tested samples revealed mass stabilization during adsorption after 8 hrs. Worth to mention, the ability of the materials to adsorb and desorb moisture is greatly influenced by their cumulatively increasing mass. This is an indication of saturation as it losses its efficiency to retain water molecules. Similar finding also was reported in [11]. After desorption, samples that lose their ability to efficiently desorb water, will start to decompose due to the presence of water molecules. Similarly, Group 3 (Fig. 4) samples adsorbed moisture with a high initial rate, which then significantly slowed down. As opposed to the other groups where the materials reach saturation after 8 hrs, Group 3 samples started to desorb moisture before the step change in relative humidity. Only one sample reaches a peak after 8 hrs; however, this is only a slight increase in comparison to the reading recorded after 6 hrs. All three samples reveal a plateau within their adsorption/ desorption curve, which reflects the point at which the weight of the sample remains constant i.e. the material is unable to adsorb or desorb moisture. This indicates that the material is moisture saturated and can no longer buffer moisture.

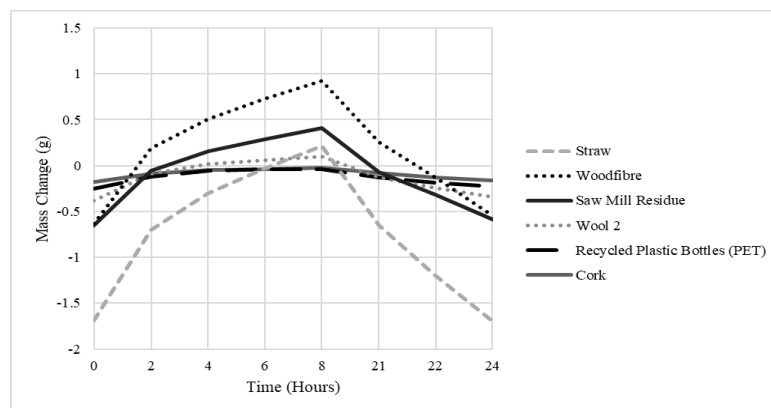


Figure 2. Adsorption and desorption curves showing categorisation of 11 samples within ‘Group 1’.

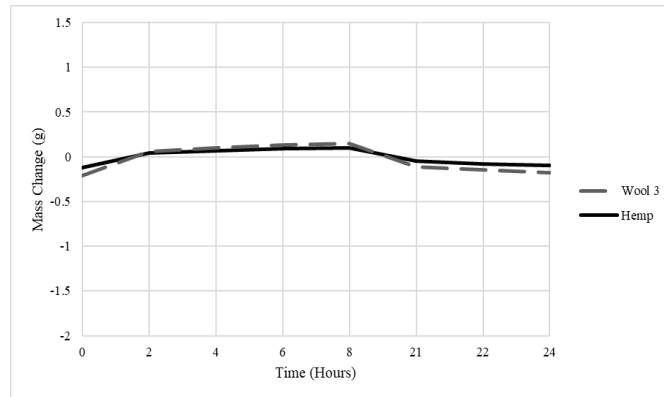


Figure 3. Adsorption and desorption curves showing categorisation of 11 samples within ‘Group 2’.

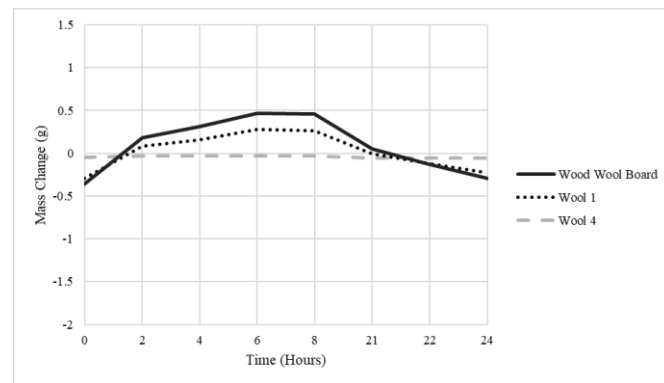


Figure 4. Adsorption and desorption curves showing categorisation of 11 samples within ‘Group 3’.

This intrinsic inability of a material to desorb moisture after a certain amount of cycles, suggests that in order for the service life of bio-based materials to be extended, a method of ‘recovering’ the insulation material is of primary importance and is currently under development.

Based upon the previous experiment, a second round of testing revealed the optimal 6 samples (*Wool 1, Wool 2, Wool 3, Saw Mill Residue, Wood Fibre and Straw Based samples*). These were subjected to cyclic testing for a longer period after which they were evaluated and re-classified into 3 Groups (See Table 2).

Table 2. Re-classification of samples into 3 Groups.

Group	Sample Type
1	Wool 1
	Wool 2
2	Wool 4
	Saw Mill Residue
	Wood Fibre
3	Straw

When evaluating the results, it becomes clear that throughout the duration of the experiment, the cyclic adsorption and desorption within the chamber has had varying effects on the materials. Throughout the latest experimentation, *Wool 1* and *Wool 2* exhibited a very similar adsorption/ desorption curve with negligible hysteresis. However, *Wool 1*, exhibits decomposition at the final cycle as it begins to lose mass from the initial dry mass. For *Wool 4*, the final cycle remains intact. However, there is approximately 1.2 g increase in mass due to water adsorption, which is expected to eventually decompose the structure of the material leading to mass loss. The final cycle of the *Saw mill residue* sample was found similar to the first cycle, however, the initial high rate of adsorption seems to have deescalated with the duration of the experiment. When comparing the shape of the curves of *Saw Mill Residue* to *Wood Fibre* samples, it becomes clear that in the latter the shape from the beginning cycle to the final has completely altered. A steep adsorption gradient was replaced with a plateau, which could be assumed to reflect the material's inability to buffer moisture. In comparison to the *Straw* sample, the *Wood fibre* sample has retained over 181.82 g/m² of water, which is significantly higher, compared to other samples (such as *Wool 1* or *Wool 2*) however, the *Straw* sample has retained the highest amount of water (over 454.55g/m²). The *Straw* based sample has also revealed a plateau within its desorption phase of cycle 1, indicating that the material can no longer efficiently buffer moisture to the local environment. When comparing *Straw* sample from the first experimental results to these results it is evident that this issue has become exaggerated as retained more and more water.

5. Conclusion

Within the scope of this paper is the preliminary work towards the development of a bio-based multifunctional insulation panel system for buildings. Moisture Buffering Capacity and Moisture Buffering Value tests were conducted on 11 commercially available bio-based materials within the UK. Furthermore, this study evaluated the various adsorption/ desorption curves, to assess materials' hygrothermal properties. 'Group 1' was highlighted as the most promising group as materials respond dynamically to hygrothermal changes in the environment whereas the capacity of water adsorption was found to be noticeably higher in comparison with Groups 2 and 3.

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