3rd International Conference on Bio-Based Building Materials

June 26th - 28th 2019
Belfast, UK

BIO-BASED AND RECYCLED MATERIALS: CHARACTERISATION AND HYGROTHERMAL ASSESSMENT FOR PASSIVE RELATIVE HUMIDITY MANAGEMENT

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Abstract

Action is needed for Europe to achieve the higher rates of renovation to reduce energy usage and decarbonize building stock. Bio-based materials are a solution to this problem as they combine their reusable and recyclable ability with an improved hygrothermal behaviour to save energy. However, the passive mechanisms and the hygroscopic characteristics associated to these materials is not yet understood, limiting the optimisation of bio-based products. 11 different bio-based insulation samples were tested with the intention of developing a 'green indoor panel' for domestic property: 4 different types of wool insulation, Hemp, Wood Wool Board, Saw Mill Residue, Wood Fibre, Straw, ICB and PET. Sample characterisation was executed via SEM imaging, thermocouples, dry and saturated thermal conductivity and density in addition to moisture buffering value (MBV) (where samples were exposed to step changes in relative humidity of 75% and 53% for 8 and 16 hours respectively). SEM imaging demonstrates the surface morphology of the sample giving an initial indication of the materials characterisation. More fibrous samples demonstrate larger air pockets, giving inherently lower thermal conductivity values in comparison to a more heterogenous sample. Furthermore, MBV is not *per si* a defining characteristic to decide the hygrothermal properties of a material but the shape of the final mass change graph should also be considered. On saturation of samples thermal conductivity values increase and some samples cannot exhibit an efficient water adsorb/desorption exchange. Using thermocouples, latent heat of vapourisation and condensation can be demonstrated as an indication of the stabilisation of the sample. From 11 samples, the innately best 3 samples have been selected for further experimentation: Wool 1, Wool 2 and Saw Mill Residue.

Keywords:
Embodied energy; bio-based insulation; hygrothermal; latent heat

1. INTRODUCTION

Buildings are accountable for over 40% of the total, global energy consumption [U.N. 2009]. It is evident that global warming is an issue affecting the built environment worldwide. This is due to an increase in the standard of living – leading to increase accessibility and usage of electricity. Giving an overall increase to both direct and indirect emissions [IEA 2014]. Since 2015 the Paris Agreement set out long term temperature limit of 1.5^{o}C [IPCC 2018]. In order to accomplish this, there needs to be a shift away from fossil fuel-based materials [IEA 2015] and an adoption of sustainably sourced, such as bio-based building materials.

In addition to this the European Union (E.U.) outlined within the Energy Performance Directive in 2018 – which would aim to renovate current building stocks to nearly or zero energy buildings [Housing Europe 2018].Whilst energy efficiency in buildings not only reduces the emissions to the environment on a European scale, it also aligns with the United Nations (U.N.) Sustainable Development Goals 11 and 13 [Di Foggia 2018]. Important to understand that a 'one size fits all' approach is not suitable nationally let along internationally [Brás et al 2014; CAT 2018]. A realistic and performance driven retrofitting tool that enable tailoring green materials for decarbonisation is essential to meet these targets [Kelly 2009].

As natural materials bio-based fibres are naturally occurring and have a relatively low environmental impact in comparison to other more widely used construction materials (such as Steel or Concrete) [Korjenic et al 2011; Peñaloza et al 2016]. An intrinsic property of bio-based materials is their hygrothermal ability and that they can readily adsorb and desorb in to the local environment [Jones and Brischke 2017]. Key factors when considering any renovation is the health and well-being of occupants but also its durability and life cycle of the product. This is particularly important when considering their use as a hygric buffer as a retrofitting tool.

The built environment will continue to look to reduce heat and cooling loads as a form of energy consumption is a key driver for the requirement of a passively operating RH regulator. A key issue associated to bio-based and recycled materials is their limited understanding therefore an inability to be optimised. By being able to characterise these bio-based and recycled materials “smart behaviour” will enable a characterisation which aims to contribute to their utilisation within the construction industry. This research paper aims to analyse fundamental characteristics of bio-based insulation materials in order to select the best performing bio-fibres. These bio-fibres will then be incorporated into the production of a passive bio-based relative humidity management panel, tailored for specific need of the existing residential building stock in U.K.

2. EXPERIMENTAL PROCEDURE

2.1. Material Characterisation

For the basis of this study, 10 bio-based samples and 1 recycled thermoplastic polymer were investigated. Samples within this paper can be found on the market, available within the United Kingdom (UK) – material characteristics are listed in Table 1.

2.2. Testing Procedure

2.2.1. Bulk Density

Calculated as per EN 1015-6 [CEN 1999], both dry and saturated densities were measured. Saturated samples were immersed in water and periodically mass was taken until full saturation was achieved.

2.2.2. Scanning Electron Microscope (SEM)

By being able to investigate the surface morphology of the samples gives an indication of the material characteristics, which was done so using Scanning Electron Microscope (SEM) Inspect S. Understanding the formation under a microscope could demonstrate a further understanding of the material’s inherent properties.

2.2.3. Thermal Conductivity

Using an ISOMET thermal conductivity meter with a 60mm diameter contact probe, samples were examined in differing hygrothermal environments such as: dry, saturated and within 1, 24-hour cycle within the climatic chamber.

2.2.4. *Moisture Buffering Value (MBV)*

In order to calculate the ability of a material to adsorb and desorb water vapour within a hygrothermal environment via Moisture Buffering Value (MBV) is measured. Exposed to a 24-hour cyclical step change of 75% for 8 hours and 53% for 16 hours at 23ºC in conformity with NORDTEST protocol [Rode et al 2005] in ISO 21453 [ISO 2008] in order to replicate a U.K. household. The calculation of this is in Equation 1.

$$\mathrm{MBV} = \frac{\mathrm{m_a} - \mathrm{m_d}}{\mathrm{A}\Delta\varphi} \quad (1)$$

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 (m^2)

$\Delta\varphi$= Difference in RH between adsorption and desorption stage (%)

Samples were placed horizontally into the chamber and wrapped in aluminium tape, with an exposed surface area of 0.01m^2.

2.2.4. Dynamic Temperature Change

Whilst within the chamber, for the first cycle of 10, 24-hour cycles, 11 samples had a thermocouple placed on the surface and at 50% depth of the sample to detect any temperature change. The thermocouples and data loggers used are function at ranges of -40ºC to 260ºC and -250ºC to 1370ºC, respectively, with an accuracy of ±0.04ºC. It is expected, that due to the changing state of water from vapour to condensing during adsorption phase but vapourisation during desorption phase, there should be a latent heat exchange. During the second cycle of 22, 24 hour cycles samples had thermocouples on the surface and 15mm down due to research evidencing an ‘optimised zone’ for latent heat exchange(Padfield, 1999; Holcroft and Shea, 2015).

Tab. 1: Sample characteristics.

Sample ID	Density (kg/m^3)	Thermal Conductivity (W/m.K)
Wool 1	18	0.039
Wool 2	31	0.035
Wool 3	45	0.04
Wool 4	30	0.039
Hemp	25	0.04
Wood Wool Board (WWB)	8	0.065
Saw Mill Residue (SMR)	50	0.038
Wood Fibre (WF)	145	0.041
Straw	200	0.0397
Insulated Cork Board (ICB)	120	0.04
Polyethylene terephthalate (PET)	13	0.04

3. RESULTS AND DISCUSSION

3.1. Bulk Density

Calculating the density of a sample gives an indication of the voids or the ability of a material to have enough permeable bonding sites for water molecules. Fig 1 demonstrates that for all samples, the saturated density is much more than that of the dry density. WF and all Wool based samples substantially increase when saturated.

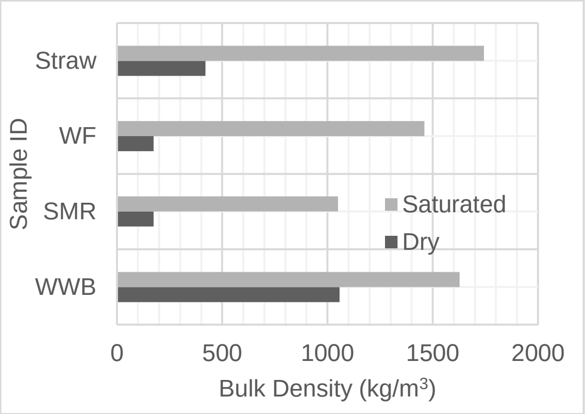


Fig 1: Saturated and Dry Density of samples.

3.3. Thermal Conductivity and SEM Images

In order to act as a bio-based insulator, samples must behave as poor thermal conductors. A low thermal conductivity value represents a better insulator and vice versa. Tab. 2 illustrated static thermal conductivity values for both dry and saturated samples, in addition to how it reacts dynamically during 1, 24-hour cycle.

Tab. 2 demonstrates that when saturated, the thermal conductivity of the bio-fibres increases in comparison to its dry self. This can be associated to the voids usually filled with air, becoming saturated with water and therefore decreasing the materials ability to behave as an insulator and acting in a more thermally conductive way [Shea et al 2013].

Whilst within the chamber, Table 2 shows that all the bio-based samples exhibit hygroscopic properties as during a high RH stage bio-fibres readily adsorb water vapour (demonstrated as an increase in thermal conductivity) from the local environment. However, within the period of low RH, all bio-based samples desorb water back into the local environment and thermal conductivity values also reduce. At the end of the singular, 24-hour cycle within the chamber, thermal conductivity Wool 2 and SMR both return to their original dry thermal conductivity value. By comparison, Straw and WWB exhibit the same hygroscopic behaviour yet do not return to the same dry state value. This behaviour can be attributed to water molecules becoming ‘trapped’ within the materials matrix and it is therefore unable to desorb from the material in the same way for which it originally absorbed. Being able to dynamically react to their hygrothermal environment is a key characteristic for the formation of the production of a passive bio-based relative humidity management panel.

SEM images within Table 2 also demonstrate two differing morphology patterns from this selection of bio-based materials. Wool 2, SMR and WWB show a much more fibrous and multidimensional microstructure while Straw has a much more homogeneous structure.

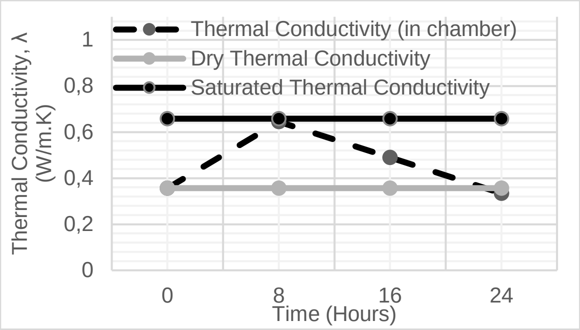
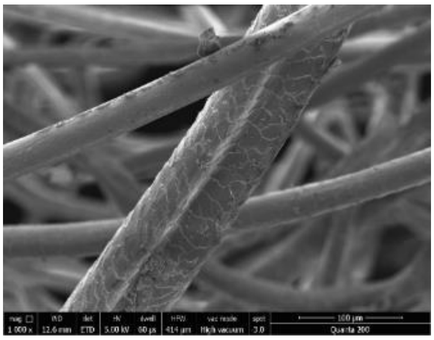
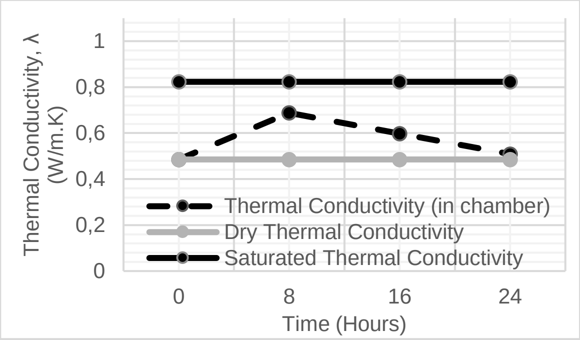
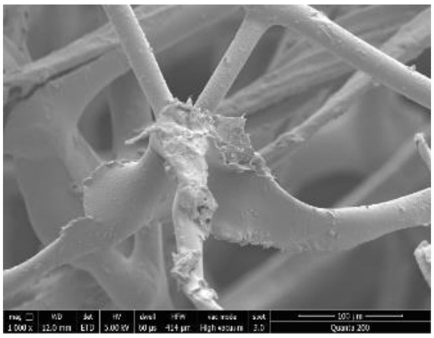
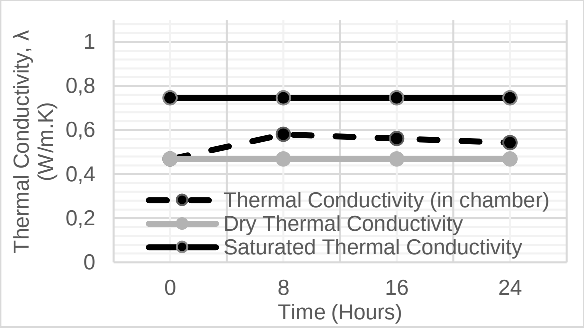
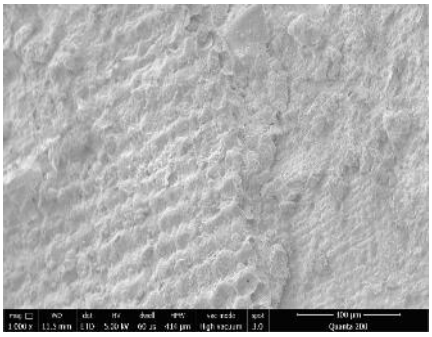
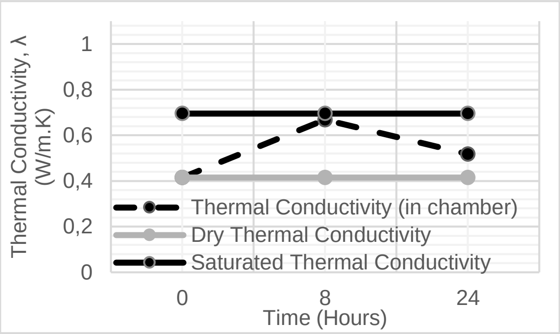
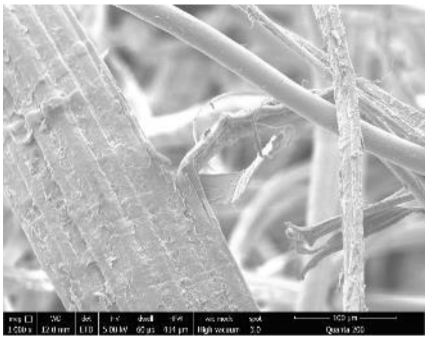
3.4. Moisture Buffering Value (MBV)

As the main objective for this research paper is the production of a moisture buffering hygric panel, MBV is an integral factor in deciphering between the preferential properties of bio-based materials. Initially samples were exposed to 10 cycles of 24 hours. As highlighted within [Romano et al 2018], using MBV as classified within [Rode et al 2005] does not sufficiently differentiate between the way in which materials adsorb and desorb within a hygrothermal environment. Using a ‘groups’ methodology (as per Romano et al, 2018) allows a new classification method in determining not only a bio-based material with the best MBV but also adsorption/desorption pattern. In order to utilise this, initially the samples with the highest MBV should be selected. From an initial 10 cycles of 24 hours the materials were classified as demonstrated in Tab. 3.

Tab 3: Materials Classification after 10 days.

Sample ID	**MBV (g/m^2 %RH)**	**MBV Classification (Rode et al, 2005)**
ICB	0.55	Moderate
Hemp	0.70	Moderate
PET	0.18	Negligible
SMR	1.70	Good
Straw	1.88	Good
WF	1.91	Good
Wool 1	1.49	Good
Wool 2	1.08	Good
Wool 3	0.10	Negligible
Wool 4	0.53	Moderate
WWB	1.06	Good

Tab 2: Thermal conductivity graph and SEM Images of samples.

Sample ID	**Thermal Conductivity Graph**	**SEM Image**
Wool 2		
SMR		
Straw		
WWB		

From the original 11 samples, 6 samples (SMR, Straw, WF, Wool 1, Wool 2 and WWB) have been selected for further experimentation due to their 'Good' classification. These samples were subjected to a further 22 cycles of 24 hours. The adsorption/desorption graphs for Cycle 1 and Cycle 22 can be found in Fig. 2 and 3.

Fig. 2 exhibits extremely high adsorption by WF and by hour 8, over 4 times as much adsorption as Wool 2, yet materials such as Wool 1 and Wool 2 have a much shallower and overall, lower initial adsorption during the first 8 hours within the climatic chamber. Despite the initial high adsorption, after only 1 cycle, WF and Straw are unable to return to their original mass at hour 0. This demonstrates that the material can adsorb within a high RH hygrothermal environment but is unable to efficiently exchange water molecules during the low RH phase and desorb. 'Trapped' water molecules have the ability to dissolve the bio-based material and lead to the material bio-degradation. By comparison, Wool 1 and Wool 2 (although they have the smallest initial adsorption rate) are able to completely desorb any water molecules that are initially adsorbed in the first 8 hours.

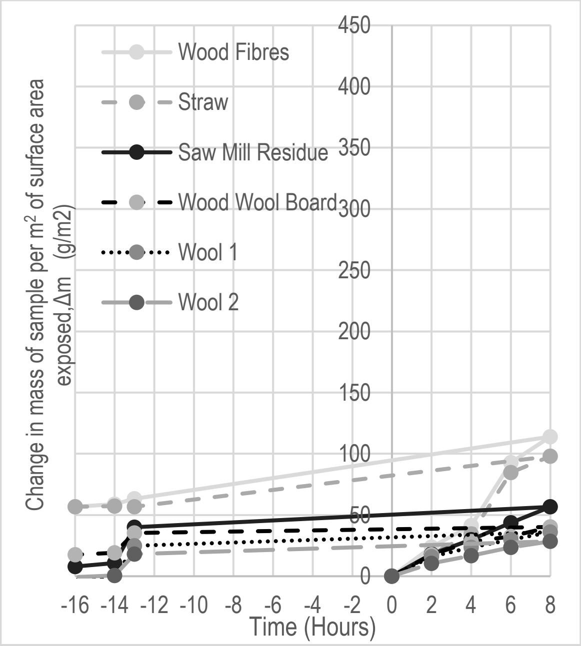


Fig 2: Adsorption/desorption graph for 6 samples after 1 day.

When comparing Fig. 2 and Fig. 3 it is evident that the change in mass per m^2 of exposed surface area vastly varies from the 1st to the 22nd cycle – demonstrating the implicit variable nature of bio-based materials [McGregor et al 2016]. Over the 22 cycles, the once dynamic moisture exchange is no longer as efficient. However as in Fig. 3 both Wool 1 and Wool 2 can efficiently adsorb and desorb after 22 cycles as they initially did during the first cycle.

Although originally, WF had the highest adsorption rate it is evident that WF, WWB and Straw have a 'trapped' moisture within the sample at the start of the final cycle and is unable to desorb any moisture adsorbed during the initial 8 hours of high RH. Fig. 3 demonstrates that Straw cyclically adsorbs and desorbs however it during the adsorption stage, water is retained within the sample and due to an inefficient moisture exchange is unable to desorb the 'held' water molecules.

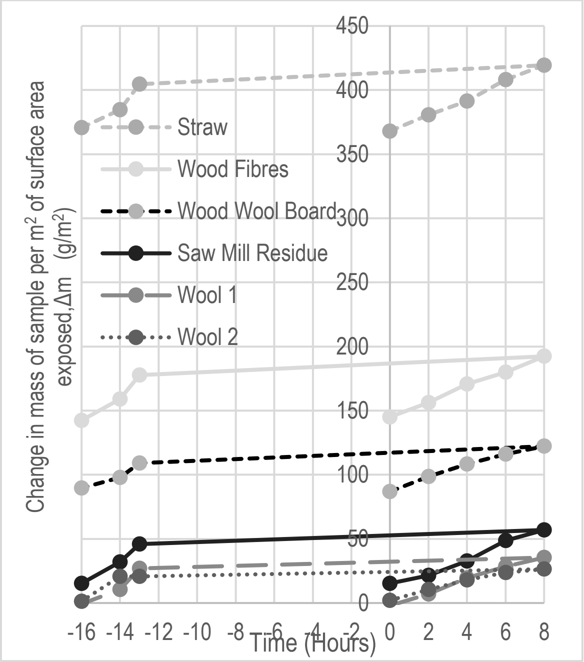


Fig 3: Adsorption/desorption graph for 6 samples after 22 days.

The adsorption/desorption graph demonstrates WF, WWB and Straw have a very shallow adsorption/desorption rate (and therefore an ineffective moisture exchange) by comparison to Wool 1,2 and SMR.The MBV and 'Group' classification of samples after 22 cycles within the chamber are in Tab. 4.

Tab 4: MBV classification of samples after 22 days.

Sample ID	**MBV (g/m^2 %RH)**	**MBV Classification (Rode et al, 2005)**
SMR	2.06	Excellent
Straw	Did Not Stabilise (2.21)	- (Excellent)
WF	1.25	Good
Wool 1	1.88	Good
Wool 2	1.23	Good
WWB	Did Not Stabilise (1.51)	- (Good)

To produce a bio-based passively controlled thermal management panel the best moisture buffering samples should be selected. Tab. 4 demonstrates only 4 out of 6 samples stabilised therefore only these 4 should be considered for selection. SMR has the highest MBV so is the best samples out of the top 6. Although WF and Wool 2 have the same MBV classification their MBV only differs by 0.02 (g/m^2 %RH) which is not enough empirical data in order to select either material. It then falls to the 'Group' classification to differentiate between them, Wool 2 fits within Group 1 (the most preferential group) yet, WF belongs to Group 2. The dynamic way in which a sample adsorbs and desorbs is integral in order to understanding the characteristics of the material, therefore Wool 2 must be selected.

3.5. Dynamic Temperature Change

Whilst within the chamber, Fig. 4 demonstrates that there was no temperature difference at the step change for each sample, but there is a sustained temperature different between the external surface and internal surface for each bio-based composite. This given temperature differential and due to there being no external heat source (due to the constant temperature of the chamber) can be attributed to latent heat.

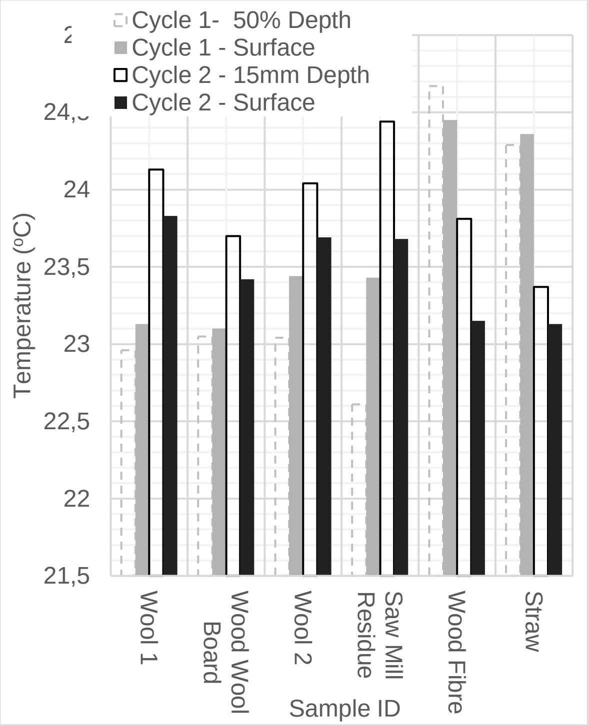


Fig 4: Temperature variation from Cycle 1 (10 days) and Cycle 2 (22 days).

4. CONCLUSION

The analysis of bio-fibres is imperative in order to gain an insight into their inherently diverse characteristics. This is inherently clear via SEM images where the surface morphology of samples differs due to their naturally occurring heterogeneous characteristics. By classifying materials simply by their MBV does not give an indication of the way in which a material dynamically reacts to its hygrothermal environment. Illustrating why the shape of the adsorption/desorption mass change graph is incredibly important when differentiating between two extremely similar samples (in this paper between WF and Wool 2). Samples must have a 'Good' classification as per Rode et al [2005] in addition to also a 'Group 1' classification as per Romano et al [2018]. Laboratory experiments have also demonstrated a latent heat exchange by samples. From 11 original samples, Wool 1, Wool 2 and SMR have been selected for further experimentation. Latent heat of vapourisation and condensation for which are not equal within all materials.

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