

Analysis of dynamic moisture movement within bio-based earth mortars

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Abstract

Understanding moisture movement within building materials is critical for the understanding of how they dynamically respond to their hygrothermal environment. Utilising low embodied energy, hygrothermal materials such as bio-fibres and earth will enable a 'green solution' to the current climate change issues surrounding carbon intensive materials such as concrete. Within this research an earth mortar with bio-fibres of 2 types of sheep wool: Wool 1 (W1), Wool 2 (W2) and a Saw Mill Residue (SMR) in addition to a plain, control sample (PL) were cast. Experimentation was completed on these materials to identify Water Vapour Permeability (WVP), Sorption Isotherms and latent heat of sorption. Results demonstrated that for WVP, SMR has the greatest value of WVP ($2.2 \times 10^{-11} \text{ kg.m}^{-1}.\text{s}^{-1}.\text{Pa}^{-1}$). PL also had the lowest value ($1.4 \times 10^{-11} \text{ kg.m}^{-1}.\text{s}^{-1}.\text{Pa}^{-1}$). For sorption isotherm, over the course of the experiment it can be demonstrated that the incorporation of fibres increases the rate in which the mortars adsorb water molecules. This is particularly highlighted as above 30% RH samples begin to increase in moisture content with this rapidly increasing from approximately 65% RH. Finally, latent heat of sorption analysis demonstrated that a dynamic change in latent heat under differing hygrothermal conditions can be identified; for all samples, even after 21, 24 hour cycles. However, SMR had the lowest quantity of latent heat even by comparison to the PL sample as there is a sustained difference of approximately only 0.5°C between samples. This establishes that the SMR sample requires less heat energy in order for the water to change to and from vapour and liquid state.

Keywords: moisture buffering, water vapour permeability, latent heat, hygrothermal behaviour, mortars, bio-fibres

1.0. Introduction

To understand how building materials dynamically respond to their hygrothermal environment, it is essential to have a greater insight into moisture movement and transport within the material. An example of a traditional building material and existing for thousands of years, using earth as a construction material is not uncommon and has been fundamental for buildings around the world [1, 2]. These techniques have been abandoned in favour of more 'fashionable' and fossil fuel intensive materials such as steel and concrete. Pacheco-Torgal and Jalali [3] identified (within Table 1) the clear embodied carbon savings for monolithic walls when using earth as a construction material compared to carbon intensive cement.

Table 1. Embodied carbon quantities for different monolithic wall constructions (taken from [3])

| Wall type | kg CO ₂ eqv |
|-------------------------------------|------------------------|
| Generic rammed earth | 26 |
| Cement stabilized rammed earth 8% | 65 |
| Cement stabilized rammed earth 9% | 70 |
| Brick or stone and blockwork cavity | 71 |

However, these materials are being rescinded due to environmental pressures and more sustainable construction techniques are regaining importance [4]. Using earth as a building material is beneficial due to its low environmental impact [5] and as it is such an abundant material, it provides locally sourced material reducing carbon emissions associated with the transportation of materials [6-8]. In terms of material properties earth presents a high hygroscopicity in addition to a low thermal conductivity, enabling it to locally regulate RH [9]. The ability to use earth as a part of an earth mortar contributes to its use as an extremely eco efficient and sustainable building material [10].

1.1. Bio-based materials hygrothermal properties

Research has demonstrated that bio-based materials are able to passively regulate relative humidity to its local environment [11]. By adding insulation as a retrofitting tool, to a residential building this also helps to reduce the heating energy in addition to acting as a view to reducing the demand of heating and cooling costs [12]. Offsetting this energy requirement will act as a direct alleviation to the overall energy consumption of each home, city and overall countries efforts in an attempt to curb global warming.

1 As a fundamental basis, all materials are affected by parameters such as temperature and
2 relative humidity explored in [13]. A high performing hygrothermal material have the ability to
3 'self-regulate' and buffer relative humidity. Bio-based insulation materials have hygrothermal
4 characteristics, which make them ideal for indoor relative humidity buffering. Insulation
5 materials respond to seasonal adjustments in temperature in relative humidity due to their
6 specific thermophysical properties. As effective insulator materials, they must have thermal
7 comfort of the occupants at the centre of their characteristics – to be cooling in the summer
8 and reduce heat requirements within the winter. The heterogeneous nature of bio-based and
9 evolving climatic conditions ensure that a 'one size fits all' approach is insufficient in order to
10 maximise the intrinsically beneficial hygrothermal characteristics [14]. Therefore, the fit for
11 purpose bio-based materials requires the analysis of relevant properties as presented below.
12

13 **1.2. Moisture Movement**

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15 Understanding the moisture movement within these mortars can be examined in several
16 different ways but with a particular focus on water vapour permeability, sorption isotherms and
17 examination of latent heat.
18

19 **1.2.1. Water Vapour Permeability (WVP)**

20 This property demonstrates a porous materials ability to transfer moisture when exposed to a
21 vapour pressure gradient as a nonlinear function of the equilibrium between the sample and
22 environmental relative humidity. Collet et al. [15] outline that this moisture movement is
23 dependent on three factors: diffusion, effusion and liquid transfer. Values of water vapour
24 permeability are calculated using wet or dry cup methods as per BS EN 12572-2016 [16] EN
25 1015-19 [17] and BS EN 15803 [18]. Osanyintola and Simonson [19] highlighted that when
26 combining bio-based materials into a vapour permeable wall is beneficial to occupant Indoor
27 Air Quality (IAQ). Further to this, Zhang et al. [20] demonstrated that the vapour permeability
28 also reduced moisture build up which could potentially extend the service life of a building
29 material. The vapour resistance within a sample is directly related to tortuosity of the pores.
30 Outlined by Padfield [21] a low vapour resistance equates to an improved dynamic moisture
31 buffering capability.
32

33 Another factor is that according to Zhang et al. [22] the diffusion of water within porous building
34 materials is not only the tortuosity affects but also the remaining saturation within the materials
35 microstructure. The literature has demonstrated that there is a significant dependency of WVP

1 on the thickness of the sample [23, 24].

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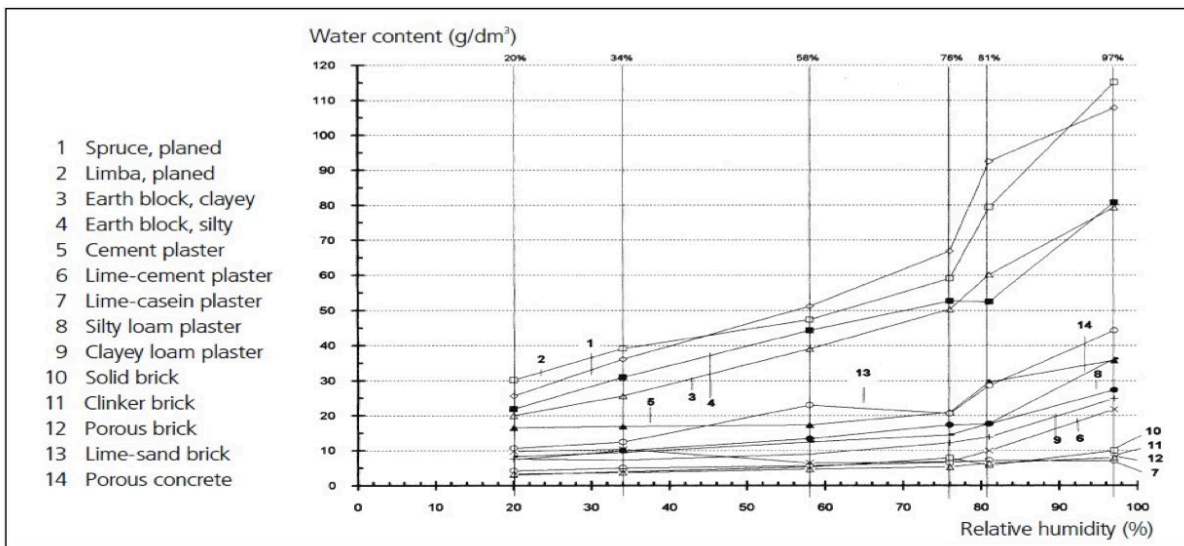
3 **1.2.1. Sorption Isotherms**

4

5 By exposing and stabilising samples to regular increases in relative humidity, the sorption
6 isotherm can be created. This gives an indication of the hygroscopic and moisture storage
7 capacity within the material. There are three layers of adsorption components which has been
8 explored in Hill et al. [25]. The difference between adsorption and desorption loops can be
9 identified as the hysteresis phenomenon. Although this phenomenon is not greatly
10 understood, it can be split into 6 groups as per International Union of Pure and Applied
11 Chemistry (IUPAC) classification loops [26, 27]. These shapes demonstrate that due to
12 capillary condensation, larger RH tends to impact and increase the hysteresis within a
13 material.

14 Further to just the raw materials, other building materials and their water sorption isotherms
15 have been investigated in Karoglou et al. [28] and Růžička et al. [29]. Particularly for
16 common building materials, Figure 1 demonstrates how the adsorption capacity is affected
17 by relative humidity.

18



19 **Figure 1.** Isothermal adsorption curves for building materials (taken from [1])

20

21 **1.2.3. Latent Heat**

22

23 This is defined as the amount of heat that is required in order to facilitate a phase change in a
24 material, without a change in temperature [30]. The affects of latent heat has been relatively

1 under researched but provides crucial information about how energy is exchanged within a
2 sample. Within hygroscopic materials there is a constant dynamic state of vapourisation and
3 condensing of water vapour on the surface of the material and as it travels through the pores
4 of the sample. As the water changes state, latent heat is released; known as latent heat of
5 condensation when water is on the surface of the material and adsorbed into the sample as
6 liquid water [31] and vice versa for latent heat of vapourisation. However, as this water is
7 exchanged the latent heat that is produced during adsorption and desorption is not equal
8 which can be attributed to the continual hysteresis as moisture is saturating throughout the
9 sample [32].

11 Within a residential property, there is evidence by Qin et al. [33], it demonstrated how heating
12 load is affected by the latent heat exchange within a 20m² office space. Where the interior
13 surface is covered with a hygroscopic finishing, heating energy was reduced by 6.5%. In
14 addition [19], researched the effects that hygroscopic building materials have on latent heat
15 exchange within a 12m² bedroom shared by two people. The effectiveness of these materials
16 resulted in around a 10% reduction in energy consumption due to latent heat of condensation.
17 [34] demonstrated that using bio-based composites can improve internal moisture buffering
18 performance.

19 Bio-based materials and their coating perform differently dependant on the moisture loading
20 conditions. Therefore the novelty of this paper lies within the understanding of how these mix
21 designs perform (as a function of time) with respect to their hygrothermal ability and moisture
22 movement ability. In addition, this paper will also propose a methodology and experimental
23 data for measuring latent heat and particularly latent heat of sorption. By utilising other
24 experiments to understand how this dynamic moisture movement within each mix design
25 affects performance with different relative humidities and lengths of time will ensure an
26 optimised mix design can be selected.

28 **2.0 Materials**

30 **2.1. Earth**

32 Collected from a construction site in Liverpool, UK from a depth of 1.5-2m. A dry particle grain
33 size distribution for both the earth and sand was conducted as per (BSI) [35] and demonstrated
34 within Figure 2. The earth within this study was sieved at 2mm to remove any construction
35 waste or larger pieces of aggregate and homogenise the earth.

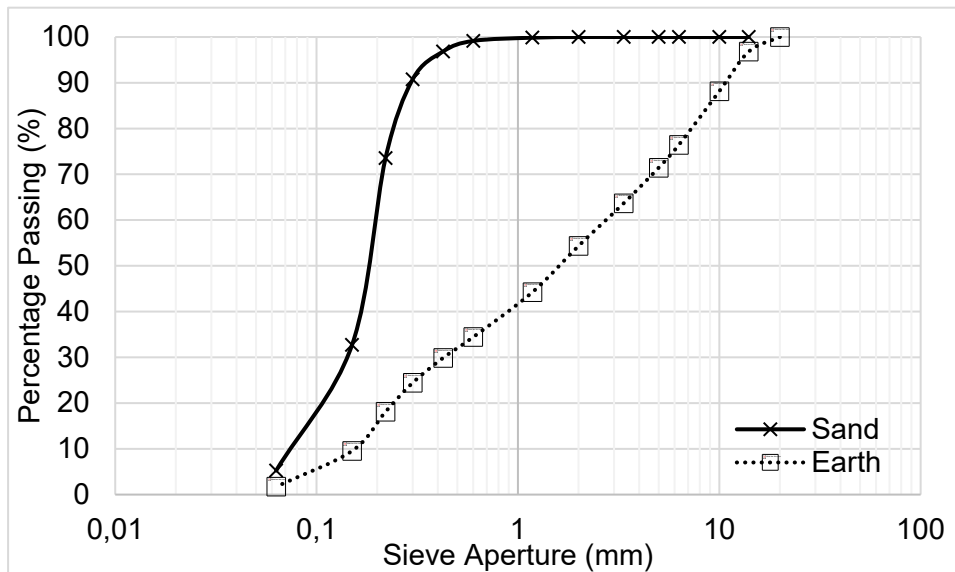


Figure 2. Dry grain size distribution of earth and sand.

2.2. Lime

This research utilises Natural Hydraulic Lime (NHL) supplied from a national builders merchant (Tarmac Limite NHL 3.5) where the requirements are defined within EN 459-1 [36]. Further to this, the dry bulk densities (as per BSI EN ISO 11272 [37]) for lime, sand and earth can be found within Table 2.

Table 2. Dry Bulk Density of mix design components.

| Mix Design Component | Dry Bulk Density (kg/m ³) |
|---------------------------------|---------------------------------------|
| Earth (after passing 2mm sieve) | 2527 |
| NHL | 940 |
| Sand | 1593 |

2.3. Bio-Fibres

The bio-fibres used within this paper are those of two varieties of sheep wool, Wool 1 (W1) and Wool 2 (W2) and Saw Mill Residue (SMR); where the hygrothermal and physicochemical properties have been investigated in [38], [39] and [40]. From these papers, a summary of these samples key physicochemical and hygrothermal properties can be found in Table 3.

Table 3. Summary of material properties from [38-40] at laboratory conditions (20°C and 53% RH).

| Sample ID | Open Porosity (%) | Dry Bulk Density (kg/m ³) | Specific Heat Capacity (at 20°C) (kJ/kg.K) | Thermal Conductivity, λ , (W/(m.K)) | Moisture Buffering Value (MBV) (g/(m ² %RH)) | Capillary Coefficient (m/s ^{0.5}) |
|-----------|-------------------|---------------------------------------|--|---|---|---|
| PL | 30.89 | 1708 | 0.741 | 0.203 | 0.98 | 2.646 |
| W1 | 30.08 | 1571 | 1.045 | 0.183 | 1.10 | 2.654 |
| SMR | 36.43 | 1410 | 1.014 | 0.179 | 1.26 | 2.376 |
| W2 | 37.59 | 1512 | 1.109 | 0.189 | 1.21 | 2.638 |

2.4. Mix Design

After all dry ingredients were mixed together (as per 1015-2 [41]) before adding bio-fibres and water. The mix design for the mortars are displayed in Table 4. Natural Hydraulic Lime (NHL) was utilised within this mix design for its strength and ability to transport moisture and enhance the earth and bio-based materials hygrothermal characteristics[42]. The NHL that was used was sourced from a national builders merchant – Taramc Limite 3.5; where it meets EN 459-1 [36].

Table 4. Mix design ratio quantities (by mass).

| NHL | Earth | Sand | Lime/Water | Bio-fibres | |
|-----|-------|------|------------|------------|---------------|
| | | | | Sample ID | Lime/Biofibre |
| 1 | 0.1 | 8.6 | 2.4 | PL | - |
| | | | | W1 | 0.0243 |
| | | | | SMR | 0.0243 |
| | | | | W2 | 0.0485 |

2.5. Curing

After all samples were cast, they were tested after 28 days of curing. The curing procedure as outlined in EN 1015-2 [41] were followed. Two different mortar sample sizes were cast, for each mix design 5 circular samples with a thickness of approximately 25mm and diameter of 80mm and 3 square shaped samples with surface dimensions of 100mm x 100mm and a depth of 35mm.

3.0. Methodology

3.1. Water Vapour Permeability

Water Vapour Permeability (WVP) was conducted by wet cup method as per BS EN 12572-2016 [16] BS EN 1015-19 [17] and BS EN 15803 [18] and bio-earth mortar samples were stored within a plastic container. To ensure there was no vapour movement around the sides of the sample, silicone sealant was used. The samples were sealed for there to be a unidirectional moisture flow. The set up for this experiment can be found within Figure 3.

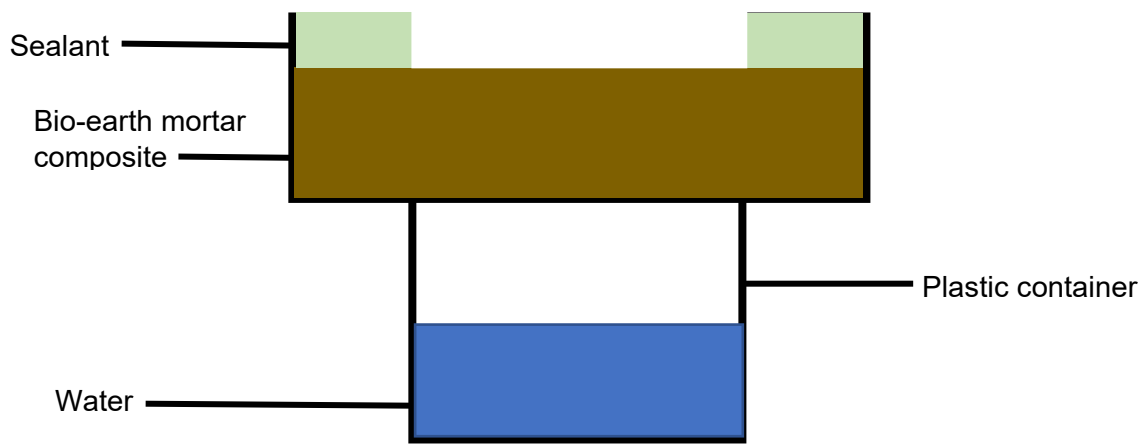


Figure 3. WVP experimental set up.

Initially samples were conditioned at 23°C at 50% RH to ensure a constant mass was achieved. The isothermal conditions were set at 23°C, using the wet cup method at 40% RH within a climatic chamber. An issue that should be considered for this method is that it does not consider how surface vapour resistance of the material may affect the overall result. Due to the gradient of moisture between the lower and upper surface of the sample, this drives a moisture gradient within the cup and the vapour is released from the sample. Every 24 hours the sample was measured until a three successive values were within $\pm 5\%$ of the mean value. WVP was calculated as per [16,17,18].

Due to this experimental set up and the sample overlapping the edge of the cup, a correction needs to be applied to the vapour transmission rate (g) as per BS EN ISO 1272:20116 [16] in Equation (1)

$$\frac{g_{me}}{g} = 1 + \frac{4 \cdot d}{\pi \cdot S} \cdot \ln \left(\frac{2}{1 + \exp(-2 \cdot \pi \cdot \frac{b}{d})} \right) \quad (1)$$

Where:

- 1 g_{me} = vapour transmission rate with masked edge (kg/ m².s)
- 2 g = vapour transmission rate ignoring masked edge (kg/ m².s)
- 3 d = thickness of sample (m)
- 4 b = width of masked edge (m)
- 5 S = hydraulic diameter (m)

6 **3.2. Sorption Isotherm**

7

8 Also known as moisture storage function, sorption isotherms demonstrate a relationship
9 between the relative humidity of the environment and equilibrium moisture content of a
10 sample. As these materials are porous, their ability to dynamically alter to their hygrothermal
11 environment is of great importance. These samples were dried in accordance with BS EN ISO
12 12570 [43] where a constant mass (with less than a 0.1% of total mass) was achieved over
13 three consecutive weighing at least 24 hours apart. Adsorption isotherms were calculated in
14 line with BS EN ISO 12571 [44] in a climatic chamber at a temperature constant of 23°C,
15 where moisture content by mass by mass, u (kg/kg) was calculated as with Equation 7.

16
$$u = \frac{m-m_0}{m_0} \quad (7)$$

17 Where:

- 18 m = mass of sample (kg)
- 19 m_0 = mass of dried test specimen (kg)

20

21 **3.3. Latent heat of sorption**

22

23 During the phase change between water molecules in the liquid and vapour state, latent heat
24 was identified over 10 cycles of the raw bio-fibres. For this experiment, each mix design were
25 cast and a thermocouple inserted into the wet mortar on the surface at 15mm from the surface
26 (approximately half way through the sample) (see Figure 4). Once cured, composites were
27 placed within a climatic chamber (see Figure 5) where the latent heat of sorption was
28 measured dynamically and continuously every 30 seconds for 21, 24 hours cycles with cyclical
29 RH step changes between 75% and 53% for 16 and 8 hours respectively. The thermocouples
30 used are K-type and have a functional temperature range of -40°C to 260°C and the data
31 loggers -250°C to 1370°C; where both have a maintained resolution of ±0.04°C.

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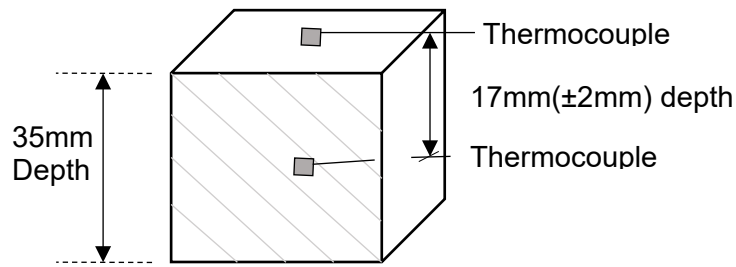


Figure 4. Experimental set up of thermocouples within earth mortar composite.



Figure 5. (L) Thermocouple cast on the surface of mortar (R) Thermocouple cast 15mm from surface of earth mortar composite.

4.0. Results and Discussion

4.1. Water Vapour Permeability (WVP)

Understanding the permeability of water vapour into the sample is important for anticipating the potential risks of moisture build up within the composite [20]. The greater the ability for water vapour to enter and exit the sample indicates that the sample has a larger breathability'. Without this breathability, the build-up of condensation within the material will reduce its hygroscopic ability. Especially in residential properties, this is particularly problematic because as the water vapour diffuses through the individual wall components, building envelope and temperatures drop to reach the dew point and form interstitial condensation. By reducing the performance of the building fabric and particularly the insulation could result in a reduced thermal resistance and especially in UK residential properties, exacerbate condensation issues. It could therefore be associated that the lower the water vapour permeability value,

1 the more likely the aforementioned issues are to arise and in turn reduce the durability of the
2 material (as highlighted in Claisse (2014)).

3 WVP of a material indicates the 'breathability' of a material - a larger value of water vapour
4 permeability indicates an enhanced transport of water throughout the composite as capillary
5 condensation leads to the microscopic pores to fill. The results for the WVP and water vapour
6 diffusion resistance factor in Table 5.

7 **Table 5.** WVP values for bio-earth mortar composites.

| Sample ID | Water Vapour Permeability ,δ ($\times 10^{-11}$) ($\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$) | Water Vapour Diffusion Resistance Factor, μ |
|------------------|--|---|
| PL | 1.4 \pm 0.1 | 3.2 \pm 0.2 |
| W1 | 1.8 \pm 0.1 | 2.4 \pm 0.1 |
| SMR | 2.2 \pm 0.2 | 2.1 \pm 0.1 |
| W2 | 1.8 \pm 0.2 | 2.0 \pm 0.2 |

8

9 From Table 5 it is shown that SMR has the greatest value of WVP (2.2 $\times 10^{-11}$ $\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$).
10 PL also had the lowest value (1.4 $\times 10^{-11}$ $\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$) as this composite has no bio-fibres,
11 the microstructural shape would be more homogeneous. By comparison to the bio-fibre
12 composites it is proposed that the breathability is increased not only on the external surface
13 but due to the tortuosity of pores interacting and combining with the bio-fibres themselves [45].
14 The value of μ demonstrates how reluctant the diffusion of water vapour is into the sample.
15 This is shown in Table 5 as PL has the lowest value of μ and therefore has the most resistance
16 for water vapour entering the sample and is the least porous and permeable.

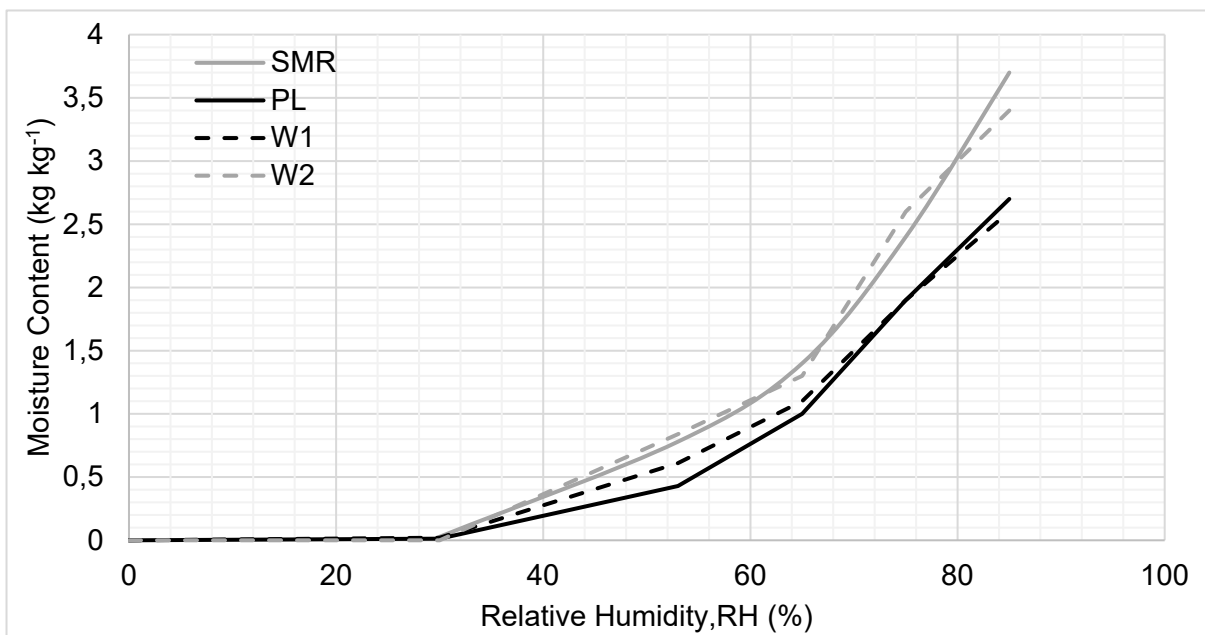
17 By comparison to Cagnon et al. [6] and Faria et al. [46] the values presented in Table 5 are
18 generally slightly lower than expected values than in the literature, which could be accounted
19 to the differing thickness of the samples. Another potential explanation could be due to testing
20 of these samples after only 28 days. As the lime has not yet fully carbonated, this could be
21 affecting the microstructure of the pores. As this measurement was calculated after only 28
22 days of curing, when considering a longer curing time, the efficiency of bio-fibres and their
23 potential degradation would be interesting to understand how this affects WVP. This is due to
24 previously research showing the degradation to building materials under cyclical drying and
25 wetting can considerably affect the thermal performance [47]. Particularly with wool, uneven
26 and continual wetting and drying deteriorates the fibre. Further to this, as the mortar cures
27 around the bio-fibers, within the mortar matrix, air voids are created. This effect on the overall

1 material properties would be noteworthy to understand the long term service life performance
2 of the composites as outlined by Zirkelbach [48]. Further analysis of the WVP could include a
3 better understanding on not only WVP as an empirical value but understanding the quantity
4 and the quality of the wetting the vapour gives across the surface of the composite; for
5 example understanding the uniformity of this across the material.

6 4.2. Sorption Isotherms

7

8 By understanding the adsorption behaviour of the composites this will enhance the
9 understanding and interpretation of hygrothermal behaviour. Investigations into other bio-fibre
10 mortars such as hemp was explored in Collet et al. [15] but the utilisation of a locally sourced
11 earth is not as well researched. Within the literature that sorption is greatly affected by
12 temperature it was imperative that the isothermal temperature was kept constant [49]. The
13 curve for how adsorption is affected over a wide range of relative humidities can be found in
14 Figure 6. Over the course of the experiment it can be demonstrated that the incorporation of
15 fibres increases the rate in which the mortars adsorb water molecules. This is particularly
16 highlighted as above 30% RH sample begins to increase in moisture content with this rapidly
17 increasing from approximately 65% RH.



18 **Figure 6.** Adsorption curves for bio-earth mortar composites.

19 Within Figure 6, it is illustrated that the largest adsorption during isothermal moisture content
20 over all the composites is SMR and the lowest is PL. W2 has similar adsorption across the
21 range of RH but not as great as SMR. Over the service range of RH it is important to
22 understand that Figure 6 also demonstrates the availability of materials to be able to accept
23 water molecules over this range. Due to the polarised nature of water molecules, van der Waal

1 forces ensure the water molecules are adsorbed into the composite. To have more adsorption
2 within the sample it could be suggested that to continually adsorb over such a large range of
3 RH, SMR and W2 have a larger quantity of van der Waal sites due to both the bio-fibre and
4 earth mortar matrix.

5 Further works should be done in order to understand the effect desorption has on the quantity
6 of hysteresis in addition to true a classification of the hysteresis loop as per IUPAC
7 classification loops [26, 27]. This would further aid the understanding of the pore structure
8 within the composite. Many different theories contribute to the understanding of what sorption
9 hysteresis is. As explored in Hill et al. [25], the isothermal sorption/desorption characteristics
10 of natural fibres and identified that the extent of hysteresis relies upon the specific fibre type
11 examined. Jiang et al. [50] outlined that there is limited research on the mechanisms behind
12 moisture sorption in specifically plant based bio-materials. It was explored in Karoglou et al.
13 [28] the sorption isotherms of common building materials were examined and it was identified
14 that all building materials even those non bio-based experience hysteresis phenomena.

15 Research by Skaar [51] outlined that within cellulose based materials capillary suction starts
16 at higher RH because of nanopores within the cell wall, yet the quantity, arrangement and the
17 mechanisms for adsorbing water is yet to be fully understood. Jiang et al. [50] states that
18 during adsorption after the first and subsequent cycles, hysteresis has been examined within
19 the sample. However, when considering these materials when combined into an earth mortar
20 matrix it is evident that this is also true. The research conducted by [50] also demonstrated
21 the top layer of these cellulose based materials that the binding force with initial layer of water
22 was stronger but weaker for subsequent layers.

23 Within Romano et al. [38], Figures 10a to 10v demonstrates when samples have a higher
24 relative humidity their storage capacity alters as water moves through the different pores within
25 the composite. At these different relative humidities it has also been explored that this alters
26 the materials thermal conductivity and other thermal properties. When relative humidity
27 increases, pores that were previously occupied by air is replaced by water where water has a
28 higher thermal conductivity. This filling of the pores and particularly the interconnected pores
29 is problematic as the mechanisms within earth based construction; and creates 'blocking'
30 within the pore structure and facilitate hysteresis [31].

31

32 **4.3. Latent heat of sorption**

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34 By casting the thermocouples to within the mortar matrix and on the surface within this
35 experimentation (due to the hygrothermal nature of these materials), any potential latent heat

1 can be attributed to the changing state of water molecules [52]. Figure 7 demonstrates the
2 temperature that has been recorded for the first 24 hour cycle at the surface and 15mm below
3 the surface of samples. From this figure, the adsorption and the further evaporation of water
4 molecules, from varying hygrothermal environments has resulted in a latent heat exchange.
5 This will also have a significant effect on the balance of heat within the sample as identified in
6 Kraniotis et al. [53].

7 Due to the relationship between moisture and heat transfer in hygroscopic materials, as the
8 accumulation of condensation of moisture increases as does indoor temperature and vice
9 versa for evaporation of moisture. As outlined in Hameury [54] water condenses from vapour
10 to liquid phase, heat is released at 2501kJ/kg vapour condensing at 0°C (latent heat of
11 vapourisation). However, within standard room temperatures varying from 10-25°C reduces
12 the latent heat of vapourisation to approximately 2477.7 – 2441.7 kJ/kg. Understanding the
13 role of latent heat within these hygroscopic materials is imperative for their full utilisation. The
14 factors which affect the latent heat of moisture within a samples depends on the addition of
15 latent heat of vapourisation and differential heat of condensation – which has been explored
16 in the literature for building materials [55].

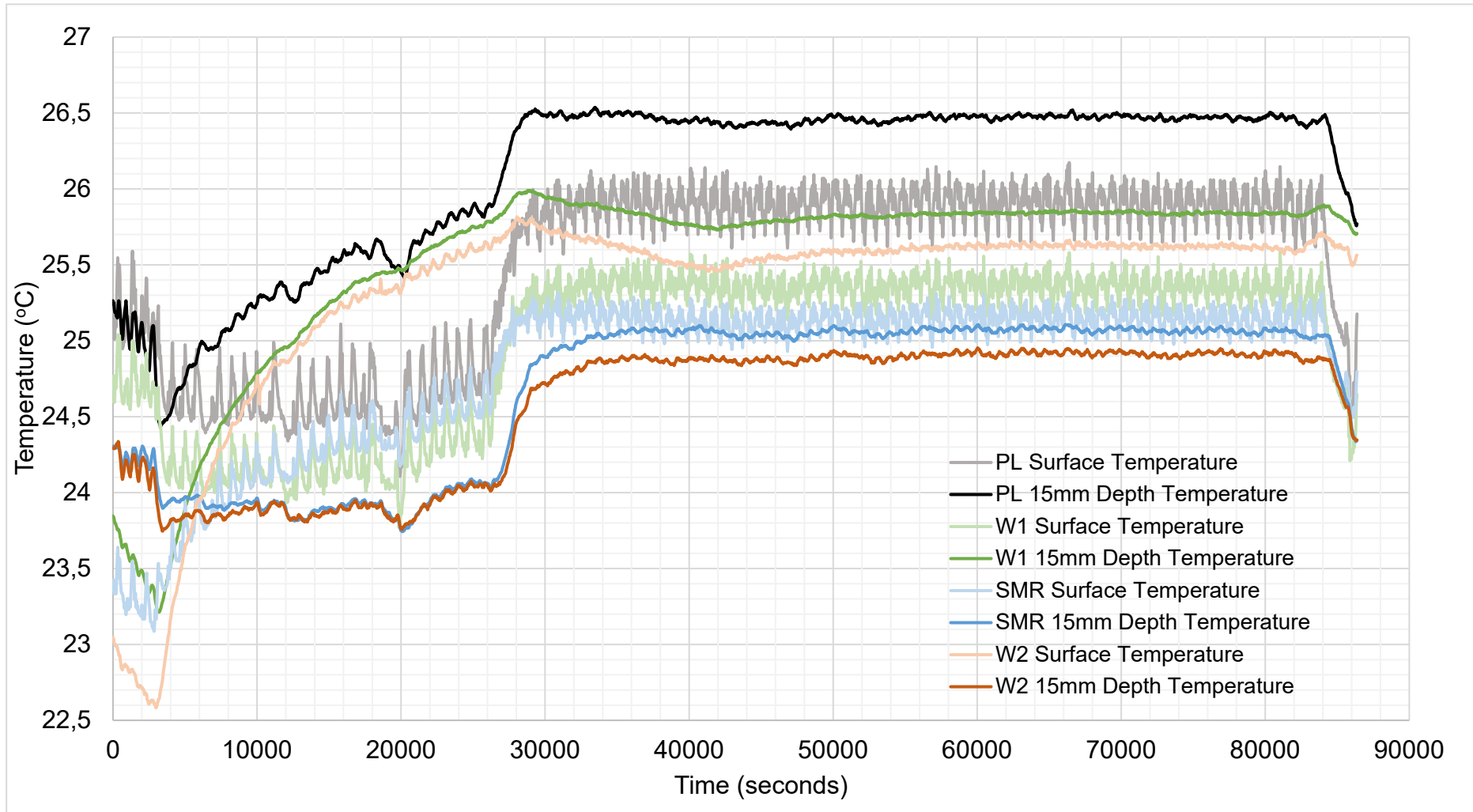


Figure 7. Dynamic temperature variation of mortar mixes PL, W1, SMR and W2 after 1, 24 hour cycle.

1 For all mix designs, there are three distinguished regions where latent heat varies. The first
2 occurs during the first hour probably due to mass sample stabilisation, the second during the
3 first 8 hours and then the desorption during the next 16 hours. These samples were tested
4 under the same dynamic hygrothermal conditions of 8 hours at 75% RH and 16 hours at 53%
5 RH which is reflected within the temperature changes in the figures – similar to that of [56], PL
6 and W1 exhibit the centre of the sample demonstrating a greater temperature than that of the
7 surface. This is shown throughout the first 24 hours of the experiment, where there is constant
8 heat flow release from the sample. Conversely, SMR and W2 demonstrate that the surface
9 temperature is higher than in the centre of the sample showing heat flow absorption into the
10 sample.

11 From the initial cycle (Figure 7) the adsorption period and a consistent increase in temperature
12 is demonstrated. However, when considering the shape of the adsorption temperature after
13 21 cycles it is clear that the temperature evolution is more defined between the two phases.
14 For the first cycle in the adsorption phase the temperature seemed to rise linearly throughout
15 the experiment but after 21 cycles the difference between two RHs is more of a clear step
16 change in temperature difference.

17 To understand the relationship between the two thermocouples within the earth based
18 composite throughout the full 21 cycles, the surface minus the centre of the sample was
19 plotted in Figure 9. There is a sustained difference in temperature of all the samples
20 throughout the duration of the experiment and no external heat source – this temperature
21 differential can be attributed to latent heat. Particularly obvious within samples after 21 cycles,
22 the quantity of latent heat is larger of the adsorption period rather than desorption. The
23 absorption period is 50% shorter than the desorption period at 8 hours compared to 16.

24 SMR also has the lowest quantity of latent heat even by comparison to the plain sample as
25 there is a sustained difference of approximately only 0.5°C between samples. This establishes
26 that throughout the experiment SMR requires less heat energy in order for the water to change
27 to and from vapour and liquid state. It could be suggested that some composites have an
28 innate ability to readily accept water molecules more than others due to the quantity of
29 available hydroxyl groups.

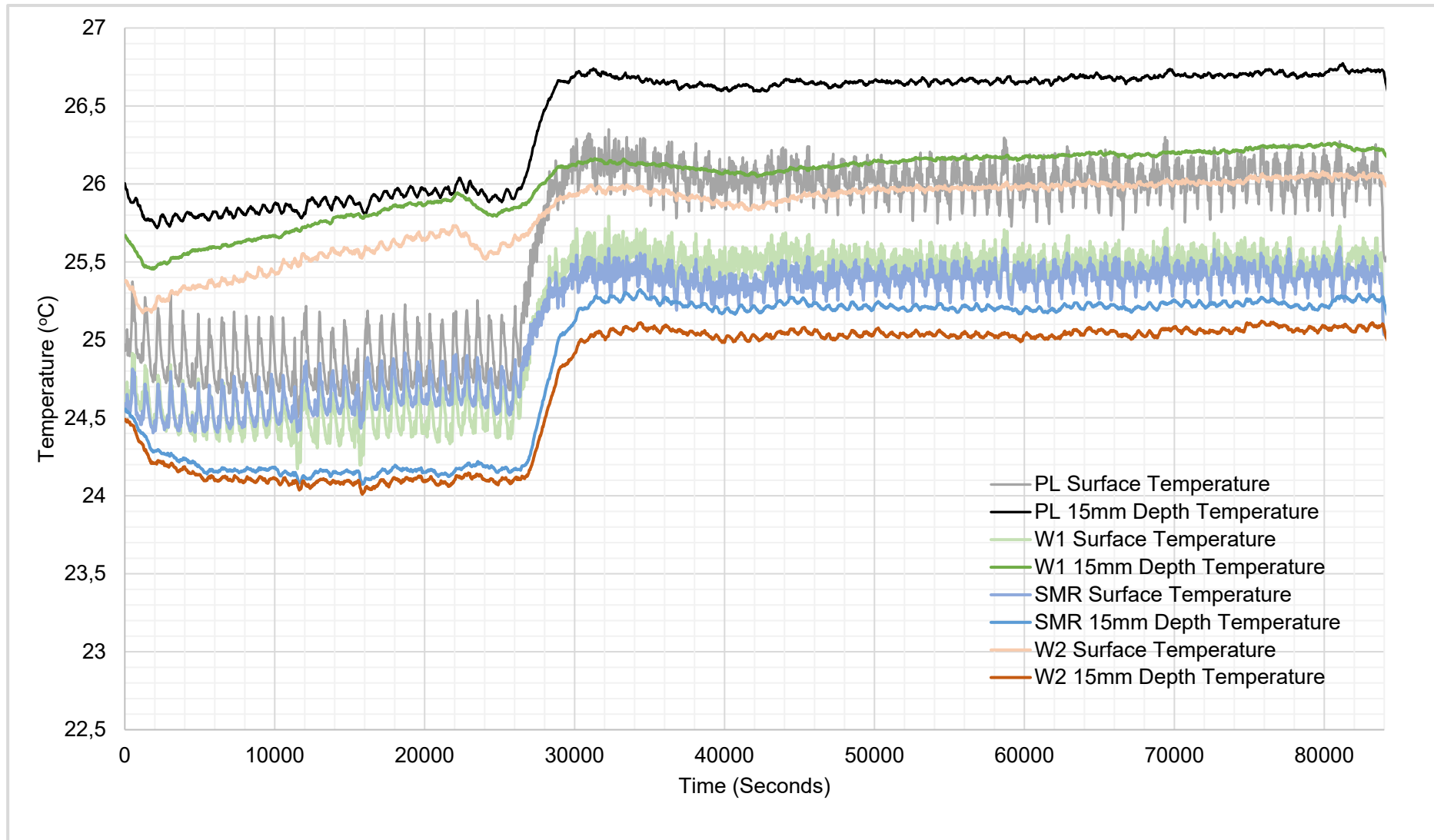


Figure 8. Dynamic temperature variation of mortar mixes PL, W1, SMR and W2 after 21, 24 hour cycles.

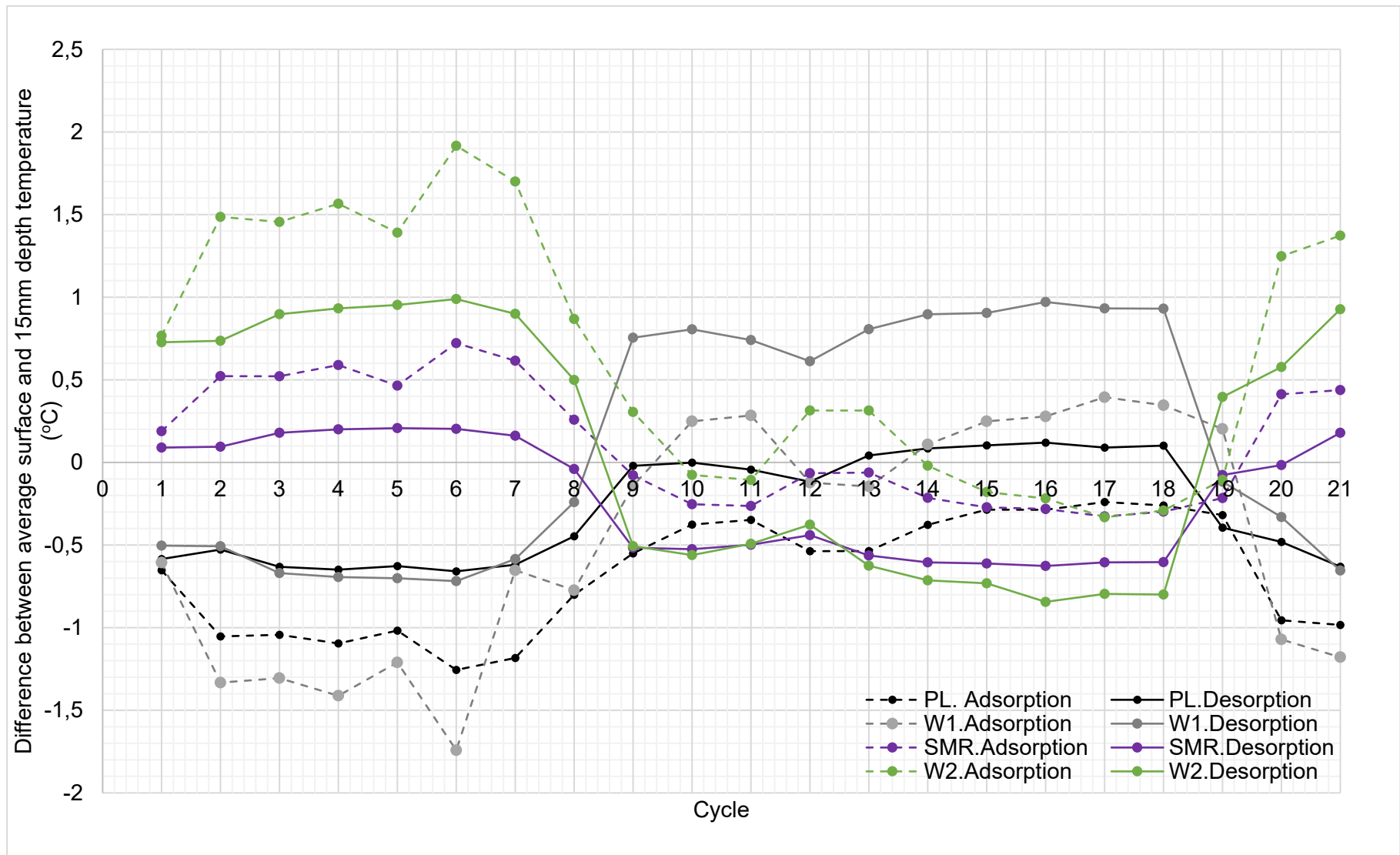


Figure 9. Difference between average surface and 15mm depth temperature over 21 cycles for all sam

1 For all samples within Figure 9, all adsorption phases are mirrored by a desorption phase and
2 whilst these phases may have different temperatures, the relationship stays the same. It is
3 clear that all adsorption and desorption phases PL and W1 demonstrate the opposite
4 behaviour of SMR and W2. For W2 until cycle 9 and SMR until cycle 8, the surface
5 temperature was greater than the centre of the sample. After cycle 8 the temperature at the
6 centre of the surface is larger than the centre for two cycles and then returns to the surface
7 temperature being greater. Conversely, PL and W1 have the same behaviour and very similar
8 average desorption temperatures until cycle 7. However, after cycle 8 the temperature change
9 for adsorption of PL is negligible and compared to the other composites with bio-fibres, the
10 heat flow through the sample (even if its vapourisation or condensation) latent heat is
11 consistently produced.

12 Research has often coupled the moisture and heat transfer in building materials[52]. Moisture
13 transport within building materials is affected by heat gradients [57]; so with regards to these
14 earth based bio-composites the implications that hygrothermal behaviour is dependant on
15 what effect latent heat has on moisture transport (via WVP and sorption isotherms). When
16 comparing the results for how moisture moves throughout the samples from WVP, sorption
17 isotherm and latent heat experiments depending on which bio-fibre as well as if there is a bio-
18 fibre in the mix design impacts the results; this is demonstrated in Table 6. From this table is
19 demonstrates that SMR and W2 have the greatest (and within this research papers content,
20 the optimum) values in terms of WVP (2.5 and $2.12 \times 10^{-11} \text{ kg.m}^{-1}.\text{s}^{-1}.\text{Pa}^{-1}$ respectively) and
21 sorption isotherms (0.78 and 0.84 kg kg^{-1} respectively). Interestingly, when considering the
22 comparative behaviour of all the different composites from both cycle 1 all the way through to
23 cycle 21, PL and W1 demonstrate consistent latent heat of condensation – even within
24 adsorption and desorption phases. Conversely, SMR and W2 experience latent heat of
25 evaporation throughout the length of the experiment. Although the values are negligible for
26 the first cycle, after 21 cycles W2 has the largest different in latent heat between adsorption
27 and desorption cycles. This is advantages behaviour as the greater the difference between
28 latent heat values from adsorption and desorption suggests that the efficient moisture
29 exchange within the sample is still dynamic after 21 days of testing.

30 Although a correlation between the materials hygrothermal properties can be understood,
31 there are still limitations to the experimentation. For this study are the effect that the air velocity
32 produced by the fans within the climatic chamber has on the surface temperature of the
33 composites. It is also important to note that the thermocouples represent only one point in the
34 centre of the material and whilst it gives a good indication of the properties, is not truly
35 presentative for the whole surface.

Table 6. Experimentation Results Comparison.

| Sample ID | Water Vapour Permeability | | Sorption Isothem | | Latent heat of sorption | | | |
|-----------|--|---|--|--|--|--|---|---|
| | Water Vapour Permeability, δ ($\times 10^{-11}$) ($\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$) | Water Vapour Diffusion Resistance Factor, μ | Moisture Content at 53% RH (kg kg^{-1}) | Moisture Content at 75% RH (kg kg^{-1}) | Average temperature difference between surface and 15mm depth at 75% RH (adsorption) during cycle 1 ($^{\circ}\text{C}$) | Average temperature difference between surface and 15mm depth at 53% RH (desorption) during cycle 1 ($^{\circ}\text{C}$) | Average temperature difference between surface and 15mm depth at 75% RH (adsorption) during cycle 21 ($^{\circ}\text{C}$) | Average temperature difference between surface and 15mm depth at 75% RH (desorption) during cycle 21 ($^{\circ}\text{C}$) |
| PL | 1.4 | 3.2 | 0.43 | 1.9 | -0.65 | -0.59 | -0.98 | -0.63 |
| W1 | 1.8 | 2.4 | 0.61 | 1.9 | -0.61 | -0.50 | -1.18 | -0.65 |
| SMR | 2.2 | 2.1 | 0.78 | 2.4 | 0.19 | 0.09 | 0.44 | 0.18 |
| W2 | 1.8 | 2.0 | 0.84 | 2.6 | 0.77 | 0.73 | 1.37 | 0.93 |

5.0. Conclusion

Understanding the movement of water within the bio-fibre composites gives an assessment of their hygrothermal characteristics. Similar to the MBV performance, SMR has the largest WVP whereas PL has the largest water vapour diffusion resistance factor. The adsorption isotherm demonstrated that SMR has the largest moisture content over a wide range of RH, this ability to adsorb water molecules could be associated to the quantity of sites available for van der Waal forces to incorporate the vapour into liquid water.

Results demonstrated that for WVP, SMR has the greatest value of WVP ($2.2 \times 10^{-11} \text{ kg.m}^{-1}.\text{s}^{-1}.\text{Pa}^{-1}$). PL also had the lowest value ($1.4 \times 10^{-11} \text{ kg.m}^{-1}.\text{s}^{-1}.\text{Pa}^{-1}$). By comparison to the bio-fibre composites it is proposed that the breathability is increased not only on the external surface but due to the tortuosity of pores interacting and combining with the bio-fibres themselves. For sorption isotherm, over the course of the experiment it can be demonstrated that the incorporation of fibres increases the rate in which the mortars adsorb water molecules. This is particularly highlighted as above 30% RH sample begin to increase in moisture content with this rapidly increasing from approximately 65% RH.

This paper has also demonstrated the effective utilisation of using K type thermocouples to measure the difference in latent heat in an earth mortar composite from both the surface and at 50% depth within both adsorption and desorption phases whilst within a climatic chamber. Finally, latent heat of sorption analysis demonstrated that a dynamic change in latent heat under differing hygrothermal conditions can be identified; for all samples, even after 21, 24 hour cycles. Overall, the sample within this paper that has the best moisture movement properties SMR as by comparison to both PL and wool based bio-fibres outperforms them.

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