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SUSTAINABLE BIO-BASED EARTH MORTAR WITH SELF-HEALING CAPACITY

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ABSTRACT

The paper describes hygrothermal, mechanical properties and self-healing capacity of a sustainable bio-based mortar repair system for earth construction. There is currently limited characterisation of materials that directly compare earth, bio-fibres and self-healing behaviour. Both prismatic and 0.1x0.1m^2 samples were cast with plain mixes, saw mill residue (SMR), straw, wool and wood pellets - executing both structural and hygrothermal experimentation gives an indication of the performance and durability of the samples. The bio-based agent added to the bio-based composite consists of bacteria. Adding bio-based agent to an earth matrix with SMR, straw and wood pellets has promising rules for hygric properties, as initial water adsorption and absorption is lessened. Thermal conductivity is reduced from 0.32W/m.K to 0.23W/m.K when bio-based agent is combined into earth-based mix design.

Keywords: Hygrothermal, self-healing capacity, bio-based mortar, saw mill residue, composite

INTRODUCTION

Over 2.2 billion people (approximately 30% of the world's population) live in earth based buildings(Costa, Rocha and Velosa, 2016). As a naturally occurring material, using earth as a construction material has many environmental, sustainable and economical benefits(Fratini et al, 2011). Due to the wide availability of earth around the world, different earth based construction techniques have arisen; generally the literature focuses on adobe blocks, rammed earth, compressed earth and cob(Hall and Casey, 2012; Quagliarini and Maracchini, 2018). Compared to conventional building materials such as concrete or steel, the relatively low energy input (Ashour et al, 2010)is extremely desirable due to the current climate change crisis in addition to its relatively low thermal conductivity. In addition to this, earth as a construction material has the ability to regular relatively humidity within an indoor environment furthermore, improving the hygrothermal performance of an earth based building(Janssen and Roels, 2009).

Despite the environmentally conscious benefits, the use of earth materials and construction in general has many drawbacks. These are generally associated to the exposure of buildings as earth is highly sensitive to deformation (Muller et al, 2016) due to its hydrophilic behaviour.

Buildings respond in a variety of ways as explored in (Minke, 2013); structural cohesion deformation and cracking are associated to having direct contact with water (Bui et al, 2009) for example: due to weathering, thermal expansion and shrinkage, mechanical impact or due to the earths inherent biological susceptibility(Gomes, Faria and Gonçalves, 2018). These key issues affecting earth construction can be organised into 3 categories: structural, environmental and chemical – which have been tabulated within Table 1. Due to the inherently different physical and chemical properties of different earth, construction typologies and environmental conditions no two earth based buildings may face the exact same deformative issues.

Table 1 – Issues affecting degradation of earthen construction.

Structural	**Environmental**	**Chemical**
Thermal expansion/shrinkage causing cracking	Weathering	Delamination/Detachment due to incompatibility
Water adsorption/absorption	Poor construction/finish quality	Chemical attack
	Biological susceptibility	

It is evident that there is a diverse nature of degradation for earthen construction and an equally vast breadth of methods of repair. Often, earth based buildings are perceived as a low technology, where there is structural or clear degradation is potentially due to insufficient or inappropriately repair work completed previously(Jones and Brischke, 2017). When damage is identified it is important to consider if the building has superficial or structural damage. Often, superficial damage can often lead to more permanent structural damage if not appropriately addressed. In some cases (particularly within Adobe blocks) it may be necessary to exchange the entire earth block. Dependant on the earthen structure type, cracks that compromise a buildings structural intensity can be repaired using a filler such as grout. By filling any voids, gaps and crack grouting regains structural permanency of the building(Silva et al, 2012). Grouting required for earthen materials and different earthen constructions is outlined by (Warren, 1999). Another method of repair (especially used within cob walls/construction) for cracks is stitching as explained within (Keefe, 1993). In the quest to produce a more durable, earth based construction composite the combination of utilising naturally occurring bio-polymers has come to fruition. (Eires, Camões and Jalali, 2015) demonstrate the large variety of bio-polymers that have been trialled in order to improve the durability of earth-based construction. Utilising traditional, ancient earth construction methods, the addition of bio-polymers also reduces water adsorption without compromising on mechanical strength(Eires, Camões and Jalali, 2014). Repair methods always need to be tailored for the specific structure. Particularly in earth rammed walls, the only method of repair is that of a new, reinforced render to be applied(Silva et al, 2016). However, it is imperative that the substrate and superstrate are chemically compatible (Gomes, Dias Gonçalves and Faria, 2013). Failing to achieve this causes delamination/detachment as the once efficient exchange of water vapour is no longer and therefore detaches the mortar from the building(Walker, 2005).

The research is focused in novel bio-composites formulations with agro-wastes exposed to aging phenomena and using bio-consolidation mechanisms to increase durability, minimising simultaneously the embodied energy and Global Warming Potential. Therefore, properties related to hygrothermal, mechanical and self-healing capacity of a sustainable bio-based mortar repair system for earth construction are presented here. This paper demonstrates preliminary research which aims to use 4 different bio-based materials, to create an earth mortar and a comparison between the addition with and without a bio-based agent. By incorporating the bio-based agent it is envisaged that this will demonstrate a self-healing capacity for a bio-based earth mortar to extend service life and boost durability for potential implementation as a repair mechanism for earth construction.

MATERIALS

Earth

Sourced in Liverpool, North West England a particle grain size distribution (as per EN 1015- (CEN, 1999a) for the earth used within this research paper can be found in Figure 1. As the earth was obtained from a construction site at a depth of approximately 1.5-2m, it was crushed in order to disseminate any larger fractions and then passed through a 2mm sieve to remove any construction waste before being combined into the mix design.

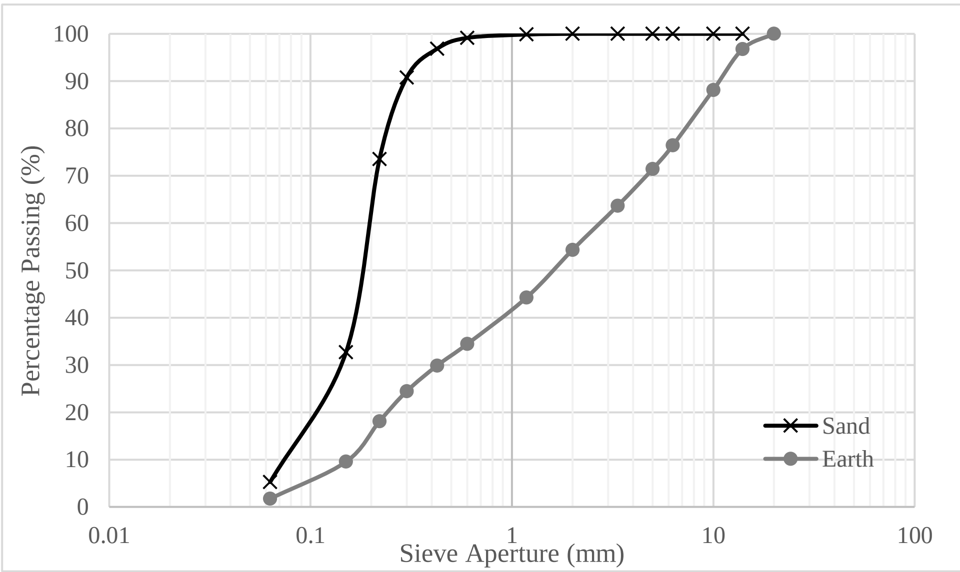

Figure 1. Grainsize Distribution Chart.

Bio-materials

Four different bio-based materials were used within this research paper, which are all currently available within the United Kingdom (UK) which are: Straw (STW), Wool (WL), Saw Mill Residue (SMR) and Wood Pellets (WP), in addition a plain sample with no bio-fibres (PL). The bio-based agent added to the bio-based composite consists of bacteria that was added to the earth composite.

METHODS

Casting

From previous preliminary experimentation, the mix design presented within Table 2 was selected. In order to calibrate the consistence of each sample, a flow table test was used. Each mix design would have a spread value between 150-160mm (conducted as per EN 1015-3 (CEN, 1999c) was selected.

Table 2. Mix design for earth-based samples.

Lime	Earth	Sand
1	0.1	8.6

For samples with bio-based agent incorporated within it, all bio-based materials were saturated and left to soak in the bio-agent for 30 minutes before being combined into the mortar mix as per EN1015-2 (CEN, 1999b).

Curing

Samples were cured at laboratory conditions (20^{o}C and 54% Relative Humidity (RH)) for 14 days before being demoulded. During the production stage, prismatic, 100 x 100 x 35 mm squares and 40mm diameter discs were cast - all samples were tested at 28 days.

Experimental Procedure

Moisture Buffering Value (MBV)

By being able to calculate how efficiently a material is able to adsorb/desorb into the local environment MBV provides a quantitative value to measure different materials to each other. After an initial 24 hours of stabilising within the climatic chamber at 23^{o}C and 60% RH, samples hygrothermal environment varied from 53% for 16 hours and 75% for 8 hours at 23^{o}C. These test conditions satisfy both NORDTEST protocol (Rode et al, 2005) and ISO 24353 (ISO, 2008) and are the same hygrothermal conditions within(Romano et al, 2018). MBV is calculated using Equation 1:

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

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 between relative humidity between adsorption and desorption stage (%)

Capillary Action

To determine the short term absorption capacity of each sample, a capillary test was carried out as per EN 1015-18: 2002(CEN, 2002). Samples were placed within an air tight container to keep hygrothermal conditions consistent. This test was continued until the water adsorption for each sample had stabilised.

Tensile Flexural and Compressive Strength

The structural properties of the prismatic samples were subjected to tensile flexural and compressive strength tests in accordance of EN 1015 – 11 (CEN, 1999e).

Thermal Conductivity

Demonstrating the samples ability to conduct heat, samples were tested using an ISOMET thermal conductivity meter with a 60mm circular contact probe.

Dry Bulk Density

To consider the differences on the internal structure for the different binders, bio-fibres or bio-products had on the mix design, dry bulk density was measured. Using callipers (to 0.01mm), the dry bulk density of samples was calculated geometrically according to EN 1015- 10 (CEN, 1999d) and a 0.001g digital balance.

RESULTS AND DISCUSSION

MBV

By understanding the way in which a material adsorbs/desorbs water molecules in a dynamic hygrothermal environment gives an indication of a materials ability to be used as a passive thermal management panel. In addition to be developed as a 'self-healing' building material, a further benefit earth construction and the combination of bio-based materials are notable for their ability to improve indoor air quality (Darling et al, 2012; Palumbo et al, 2018). As all samples had the same exposed surface area they can compared via the change in mass of each sample per m^2, the first cycle within the climatic chamber is exhibited in Figure 2.

Figure 2 demonstrates that all samples have an initially high adsorption rate, however, bio-straw has initially lost free water within the sample and lost mass until hour 4. After hour 4, the sample then begins to regain mass until the end of the adsorption phase (end of hour 8). Interestingly, after just 1, 24 hour cycle none of the samples are able to return the same, original mass that they had at hour 0.

By comparison to Figure 2, Figure 3 demonstrates that after 10 cycles, the mass of the different bio-based materials varies much more in terms of materials retaining and gaining mass in comparison to the first cycle but also losing mass. Due to the heterogeneity of bio-based materials, it is understood that all the bio-based materials will intrinsically not react in the same manner, which is exemplified within the differences between Figure 2 and 3.

After the first 24 hour cycle, the samples were exposed to 9 further cycles, Figure 3 shows the adsorption/desorption graph for the 10^{th} cycle of 24 hours. Figure 3 demonstrates that while WP and bio-WL retain the most mass (and therefore water molecules), for this cycle they almost return to their original mass at the start of the cycle – so although the molecules have been retained, there is still evidence to suggest that there is an efficient water molecule exchange happening during the adsorption and desorption stages. After 9 cycles both WL and bio-WP are able to continuously adsorb and desorb efficiently and effectively by being able to return to their original mass from the start of the experiment. Further to this bio-WP is able to adsorb more during periods of high RH and still able to completely desorb it demonstrating its ability as a material to have a much more efficient moisture transfer than that of WL.

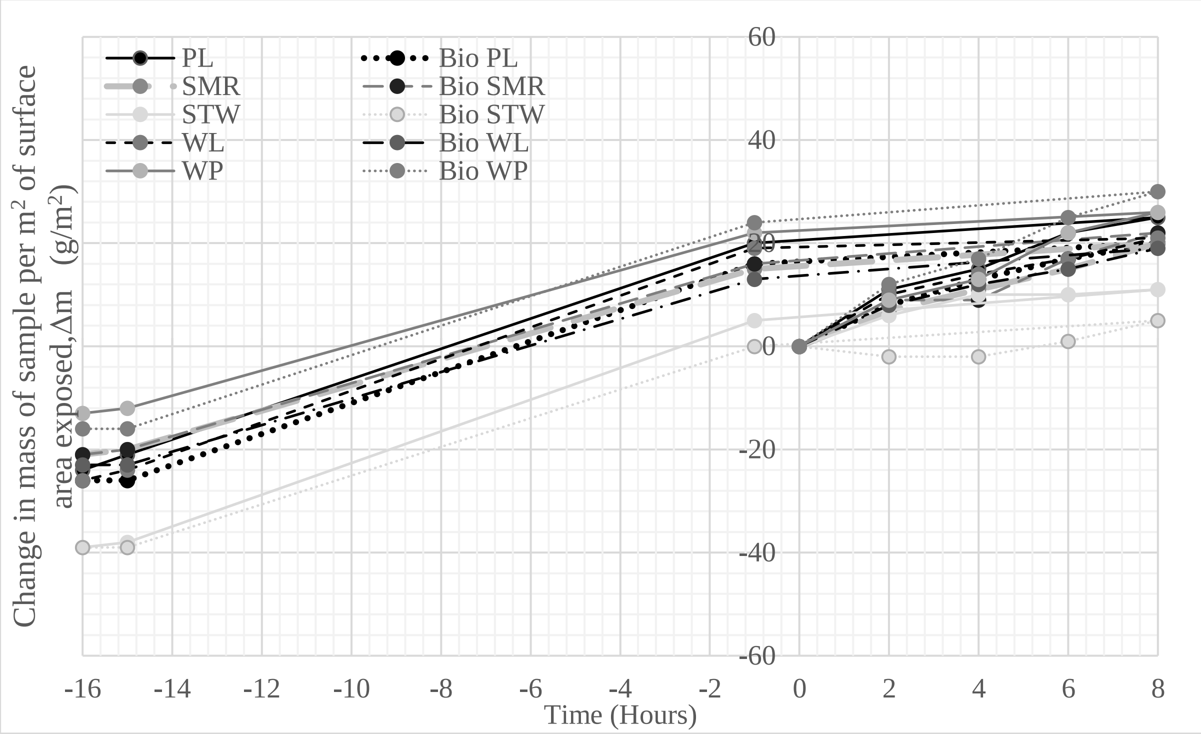

Figure 2. Adsorption/Desorption graphs for all 10 samples after 1, 24 hour cycle.

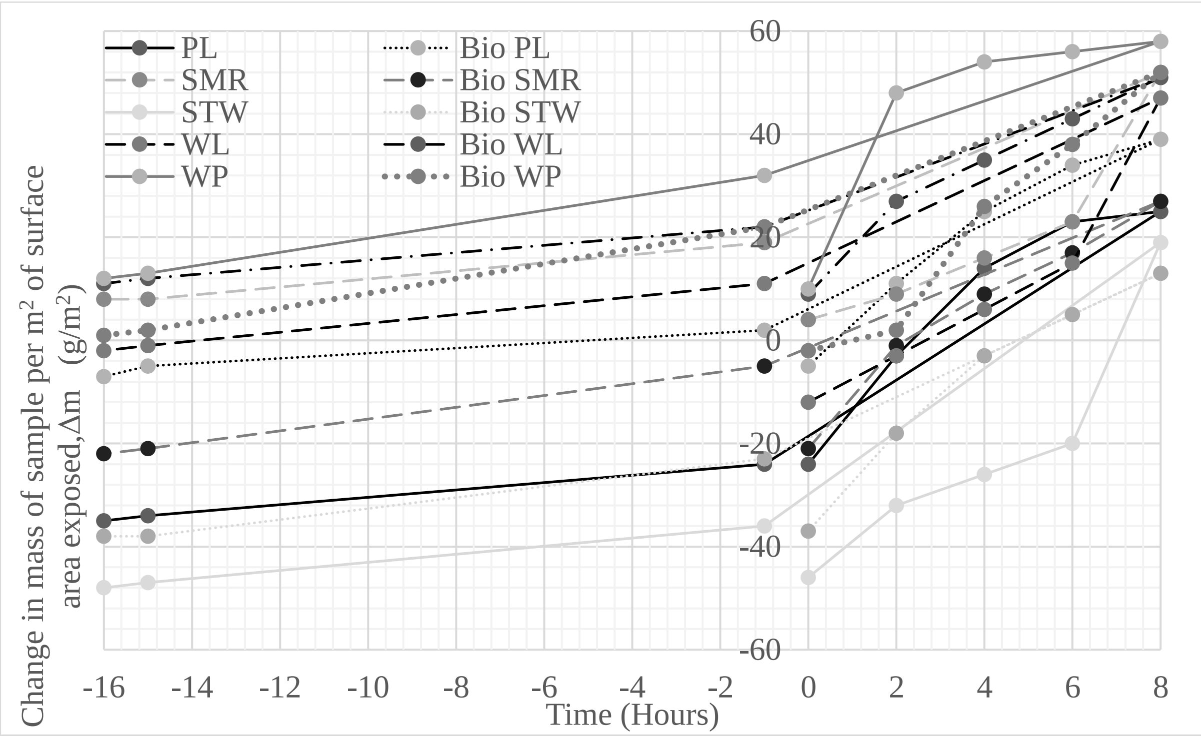

Figure 3. Adsorption/Desorption graphs for all 10 samples after 10, 24 hour cycles.

The MBV for samples after 10 cycles is in Table 3. From this period within the chamber, it is evident that the addition of the bio-agent had an extremely positive affect on bio-WP and saw a significant change in MBV, with an improvement of 0.36 g/ (m^2 %RH). Further to this, SMR also remains unaffected by the addition of the bio-agent and also remains one of the best MBV results out of all of the samples. This is extremely positive as it demonstrates that SMR could be utilised with a bio-agent whilst its hygric properties are not affected.

Table 3 – MBV values after 10 cycles of 24 hours.

Sample ID	MBV after 10 cycles of, 24 hours (g/(m^2 %RH))
PL	0.86
Bio PL	0.82
SMR	1.14
Bio SMR	1.14
STW	1.09
Bio STW	0.82
WL	0.91
Bio WL	0.86
WP	1.05
Bio WP	1.41

Capillary Action

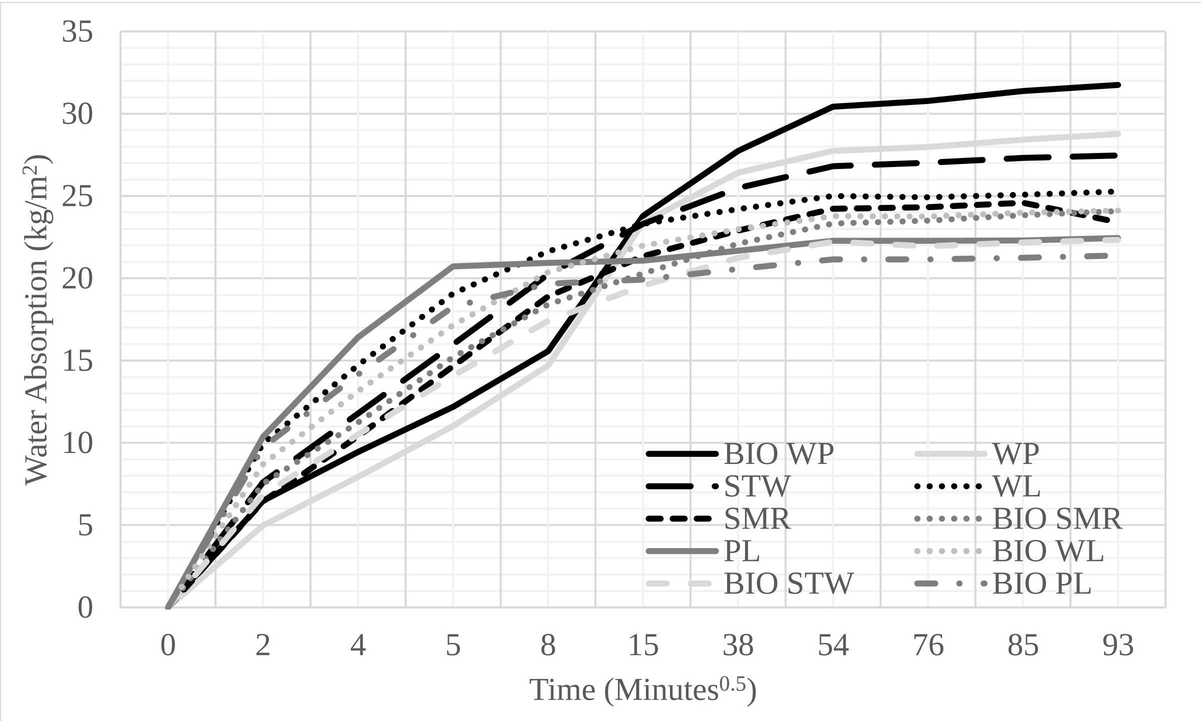

Figure 4. Capillary Action for Samples.

As mentioned previously, a key issue associated with earth-based construction is its high sensitivity to deformation due to its hydrophilic behaviour – especially weathering. So with regards to the bio-agent to be utilised for its 'self-healing capacity' an initial low rate of absorption would be desired. In terms of initial water adsorption, Figure 4 demonstrates the capillary action for all samples, it also shown that bio-WP and WP have the lowest coefficient of water adsorption. During this same period the plain sample with no bio-based materials nor bio-agent has the highest absorption exhibiting earth constructions affinity for water. When considering the samples in the context of longer exposure and the plateau region within Figure 4 shows that bio-PL and bio-STW have the lowest water absorption. When considering the durability of earthen construction and the service life it may provide, the consideration of the long term water absorption is imperative. It is clear that for some bio-materials, the addition of a bio-agent does improve its capillary action.

Tensile Flexural and Compressive Strength

Structural tests for samples are demonstrated within Figure 5 and show both compressive and tensile flexural strength. Compressive strength varies from 0.43 – 0.52 N/mm^2 and tensile flexural from 0.09-0.23 N/mm^2. Comparing bio-product and non-bio-agent based samples, STW, WP and PL samples actually improve in their structural ability with bio-agent in the mix deign. However, SMR decreased in both compressive and tensile flexural strength when combined with the bio-product.

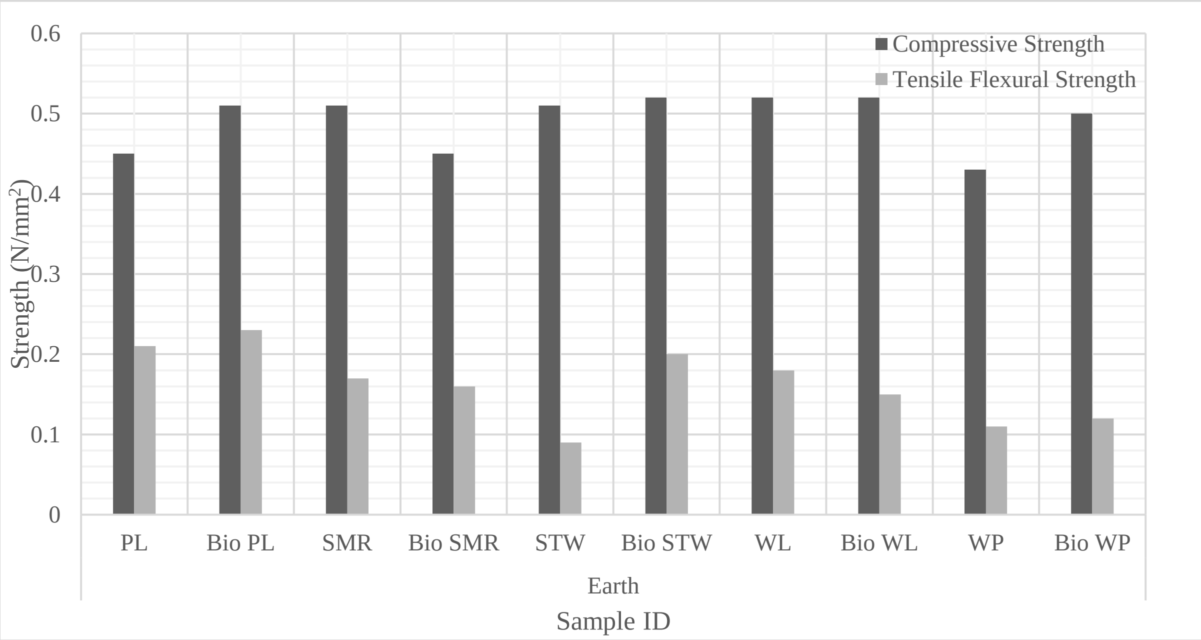

Figure 5. Compressive and Tensile Strength of Samples.

Thermal Conductivity

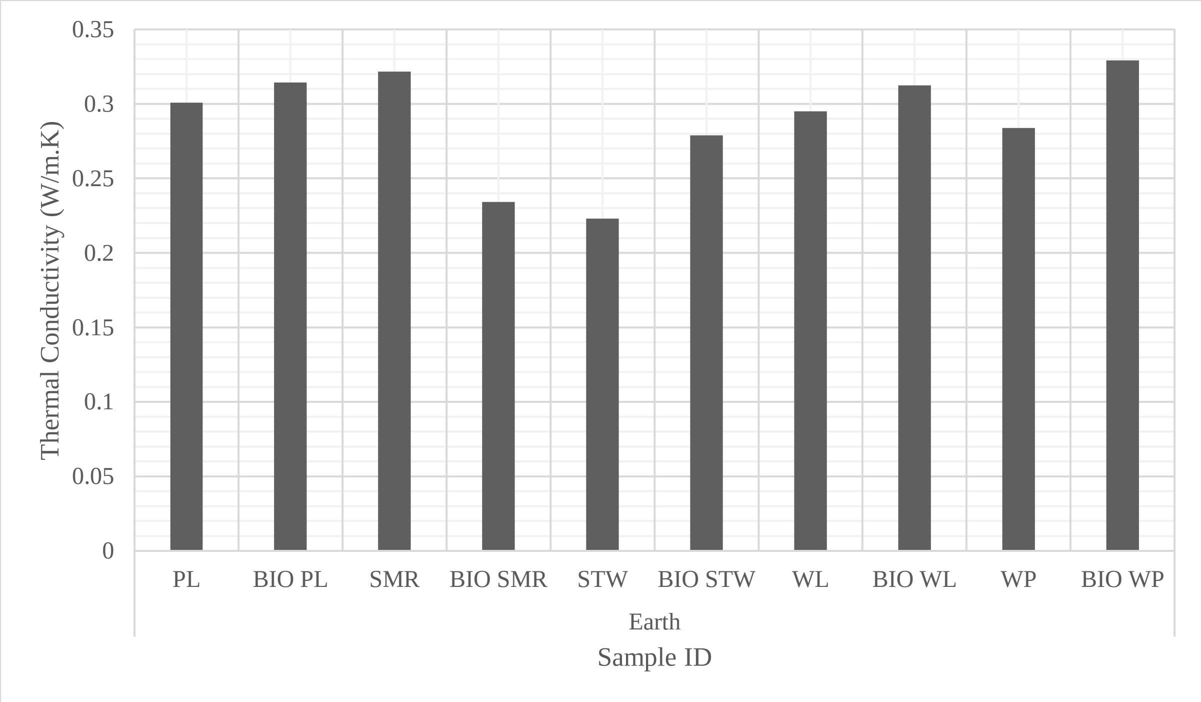

Figure 6. Thermal Conductivity of Samples.

Thermal conductivity for earth-based samples are presented within Figure 6. The addition of bio-product significantly decreases the thermal conductivity value of SMR from 0.32W/m.K to 0.23W/m.K. When considering the other benefits of using a bio-product with an earth mortar, by being not only able to improve a materials cracking resistance but has also vastly improves its insulating properties. Without bio-product, earth mortar with STW had the lowest thermal conductivity value of all. This could be associated to its long, hollow fibres of STW creating air pockets and therefore reduces thermal heat transfer(Garas and Allam, 2011). Despite, SMR there is no obviously, correlation between the addition of the bio-agent and thermal conductivity.

Dry Bulk Density

The utilisation of dry bulk density as a characteristic of a material gives an indicative demonstration of air gaps or voids within a sample. The average dry bulk density of each sample can be found within Figure 7, the densities range from 1231to 1679kg/m^3. All samples except for WP saw a reduction in density when bio-product was combined within the mix design. When comparing the bulk density of samples, it is evident that on the addition of bio-product there is no clear, significant effect on the dry bulk density of the bio-material earth mortar.

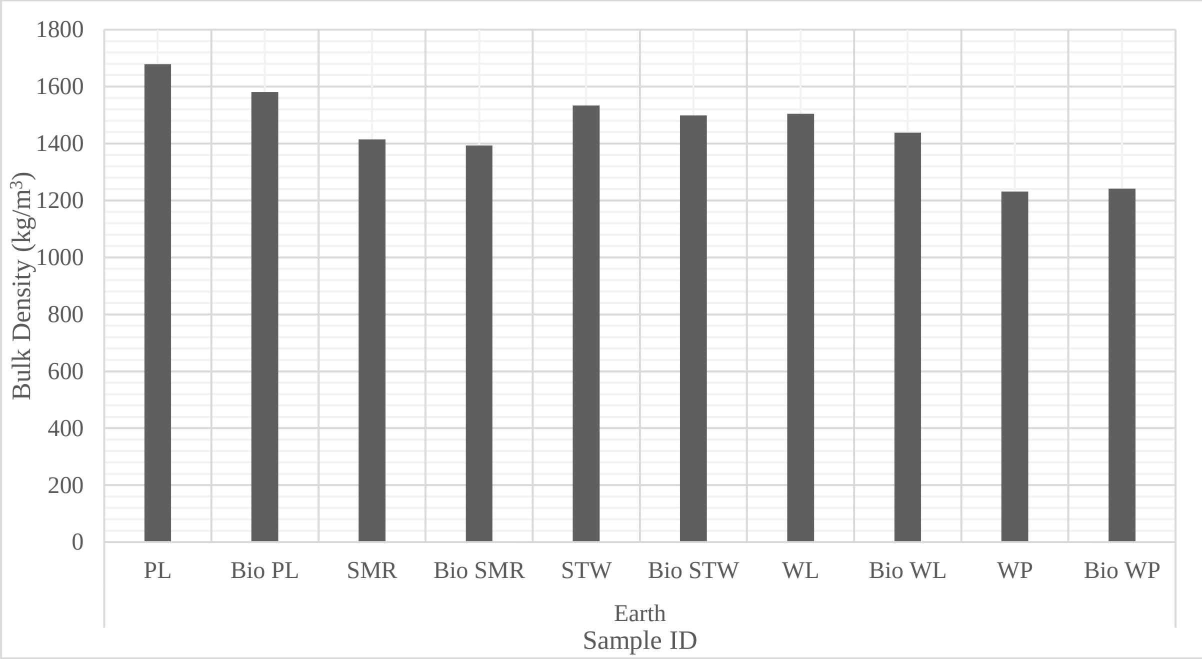

Figure 7. Bulk Density of Samples.

CONCLUSION

The potential of incorporating a bio-product to within a mix design in order to give a self-healing property will extend the service life and boost the durability of samples. It is inherently clear that due to their natural variety, different bio-fibres have differing characteristics when incorporated as part of a mix design. From the four different bio-fibres within this research paper the hygric properties of using bio-Wood Pellets (WP) are significantly boosted, whilst bio- Saw Mill Residue (SMR) is unaffected. Further to this the addition of the bio-agent also increased the ability of bio-SMR as a thermal insulator and bio-WP initial capillary adsorption is also reduced. Whilst the general structural properties of the mix design would not be satisfactory, the other material properties provide a basis that the self-healing capacity of bio-based earthern construction materials is promising.

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