The impact of bio-aggregate addition on the hygrothermal properties of lime plasters

D.Maskell[1a], A.Thomson[1b], M.Lawrence[1c] A.Shea[1d] P. Walker[1e]
[1] BRE Centre for Innovative Construction Materials, University of Bath, Bath, UK
[a]D.Maskell@bath.ac.uk, [b]A.J.Thomson@bath.ac.uk, [c]M.Lawrence@bath.ac.uk, [d]A.Shea@bath.ac.uk, [e]P.Walker@bath.ac.uk

Keywords: Hemp, Straw, Thermal Conductivity, Specific heat capacity, Moisture buffering.

Abstract. The requirement to improve the environmental impact of buildings has driven changes in their design and the materials used to build them. Notably the amount of thermal insulation has increased together with improvements in envelope airtightness, with the aim of reducing operational energy use. However, an unintentional consequence of these changes has in some cases been a reduction in the indoor environment quality due to insufficient ventilation.
Some bio-based building materials, including aggregates, as well as lime and clay, have the potential to improve indoor environment quality due to their hygrothermal properties. Bio-based insulation materials are currently used as a direct replacement for higher environmental impact materials, however, their use as an aggregate in a plaster allows them to become part of the exposed surface area of walls, contributing to an improved indoor environment quality through passive humidity buffering. The incorporation of bio-aggregates within lime plasters has therefore been investigated to understand their potential for improving hygrothemal properties. In this study hemp shiv and straw have been added in various mass fractions to lime plaster. The effects of aggregate size and mass fraction on performance have been investigated.

Introduction

European Union directive (2010/31/EU) [1] will require that all new buildings within the EU will be nearly zero-carbon by 2020. The current focus to improve building energy performance is through the reduction in heat losses through increased levels of thermal insulation, and a reduction of unintended heat losses through improved airtightness. Space heating accounts for up to two thirds of a European domestic houses' fuel consumption [2]. However, an unintended consequence of the improved airtightness has been a deterioration in the indoor air quality [3]. A significant parameter is Relative Humidity (RH) of the air, which influences both the comfort of occupants and Indoor Air Quality (IAQ). Optimum levels of RH are between 40% and 60%, with levels outside of this optimum range associated with discomfort, health risks and possible degradation of building materials [4, 5, 6].

The passive, rather than active, regulation of indoor environment minimises energy consumption. However, as the operational energy of buildings' reduces the proportion embodied within the fabric becomes increasingly important; some forecasts suggest the embodied element could account for up to 95% of the full life-cycle carbon footprint [7]. Materials with a low environmental impact, that can passively regulate the indoor environment, are therefore desirable. The development of plasters, optimised for the improved hygrothermal properties, is the focus of this paper.

Clay and lime based plasters have been shown to passively interact with the internal environment [8, 9, 10]. Padfield [9] showed experimentally that clay has a greater capacity to buffer humidity than lime based plasters. Lime, however has also been increasingly used in combination with hemp to form a rigid insulation material: hemp-lime [11, 12]. In 2006 Evrard [13] suggested that the creation of a hemp-lime plasters would improve humidity buffering potential. Straw is another potential bio-aggregate that has been increasingly investigated with respect over its insulative properties [12]. Therefore, there is scope for the inclusion of bio-based aggregates such as straw and hemp within a lime plaster to help to passively regulate indoor environment through hygrothermal action, which considers the combined movement of heat and moisture. The addition of lightweight aggregates will also reduce plaster density, and consequently thermal conductivity.

The aim of this study is to develop a low impact coating material that can aid in the passive regulation of the indoor environment. This paper presents the findings from an experimental study that investigated the influence of bio-based aggregate additions on the hygrothermal properties of lime coatings. The investigation considered straw and hemp as bio-aggregates within a lime based plaster. As the cell structure of these two bio-aggregates is inherently different, the effect of aggregate size may have varying effects and so has also been considered. Thermal conductivity and moisture buffering potential were the focus of the testing, as these give a clear indication of the potential improvements in the regulation of temperature and relative humidity of an internal environment.

Materials

The lime used the study was a commercially available pre-formulated lime plaster with no additional sand or other aggregates, manufactured by BCB. Two different types of bio-based aggregates were considered for this study: straw and hemp. These aggregates were added in different mass fractions and different fibre lengths.

Wheat straw takes the tubular form of its stalk, which creates a large void ratio for the same density compared to other cellulose material. Hemp shiv is the inner part of hemp plant stem, in the form of ligneous particles, left after stripping the outer fibres [14]. Hemp shiv particles have a tubular, anisotropic structure composed of conducting vessels with a diameter between 10 to 20µm. The effect of the size of the bio-based aggregate was investigated through the preparation of mixes with two aggregate sizes. The variation of aggregate size was achieved through the testing of otherwise identical mixes with two different aggregate sizes. The different sizes were achieved through first cutting the straw and hemp using a conventional food processor and grading the sizes by sieving. The two sizes of aggregates therefore represent relatively narrow ranges of particles sizes as shown in Table 1.

Table 1 Range of test straw and hemp particle sizes

Designation	Range mm
‘Small’	0.5 - 1.0
‘Large’	2.0 - 4.0

The effect of aggregates on lime plaster performance, including the variable particle sizes, was investigated through two mass fractions in addition to control samples without aggregates. The two different sizes of straw and hemp particles were tested in proportions s of 10% and 20% by mass of lime.

Experimental Methods

While the focus of the paper is on the determination of the improvement of thermal conductivity and humidity buffering properties, workability as well as physical and mechanical properties were also measured..

Workability properties: The consistency of the freshly prepared plaster was determined using a flow table in accordance with EN1015-3 [15]. The water content of the mix was adjusted to ensure a flow of 165± 5 mm was achieved with each mix.

Physical and mechanical properties: The bulk density of the hardened mixes were determined in ambient conditions following EN 1015-10 [16]. The flexural and compressive strength was determined in accordance with EN 1015-11 [17]. Specimens were loaded under displacement control at a rate of 0.2 mm/min and 0.5mm/min for the determination of flexural and compressive strength respectively.

Determination of thermal conductivity: Thermal conductivity of the specimens was measured at the University of Bath using a heat flow meter, LaserComp FOX600, following ISO 8301:1991 [18]. The temperature dependent nature of thermal conductivity was considered using the same standard and measured at 10°C, 20°C and 30°C with 20K temperature differential between the plates. Prior to the testing the specimens were dried for two days at 60°C.

Moisture buffering properties: Moisture buffering properties were determined in accordance with ISO 24353:2008. This method required specimens to be preconditioned at a Relative Humidity of 63% and a temperature of 23°C, followed by a cyclic climatic test. Four cycles of the following conditions are run whilst the mass of the specimen is continuously recorded:

- Step 1: 12h, relative humidity of 75% and temperature of 23°C;
- Step 2: 12 h, relative humidity of 50% and temperature of 23°C.

Specimens were prepared in phenolic plywood moulds measuring 150 x 150 x 20 mm thick. Aluminium tape was used to seal the back and sides of the specimens to ensure vapour exchange only occurred through a single face of the material. An air-permeable shield was placed around the mass balance to minimize the influence of air movement over the surface of the specimens during the testing. An anemometer was used to measure wind speed at the specimen surface and was found to be an average of 0.1 m/s.

Results and discussion

Workability and mechanical properties. The flow table test provides the amount of water needed to achieve the desired spread of 165 ± 5mm; Table 2. Three specimens of each mix were tested for the density and flexural strength with six specimens tested for compressive strength. The mean results are presented in Figs. 1- 3.

Table 2 Workability properties of lime with the addition of bio-aggregates

Aggregate	Designation	Mass fraction	Water content [% binder mass]	Slump [mm]
Straw	Small	10.00	65.7	162
	Small	20.00	140.0	161
	Large	10.00	66.6	162
	Large	20.00	144.0	167
Hemp	Small	10.00	54.0	163
	Small	20.00	93.7	169
	Large	10.00	52.9	165
	Large	20.00	52.9	165

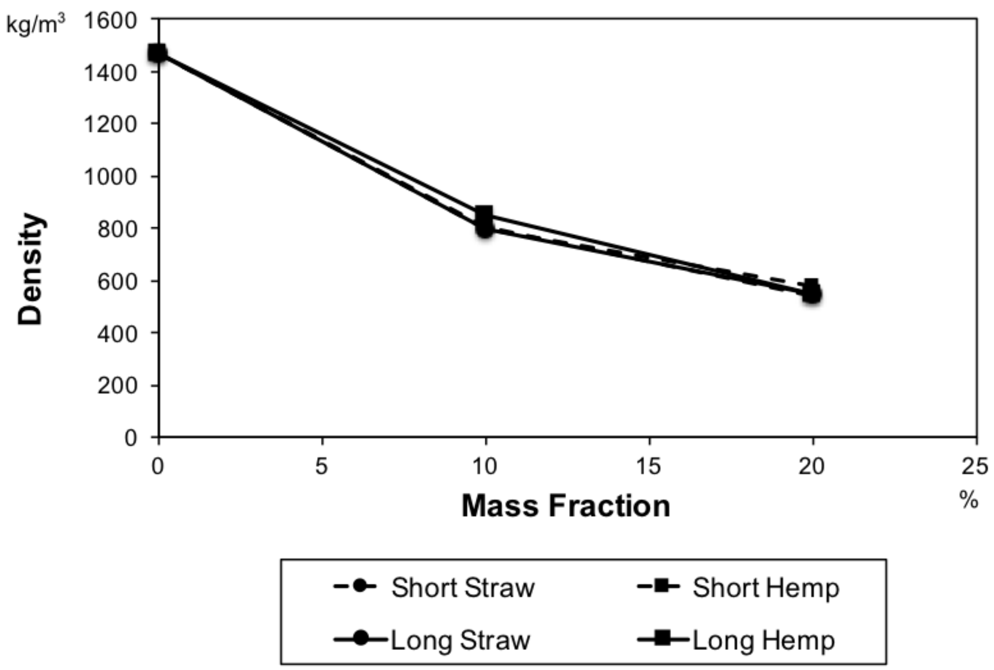

Figure 1 Density versus bio aggregate mass fraction

For certain mixes, even with water to achieve the desired flow, the workability was deemed undesirable. While the spread of the material was comparable to the desirable slump, the material was observed not to flow as common with other plasters tested by this method. This can be attributed to the large amount of aggregates that prohibited cohesion and therefore plastic flow of the material.

As intended, the addition of bio-aggregates reduced the density of the coatings and as expected this reduced the mechanical strength properties. The addition of small quantities of bio-aggregates resulted in disproportionate decreases in the physical and mechanical properties both types of bio-aggregate used.

As expected there is a strong correlation (r value of 82%) between the increasing water content and the decrease in density. The addition of bio-aggregates is likely to increase water demand to meet workability criteria, as the open pore structure of the aggregates has the capacity to absorb significant quantities of water. Absorption of the water into the bio-aggregates has also altered the setting reactions of the lime over time, similar to that observed with organic admixtures into cement [19]. In addition, the presence of the bio-aggregates would have imparted a distinct porous structure dependent on the bio-aggregate of the resulting coating materials.

Mechanical performance levels of the lime based coatings with bio-aggregates have been significantly reduced compared to the control. This is partially attributed to the reduction in density, with a very strong correlation of 95% between density and both compressive and flexural strength. However, as seen from Figures 2 and 3, and there is a statistically significant difference in performance at 10% of hemp and straw regardless of particle size. The particle sizes had a negligible effect considering the mechanical properties.

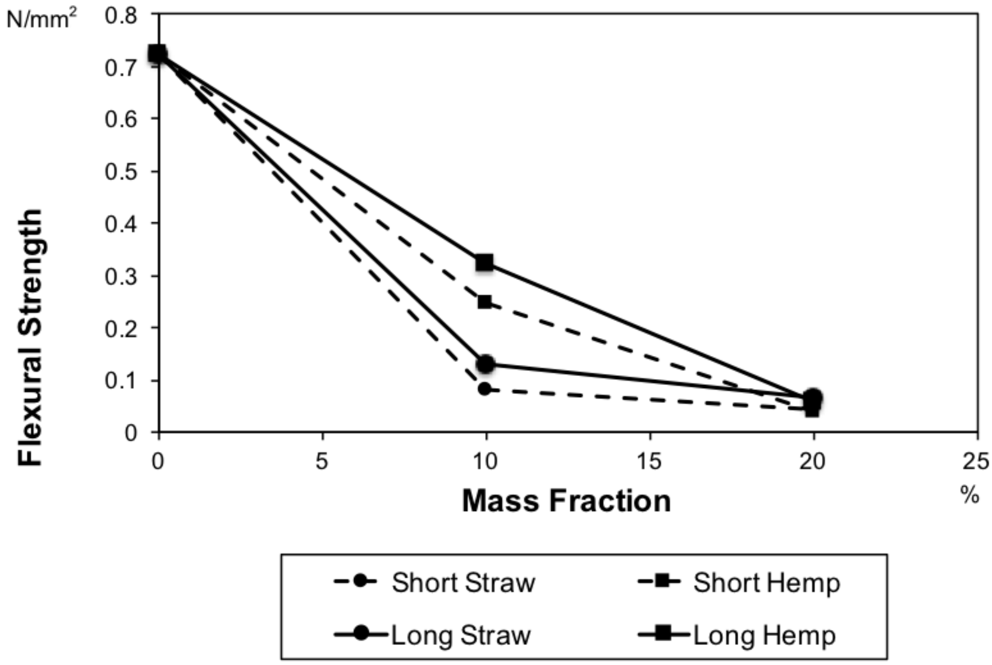

Figure 2 Flexural strength versus bio aggregate mass fraction

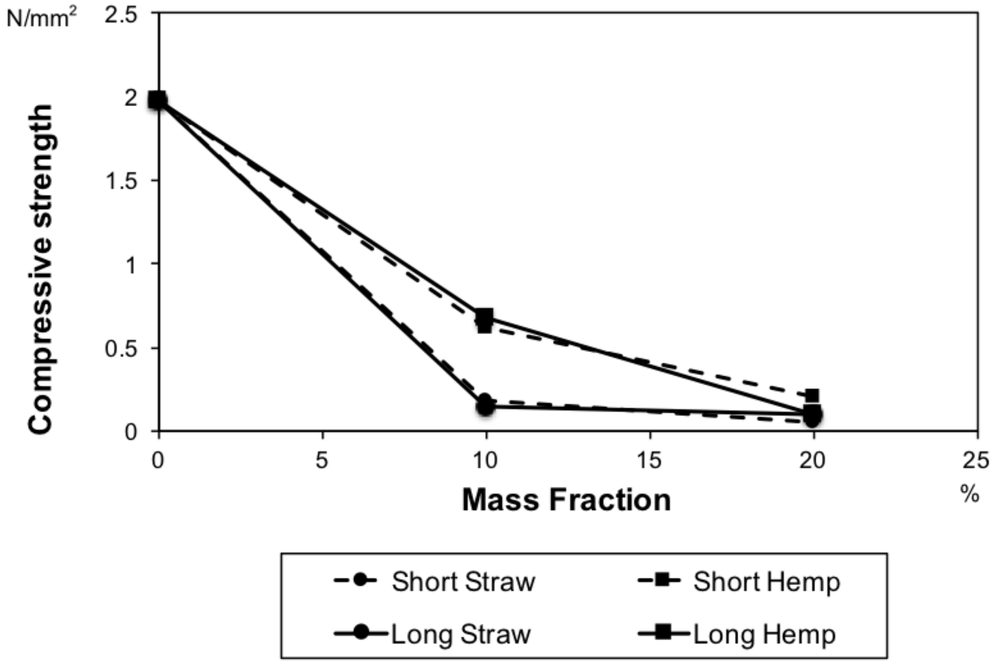

Figure 3 Compressive strength versus bio aggregate mass fraction

Thermal properties. Three specimens of each lime mix were tested; the average results are presented in Figures 4-6. Addition of bio-based aggregates was expected to reduce thermal conductivity. While the inclusion of bio-based materials may have other beneficial hygrothermal properties only the temperature dependent thermal properties were considered.

As expected the decrease in density resulted in decreases in thermal conductivity. As with the mechanical properties reductions in thermal conductivity generally seemed independent of the length of straw or lime tested, but there were notable variations between the two types of bio-aggregates. This is likely to be due to the inherent chemical and physical nature of the aggregates including the micro-porosity and the surface properties of the aggregates [20]

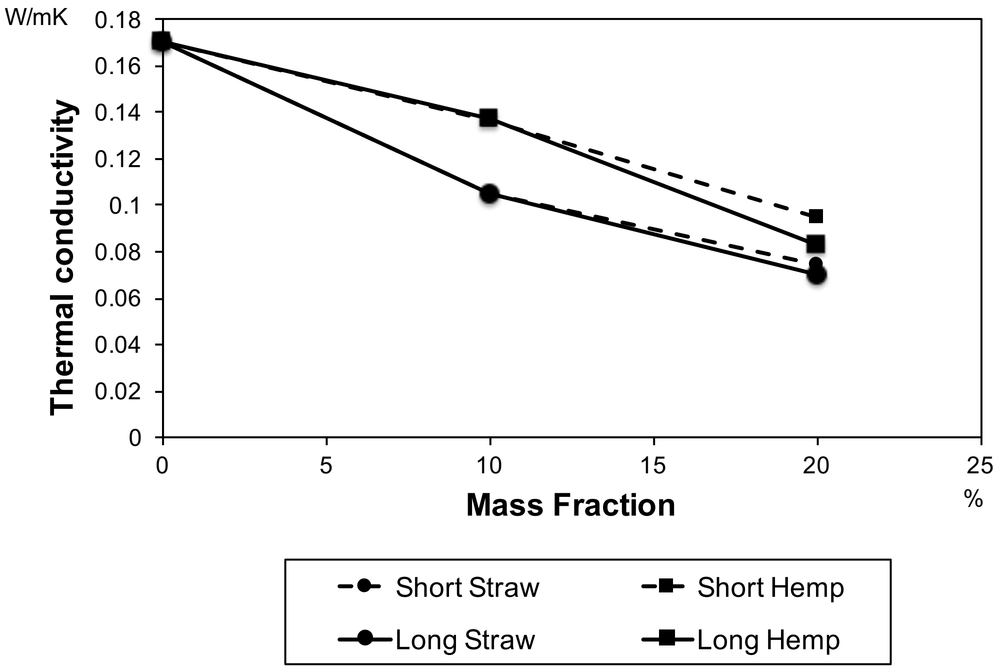

Figure 4 Thermal conductivity of lime-based coatings at 20°C

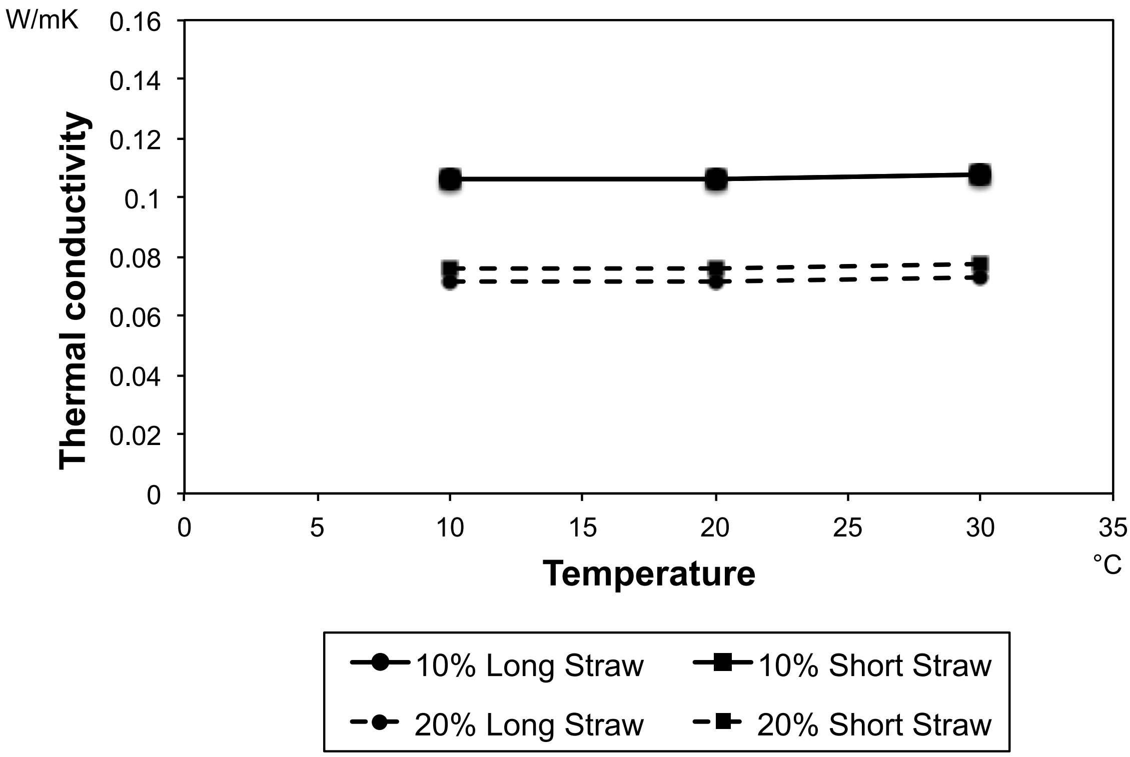

Figure 5 Temperature dependent thermal conductivity of straw addition to lime-based coatings

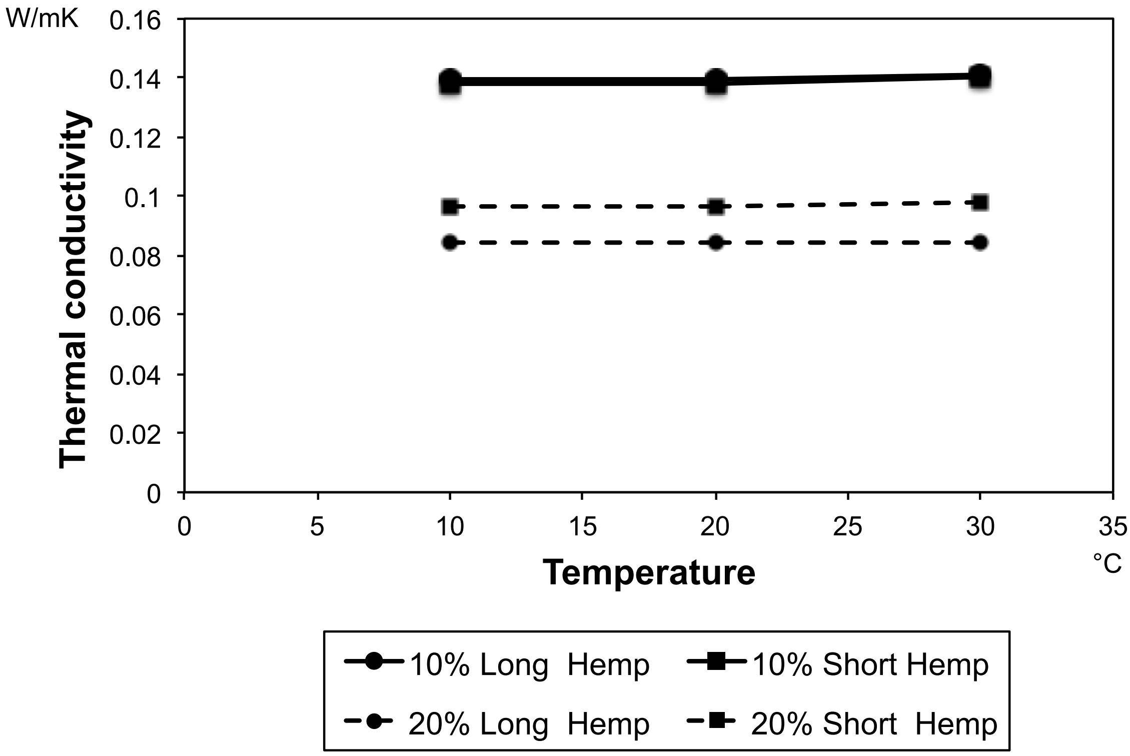

Figure 6 Temperature dependent thermal conductivity of hemp and straw addition to lime-based coatings

Moisture buffering properties. An important objective of making bio-based aggregate additions to lime coatings was to enhance their moisture buffering potential. The inclusion of straw and hemp aggregates was expected to either change the pore structure of the lime coating and/or actively participate in the internal environment regulation. The data for adsorption and desorption mass content are presented below in Figure 7 and Figure 8. As anticipated the inclusion of bio-aggregates improved the adsorption and desorption mass content, however, the extent of this improvement varies considerably.

The results for the hemp and straw aggregate additions suggest that the use of longer (2-4mm) straw and shorter (0.5-1mm) hemp provide better moisture buffering capacity than short straw and long hemp. However, this is only really notable at the 20% mass fraction at which point the workability of the mix was also significantly compromised.

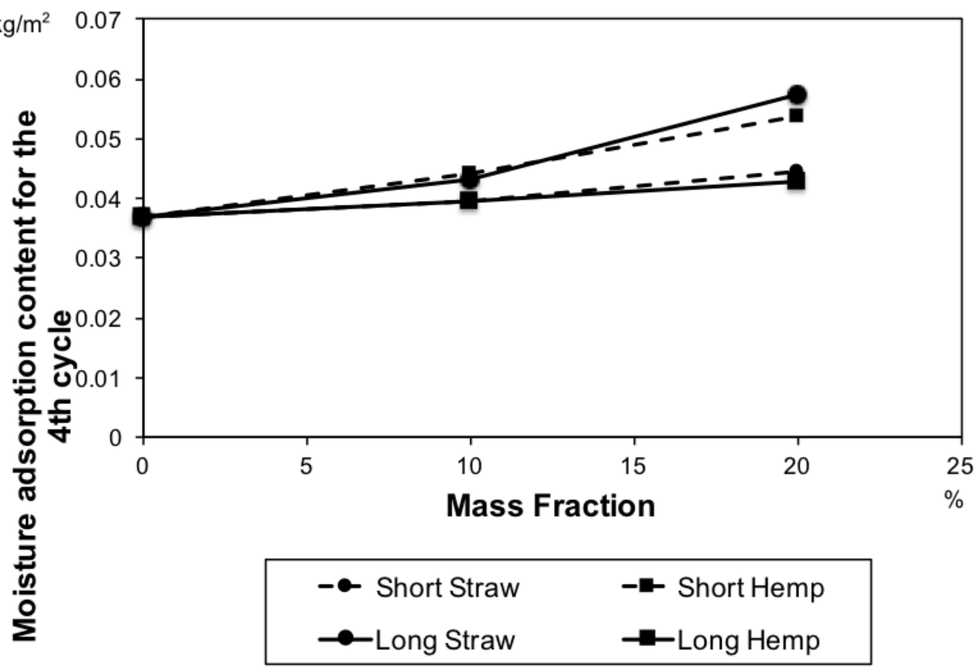

Figure 7 Moisture adsorption versus bio aggregate mass fraction

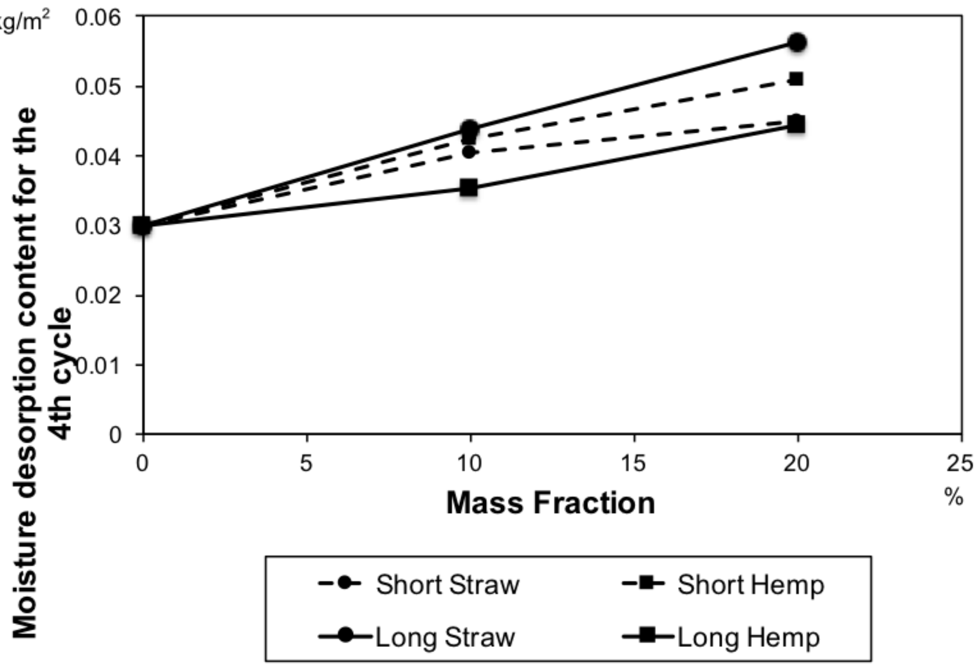

Figure 8 Moisture desorption versus bio aggregate mass fraction

Summary and conclusions

The addition of bio-aggregates has, as expected, changed the properties of lime plasters, ultimately improving the hygrothermal properties. These improvements were however at expense of significant reductions in mechanical performance. The addition of aggregates, particularly those intended to improve the hygric properties of the final plaster, meant that significantly more water was required to achieve the desired workability. For certain mixes, even with sufficient water to achieve the desired flow, the workability was deemed undesirable. The appropriateness of the flow table as a method for determining the suitable workability of coatings with high fractions of bio-aggregates could be potentially investigated.

The type, size and amount of bio-aggregate were all shown to contribute, in varying degrees, to the hygrothermal performance of the coating. The significance of type and size of bio-aggregate to the measured properties is strongly observed at 10% mass fraction, but the significance of type and size is diminished at 20% mass fraction. The effect of the fibre lengths are considered to be less important. While there is scope for a more detailed study into the effect of bio-aggregate size, there was considerable effort required to cut and filter the particular size and an appropriate methodology would need to be developed for larger commercial scale production.

There is no universal plaster that performs the best across the range of tests considered. Therefore, an optimised lime based plaster would depend on the required design parameters. This could mean further developments into the mix design are recommended. This would included optimisation of the lime binder and other non-bio based aggregates.

Acknowledgements

The work presented in this paper has received funding as part of the ECO-SEE project from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 609234.

References

[1]2010/31/EU, European Parliament, Council Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings, 2010

[2]Economidou, M., Atanasiu, B., Despret, C., Maio, J., Nolte, I., & Rapf, O. (2011). Europe's Buildings under the Microscope. A Country-by-Country Review of the Energy Performance of Buildings. *Buildings Performance Institute Europe (BPIE)*.

[3]Crump, D., Dengel, A., Swainson, M. (2009). Indoor Air Quality in Highly Energy Efficient Homes. NHBC Foundation Research Review NF18. IHS BRE Press. ISBN 978 1 84806 104 0.

[4]Fang, L., Clausen, G., & Fanger, P. O. (1998). Impact of temperature and humidity on the perception of indoor air quality. *Indoor air*, *8*(2), 80-90.

[5]Toftum, J., Jørgensen, A. S., & Fanger, P. O. (1998). Upper limits of air humidity for preventing warm respiratory discomfort. *Energy and Buildings*, *28*(1), 15-23.

[6]Lucas, F., Adelard, L., Garde, F., & Boyer, H. (2002). Study of moisture in buildings for hot humid climates. *Energy and Buildings*, *34*(4), 345-355.

[7]Sturgis, S., & Roberts, G. (2010). Redefining zero: Carbon profiling as a solution to whole life carbon emission measurement in buildings. *RICS research, Royal Institute of Chartered Surveyors, London*.

[8]Koronthalyova, O., & Matiasovsky, P. (2005). Hygroscopicity of non-matured and matured plasters. *Proceedings of Thermophysics 2005*, 43-49.

[9]Padfield, T. (1998). The role of absorbent building materials in moderating changes of relative humidity. *Department of Structural Engineering and Materials, Lyngby, Technical University of Denmark*, *150*.

[10] McGregor, F., Heath, A., Shea, A., & Lawrence, M. (2014). The moisture buffering capacity of unfired clay masonry. *Building and Environment*, *82*, 599-607.

[11] Barclay, M., Holcroft, N., & Shea, A. D. (2014). Methods to determine whole building hygrothermal performance of hemp–lime buildings. *Building and Environment*, *80*, 204-212.

[12] Shea, A., Wall, K., & Walker, P. (2012). Evaluation of the thermal performance of an innovative prefabricated natural plant fibre building system. *Building Services Engineering Research and Technology*, 0143624412450023.

[13] Evrard, A. (2006, September). Sorption behaviour of Lime-Hemp Concrete and its relation to indoor comfort and energy demand. In *Proceedings of the 23rd Conference on Passive and Low Energy Architecture, Geneva, Switzerland*.

[14] Magniont, C., Escadeillas, G., Coutand, M., & Oms-Multon, C. (2012). Use of plant aggregates in building ecomaterials. *European Journal of Environmental and Civil Engineering*, *16*(sup1), s17-s33.

[15] EN 1015-3:1999 Methods of test for mortar for masonry. *Determination of of consistence of fresh mortar (by flow table).* London: BSI.

[16] EN 1015-10:1999 Methods of test for mortar for masonry. *Determination of dry bulk density of hardened mortar.* London: BSI.

[17] EN 1015-11:1999 Methods of test for mortar for masonry. *Determination of flexural and compressive strength of hardened mortar.* London: BSI

[18] ISO 8301:1991. Thermal insulation -- Determination of steady-state thermal resistance and related properties - Heat flow meter apparatus. Internal Standardization Organization (ISO).

[19] Uchikawa, H., Sawaki, D., & Hanehara, S. (1995). Influence of kind and added timing of organic admixture on the composition, structure and property of fresh cement paste. *Cement and Concrete Research*, *25*(2), 353-364.

[20] Bledzki, A. K., Mamun, A. A., & Volk, J. (2010). Physical, chemical and surface properties of wheat husk, rye husk and soft wood and their polypropylene composites. *Composites Part A: Applied Science and Manufacturing*, *41*(4), 480-488.