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THERMALLY MODELLING BIO-COMPOSITES WITH RESPECT TO AN ORIENTATED INTERNAL STRUCTURE

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ABSTRACT

To wean us from our destructive fossil fuel dependency we must produce buildings that are better in both their occupied energy use and their embodied energy content. Bio-composites formed from cellulose aggregates and binders have a low embodied energy and provide an excellent balance of insulation and thermal inertia; when used correctly they can produce efficient and healthy buildings with considerably lower embodied energy than traditional alternatives. These materials are however naturally variable depending on their production method and this has hindered their uptake in a culture of standardised, performance based codes. In order to gain wider use it is important that we can model their behaviour representatively.

An important, overlooked, factor in the behaviour of these materials is the internal structure on a macro scale, in particular the orientation and distribution of the aggregate. As the particles have a defined aspect and orientated structure themselves, the orientation of the particles within the composite may have a considerable influence on the hygrothermal properties. While this is a concept widely acknowledged, the internal structure of bio-composites has not been characterised or adequately incorporated into behavioural models.

This work implements a novel method of material characterisation based on digital image analysis to classify the internal structure of specimens of hemp-lime. The results indicate that the internal structure is highly anisotropic with strong directionality in the hemp particles governed by the construction process. A parameter corresponding to degree of directionality has been developed together with a thermal conductivity model based on a weighted average between bounding conditions.

INTRODUCTION

Buildings are a major contributor to emissions and energy use, both in their embodied content and in their service life through occupation; in the UK buildings account for 50% of the total carbon dioxide emissions (Department for Business 2010). This is seen both here and around the world as an area of significant saving potential. The materials used in construction and retrofit of buildings are critical as not only do they affect the quality of the indoor environment but also have a large influence on how well the building will perform over its life, the energy cost of its creation, and how readily it can be decommissioned and recycled.

Hemp-lime, also referred to as hempcrete and lime hemp, is the most widely known bio-composite concrete. It is produced by mixing chopped hemp stalk (known as shiv), powdered lime binder and water to form a loose granular mix that is cast into shuttering (figure 1) or sprayed against a substrate. Once dried and set the resulting material is a low strength lightweight insulation with a modest U-value for standard 200mm wall thicknesses in the order of 0.36 W/m^2K (Bevan et al. 2008). The unique porosity of hemp-lime and the interaction this has with moisture, produces an effective thermal mass that can dampen the effect of external temperature fluctuations and reduce space heating and cooling needs if employed correctly and allows it to outperform other comparable constructions in dynamic conditions (Evrard 2006, 2008; Lawrence et al. 2011; Tran Le et al. 2010). In addition hemp-lime buffers moisture, improving the internal environment (Evrard 2006), captures VOCs and provides all of this at a net absorption of around 36kg of CO_2 per square metre of waling (Ip and Miller 2012).

Figure 1: Stages of hemp-lime production: Hemp shiv, powdered lime binder, cast wet material, resultant dried material

Despite the benefits of hemp-lime it is not yet widely used. The construction industry rightly considers hemp-lime as a variable product, requiring special training and carrying associated risk. When cast on site has a very slow drying time that is worsened in wet climates; it is all but impractical to cast hemp-lime in the UK during the winter months (Allin 2012; Harris et al. 2009; Skandamoorthy and Gaze 2013). In addition to this it is hard to accurately specify and design as performance varies significantly with mix formulation and method of application. To overcome this, prefabrication is seen as an important tool as it removes a lot of the problems associated with onsite work (Walker and Thomson 2013) and has certainly worked for other natural materials such as straw and sheep's wool, where prefabrication has allowed for a certified, low risk products. In order to produce the most competitive prefabricated hemp-lime product, or bring more consistency to the performance of hemp-lime cast on site, it is important that we understand the behaviour of the material and can accurately predict its performance.

Thermal conductivity is a crucial performance criterion for any insulation. Efforts have been made to predict the thermal conductivity of hemp-lime based on its constituents with some success (Arnaud 2000; Pierre et al. 2014). A large perceived gap in our understanding of hemp-lime however is the impact of the macro scale structure formed as a result of the casting or spraying process. It is often acknowledged in the literature that hemp-lime is anisotropic (Elfordy et al. 2008; Magniont et al. 2012; Nguyen et al. 2009; Tronet et al. 2014) but this anisotropy has not been classified and thus not properly incorporated into our understanding of performance. This is slowing the development of the material and hindering our ability to predict the properties.

In this work a novel image analysis method to classify the macro structure of bio-composites has been employed. This describes and numerically classifies the degree of orientation within the structure allowing links to be drawn directly to the method of forming. A model of thermal conductivity has been proposed that incorporates the observations and accounts not only for the nature and ratio of the constituent materials but also the nature of the internal structure. The internal structure of hemp-lime

There are already several established relationships between the mix design of hemp-lime and the thermal properties. The ratio of hemp to lime used in the mix has been shown to be critical to both the structural and the thermal properties of the material with a higher binder content improving the strength but increasing the density and thermal conductivity (Arnaud and Gourlay 2012; Collet and Prétot 2014; Magniont et al. 2012; Murphy et al. 2010). In addition it has been shown that compaction of the mix has a similar effect as it consolidates the particles, removing voids, and producing a stronger but more thermally conductive material (Elfordy et al. 2008; Nguyen et al. 2009). The nature of the constituents, grading of shiv and the formulation of the binder, has also been examined (Benfratello et al. 2013; Hirst et al. 2010; Murphy et al. 2010). Generally the effects of changing these was found to be of significantly smaller magnitude than those observed for changes in binder ratio and compaction and indicates that the interaction between the components may governs the overall properties rather than the properties of the individual constituents. A stronger lime binder for example will not necessarily increase the compressive strength and can even be shown to reduce it (Hirst et al. 2012).

Hemp shiv particles are generally of an elongated form due to the nature of the plant stalk and the method of harvest (Bevan et al. 2008). Most of the literature attributes directionality within the internal structure to the way these particles align in the forming process. In the case of cast hemp-lime walls it is considered that the particles of shiv will tend towards the horizontal plane as material is placed and compacted downward, with sprayed, that they will tend towards the plane perpendicular to the direction of projection (Duffy et al. 2014). It was noted by Gross (Gross 2013) that hemp-lime composites cast to the same mix specification and the same direction, but tested structurally in different orientations, not only exhibit a different failure strength but also a different failure mode.

As the layout of the shiv structure will determine the distribution of the air voids within the material, it follows that the thermal conductivity of hemp-lime will not be isotropic. Nguyen et.al. (Nguyen et al. 2009) considered heavily compacted samples of hemp-lime made using a range of hemp/binder ratios and compaction levels. Thermal conductivity was measured in two directions: parallel to and perpendicular to the compacting force and the results showed a consistently higher value of thermal conductivity perpendicular to the compaction direction by a factor of almost one and a half. A perceived visual directionality of particles was also noted.

A study by Pierre et.al. (Pierre et al. 2014) considered thermal conductivity of sprayed hemp-lime samples in two directions, parallel and perpendicular to the direction of projection, and also found a discernible difference but of a lower magnitude than Nguyen. The work goes on to apply Krischer’s model of thermal conductivity to model the behaviour. Krischer’s model proposes thermal conductivity of a mixture can described by a weighted harmonic mean of two cases where the components are in series and parallel respectively and the weighting factor relates to the material structure (Carson and Sekhon 2010; Krischer and Kast 1978). The model was accurate at predicting the experimental results and demonstrates the appropriateness of this type of model. It should be noted that in this study the weighting factor used, as well as two other material parameters, were estimated from fitting the model to the thermal conductivity data. As a result the weighting factor was determined to be the same in both directions while the porosity was found to alter; a result that by inspection not representative.

The nature of hemp shiv particles means that the traditional aggregate grading method of sieving is inappropriate. To overcome this the use of digital image analysis has been adopted by many to allow a more representative form of grading to be conducted (Arnaud and Gourlay 2012; Glé et al. 2013; Nguyen et al. 2009). The method entails the imaging of the two dimensional elevation of arranged hemp particles using a flatbed scanner. The images are processed and particle analysis software is used to identify and classify the particles allowing the production of frequency grading of both size and shape. Image analysis methods have already been used in situ on other composites like asphalt (Bessa et al. 2012; Coenen et al. 2012; Roohi Sefidmazgi and Bahia 2014) and naturally orientated materials like soils (Shi et al. 1998) in order to determine the distribution of aggregates within their makeup. By doing this it has been possible to classify the internal structure of these materials and link it to both the forming process and the resultant physical properties.

In this study image analysis is used to classify the internal structure of hemp-lime. The findings are then incorporated into a modified weighted harmonic mean model of thermal conductivity, where the critical weighting factor is representative of the structure. This is an improvement on existing models as it accounts for the materials manufacture and orientation as well as the mix ratio and environmental conditions.

METHODOLOGY

Nine, 150mm cube, specimens of hemp-lime were produced using Tradical® HB blended binder and construction grade hemp shiv produced in the UK. All specimens were produced using a small pan mixer by first mixing the binder with water to form slurry before adding the hemp and mixing briefly until evenly combined and transferring to moulds. Six specimens were produced using a standard “wall mix” of 21% hemp, 36% binder and 43% water by weight. Half of these were lightly tamped with the other tamped firmly to use 20% additional material. The target dry density for the samples were 400kg/m^3 and 330kg/m^3 respectively. The other three samples were produced using a lower binder ratio of 1:1.7 and again lightly tamped to give a target density of 275kg/m^3. The samples were all conditioned at 20°C and 60% relative humidity for a minimum of 28 days.

Image acquisition:

To produce the sections for imaging, two specimens from each mix were cut into six 25mm thick slices using a fine toothed band-saw. One specimen was sliced parallel to the direction of compaction, YZ plane, and one was sliced perpendicular to the direction of compaction XY plane (figure 2). To enhance the contrast of the components a pigment was added to the lime giving it a distinctive hue and a coloured resin was used to fill surface voids. The resin also enhances the durability of the samples allowing the faces to be sanded to a smooth finish, thereby removing any marks made by the cutting process that could be misidentified by the software. Image collection from the fully prepared samples was conducted using a flatbed scanner at a resolution of 2400dpi producing images of the central 115mm by 115mm square of each face to ensure any impact of the mould edges were minimised.

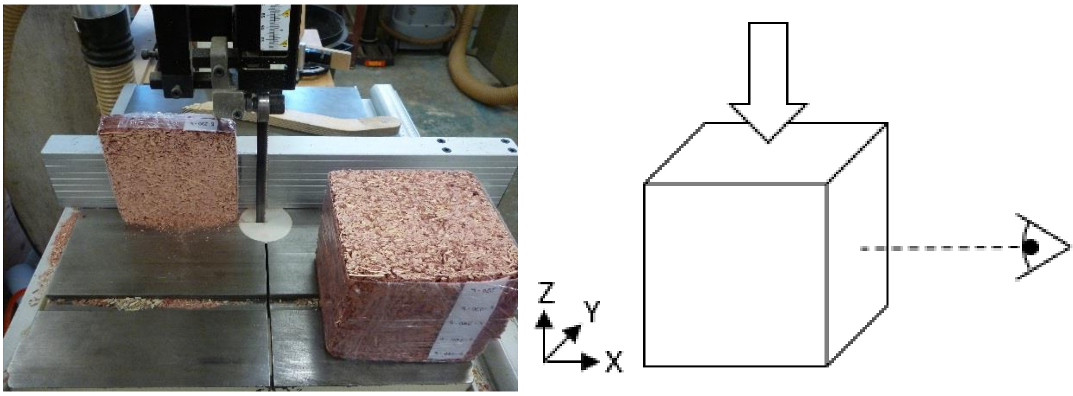

Figure 2: The sectioning of a pigmented hemp-lime sample using a band saw, the reference axis used where the arrow indicates the direction of compacting force

Image enhancement

Image enhancement was used to aid the correct identification of particles utilising a similar set of processes as used for other materials (Bessa et al. 2012; Coenen et al. 2012; Roohi Sefidmazgi and Bahia 2014) as well as for hemp grading (Arnaud and Gourlay 2012). A median filter with 20px radius was applied to remove anomalies and noise. A colour hue threshold filter of 15<hemp<50<air<230 was applied to segregate out the components and convert the image into binary. Finally three iteration of opening algorithm were used to clean the edges of the binary image and remove any noise produced in the threshold operation. The stages of the process are shown in figure 3. The values used were those visually judged to give the most reliable identification of particles out of a total of 288 considered permutations.

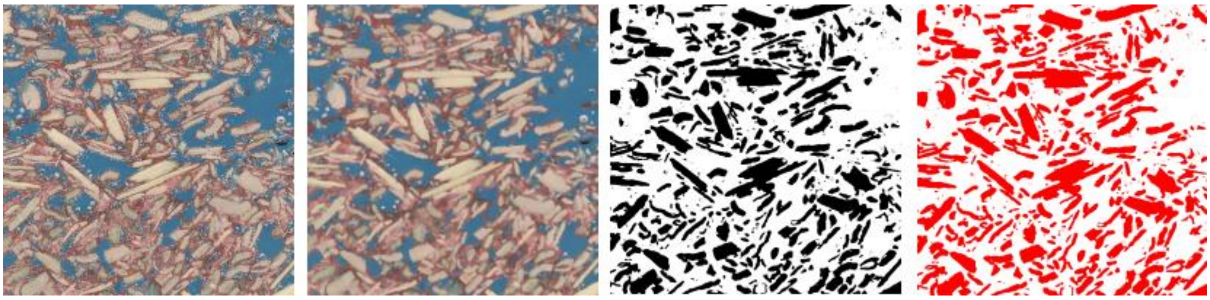

Figure 3: The stages of image enhancment: scanned image, median filtered, threshold filtered, opened

Image analysis

Image analysis was conducted using the program ImageJ and the inbuilt measure and particle analysis tools. The measure tool was used to determine the percentage area of the component parts while the particle analysis tool was used to identify all discrete binary objects, representing particles of shiv, and calculate a selected set of properties for them. The Feret Angle was used to classify a particle orientation and is defined as the angle to the horizontal that the Feret Diameter makes, where the Feret Diameter is the longest line possible between two perimeter pixels. To produce a useable output from the particle data it was necessary to group the data to produce a statistical representation of particle orientation for the slice. Groupings of 10 degrees were used as it has proven to provide good results for similar analysis of other materials (Shi et al. 1998).

RESULTS

Table 1 gives the grouped frequency distribution of particle orientation for all 6 specimens analysed. A clear degree of orientation was found in all 3 mix variations with all the specimens sectioned in the ZY plane exhibiting a strongly biased distribution towards the horizontal. Transversely all the specimens sliced in the XY plane were found to have a much more even distribution. Figures 4 and 5 show the cumulative grouping of the 330 target density samples sliced in the XY plane and YZ plane respectively and demonstrates the striking difference between the two orientations.

In order to easily compare the frequency data, second order polynomials were fitted to the distributions to estimate the form of the continuous distribution. The fitted polynomials for all three samples sliced in the ZY plane are shown in figure 6. The degree of orientation varies with degree of compaction and more broadly density, with denser samples showing a higher degree of directionality.

In addition to the degree of orientation, the volumetric ratios of components observable at the macro scale was also found to vary with density. Table 2 shows the average volumetric percentage of the components in all six specimens and indicates, as would be expected, that the volumetric ratio of air observed at this scale decreases with increasing compaction and density.

Table 1: The frequency distribution of shiv orientations for 3 mixes observed in 2 directions

Specimen ID	Frequency as a percentage of the total																	
	$0 \le X \le 10$	$10 \le X \le 20$	$20 \le X \le 30$	$30 \le X \le 40$	$40 \le X \le 50$	$50 \le X \le 60$	$60 \le X \le 70$	$70 \le X \le 80$	$80 \le X \le 90$	$90 \le X \le 100$	$100 \le X \le 110$	$110 \le X \le 120$	$120 \le X \le 130$	$130 \le X \le 140$	$140 \le X \le 150$	$150 \le X \le 160$	$160 \le X \le 170$	$170 \le X \le 180$
275 YZ	10.07	9.97	6.99	6.40	4.28	3.24	2.31	1.97	1.44	1.57	2.47	2.63	3.45	5.71	6.96	9.22	10.84	10.47
330 YZ	10.75	11.84	9.74	6.38	4.51	3.01	2.67	1.76	1.35	1.35	1.48	1.85	2.97	3.70	6.19	9.01	10.34	11.09
400 YZ	11.99	13.73	9.83	7.14	5.00	3.24	2.09	1.64	1.07	0.93	1.14	1.78	2.38	3.55	4.66	7.78	10.66	11.38
275 XY	3.91	6.29	6.38	5.56	5.91	5.94	6.08	6.10	3.82	3.98	6.15	5.96	6.17	5.72	5.98	6.60	5.70	3.75
330 XY	4.04	7.14	7.03	6.80	5.76	5.70	5.40	5.32	3.05	3.61	5.09	5.28	6.02	5.47	6.28	6.72	6.94	4.33
400 XY	3.68	6.24	6.22	6.27	6.33	6.56	6.17	6.69	4.00	3.95	5.99	5.85	5.47	5.11	6.17	5.95	5.51	3.84

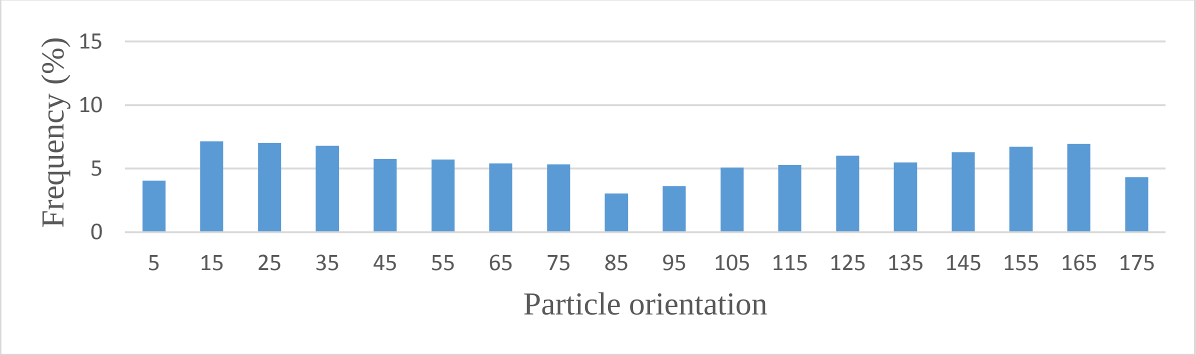

Figure 4: Frequency distribution of shiv orientations of the 330kg/m^3 target density sample sectioned in the XY axis

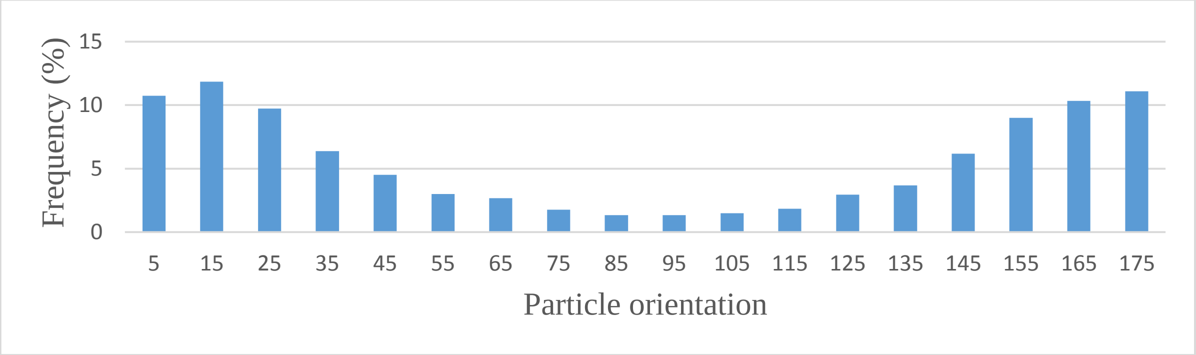

Figure 5: Frequency distribution of shiv orientations of the 330kg/m^3 target density sample sectioned in the YZ axis

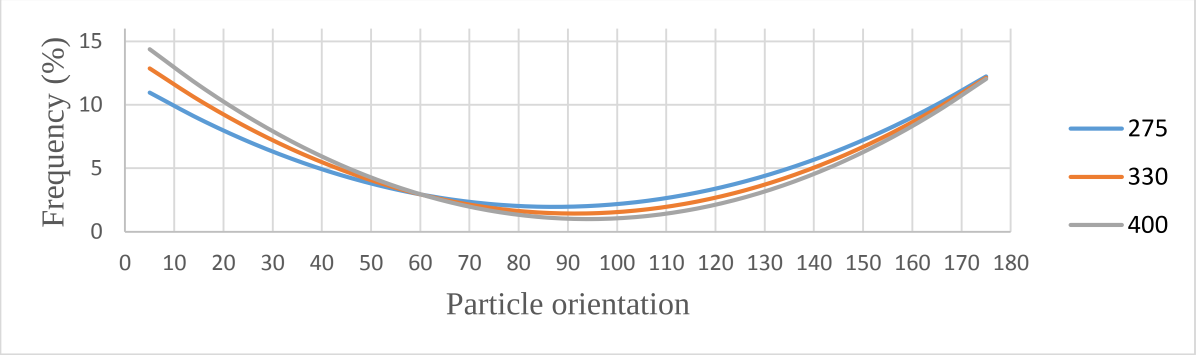

Figure 6: Frequency distribution of shiv orientations of specimens sectioned in the YZ axis

Table 2: The average volumetric percentages of components air, hemp and lime observable at the macro scale

Specimen ID	Percentage of observable voids	Percentage of observable hemp	Percentage of observable binder
275 YZ	61.72	25.41	12.88
330 YZ	31.04	35.34	33.62
400 YZ	22.50	40.76	36.74
275 XY	69.58	20.28	10.14
330 XY	38.92	34.23	26.85
400 XY	23.63	44.39	31.98

MODELLING

A theoretical model of thermal conductivity that accounts for the ainisotropic structure has been developed. Krischer's model (Krischer and Kast 1978) proposes the conductivity of a mixture, λ (1), can be described by the weighted harmonic mean of two situations in which the constituent materials are aligned, in parallel, λ_p (2), and in series, λ_s (3), respectively. These cases can be thought of as the theoretical maximum and minimum bounds for the given ratios of the components; the weighting factor, *f*, therefore accounts purely for their arrangement and structure (Carson and Sekhon 2010). If r_h, r_l, r_w, r_a and λ_h, λ_l, λ_w, λ_a are the volumetric ratios and thermal conductivities of hemp, binder, water and air respectively:

$$\lambda = \frac{1}{\frac{f}{\lambda_p}+\frac{1-f}{\lambda_s}} \tag{1}$$

$$\lambda_p = r_h\lambda_h + r_l\lambda_l + r_w\lambda_w + r_a\lambda_a \tag{2}$$

$$\lambda_s = \frac{1}{\frac{r_h}{\lambda_h}+\frac{r_l}{\lambda_l}+\frac{r_w}{\lambda_w}+\frac{r_a}{\lambda_a}} \tag{3}$$

Through consideration of the internal structure it is proposed that *f* should be dependent on the degree of orientation and connectivity of the hemp and binder observed at the macro level: an increase to either logically producing a tendency towards a parallel arrangement. It is proposed that *f* is therefore the function of two indexes I_1 *and* I_2 that are derived from image analysis of any plane parallel to the axis of consolidation force, Z (reference figure 2). A linear relation is proposed for both variables where *a*, *b* and *c* and constants:

$$f = aI_1 + bI_2 + c \tag{4}$$

It is proposed that index I_1, reflective of orientation, should be the ratio of particles tending towards a parallel with heat flux out of the total observed and so generally could be considered to have one of two values depending on the direction of heat flux. For heat flux parallel to the Z axis, where *n* is the number of particles with an orientation between the stated bounds and *N* is the total number of observed particles:

$$I_{1Z} = \frac{45 < n \leq 135}{N} \tag{5}$$

For heat flux perpendicular to the direction of compaction, XY plane, only a half of the observed particles should be considered, as the compaction only influences the probability of particles tending to the Z axis and thus there is still a random distribution of orientations in the XY plane as observed in the results, figure 4, therefore:

$$I_{1XY} = \frac{1-I_{1Z}}{2} \tag{6}$$

For a given material, density varies in proportion to the volume of air voids and this is reflected in the model through the volumetric ratio of the components. The voids however can be considered at two scales: the macro (visible caused by spaces between particles), and the micro (naturally occurring within the hemp and lime) and the ratio of these alters the structure and critically the connectivity between the solid components and so should be reflected in the weighting factor. It is therefore proposed that the index I_2, should be the ratio of observed air voids out of the total area:

$$I_2 = \frac{A_{air}}{A_{total}} \tag{7}$$

Through linking the weighting factor *f* to the two indexes the model is able to reflect not only the mix ratio and moisture content of the sample, but also the methodology of production and the anisotropic nature. Calibration is however required in order to find the nature of the function in equation 4 through fitting to experimental results.

DISCUSSION

The image analysis, conducted in two directions with respect to consolidation force, provides clear evidence that the forming process has a distinct impact on the structure of the material at the macro scale. This is consistent with the theories within the literature that propose any applied force will encourage particles to rotate towards a perpendicular plane. This work only considered a few examples of cast hemp-lime and so has not as yet evaluated whether this is also true of sprayed material or material formed through other methods of forming. It is however considered likely that a similar phenomenon will be observed.

A comparison of the 330kg/m^3 target density samples and the 400kg/m^3 target density samples, formed using the same mix constituents but different degree of compaction, indicates that an increased amount of compaction does increase the extent of orientation found as well as the density. It is possible to then infer from the model that compaction would increase the global thermal conductivity but also increase the disparity between the thermal conductivity measured parallel and perpendicular to the compaction. This is supported by the literature where two independent studies considering different densities found a distinct difference in the discrepancy between the thermal conductivity considered in the two directions (Nguyen et al. 2009; Pierre et al. 2014).

A comparison of the 330kg/m^3 target density samples and the 275kg/m^3 target density samples, produced to differing mixes but the same perceived level of compaction, was found to produce a similar change in degree of orientation. It is possible that an increase in the binder content encourages orientation through providing more bonds between particles and increasing self-weight and thus natural compaction. While this may account in part for the results it is more probable that the degrees of compaction were not even. Compaction was controlled by altering the amount of fresh material used to achieve a target dry density. The target densities and mixes were taken from the standard densities for the mixes when used in industry and not from test specimens compacted with the same force; it is therefore not possible to claim that the two sets were compacted to the same degree. By measuring the wet mix bulk density without any compaction the true level of compaction may be found and compared for mixes of differing design in the future tests.

The volumetric ratios of visible components found in the image analysis indicates how the level of macro scale air voids varies with consolidation. This inherently indicates that as the material is consolidated the ratio of macro scale air voids to micro scale air voids changes significantly, something that is not reflected in the measure of porosity or density and is likely to be influential in the behaviour of the material. The results are supported by the findings of Cerezo (Cerezo 2005) who produced graphical representations of the constituent volume ratios of several densities of hemp-lime.

The model used for thermal conductivity, an adapted version of Krischer weighted harmonic mean, is based on established principles from other areas and has already been adapted to hemp-lime with a good degree of success. The model proposed here builds on the work of Pierre (Pierre et al. 2014) but critically allows all the key parameters to be obtained from measurable properties that can be linked to the construction process, making it a potential design tool. In addition the model fully accounts for the anisotropic nature of the material and the broader nature of the macrostructure by linking the weighting parameter, acknowledged as a reflection of the internal structure, to indexes that classify the macro scale structure of the material. The model is therefore able to account for the entire range of mix parameters, the moisture content, the forming process and the direction of heat flux.

Currently the model is theoretical only and a large amount of additional work will be required in order to calibrate it and determine its effectiveness. The calibration is needed to determine the nature of the function in equation 4 that links the dimensionless indices describing the structure to the weighting factor that accounts for structure in the model. Until this has been completed it is unknown if the model will be successful. However, it is evident from the results of image analysis that there are distinct variations in the macro scale structure that must be accounted for. If the model is found to successfully represent the data it could provide a valuable tool for improving bio-composite concrete design and may provide a springboard towards the improved modelling of other properties including.

CONCLUSION

A novel approach to classifying bio-composites using digital image analysis was developed and used on samples of hemp-lime formed with three mix variations. A high degree of orientation of the hemp particles was observed with a clear tendency towards alignment in planes perpendicular to the direction of consolidating force. A simple numerical parameter extracted from the image analysis, related to the degree of orientation within the material, was used in a simple but versatile model of thermal conductivity. The model requires minimal data input and accounts for wide range of variations thus could be used to tailor and optimise the composition of the material to meet requirements. The importance of the macrostructure in regards to the global material properties is clearly evident and will be important in taking the material forward and realising its potential.

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