CHARACTERISING THE ANISOTROPIC NATURE OF BIO-COMPOSITES

Joe Williams [1,*], Mike Lawrence[1], Pete Walker[1]
[1]BRE Centre for Innovative Construction Materials (BRE CICM), University of Bath, Claverton Down, Bath BA2 7AY. *Email: J.P.Williams@bath.ac.uk

ABSTRACT

Buildings contribute substantially to our greenhouse gas emissions and energy demands both in their occupation and construction. Their construction also consumes large volumes of finite resources. Sustainable, low embodied energy, high performance crop based materials therefore offer great potential. Hemp-lime is a bio-composite concrete, mass infill material with a greatly lower embodied energy than equivalent traditional constructions. It also exhibits beneficial hygrothermal properties that can improve both a building's energy performance and the comfort of its occupants by buffering humidity and temperature. It is however widely considered insufficient structurally, limiting its scope for application. A lack of understanding and acknowledgment that hemp-lime and other similar bio-composites are anisotropic, but instead have a directional internal structure, has hindered the development of stronger and more versatile products. In this work a range of methods based on digital image analysis and computer tomography were trialled with the aim of identifying the nature of hemp-lime's internal structure and providing a methodology to classify it. The results from both digital imaging and computer tomography scanning indicate that the internal structure of the specimens considered was highly anisotropic; a strong directionality in the hemp particles was found to be induced by the construction process. The novel assessment methods developed to allow the numerical classification the internal structure that may be used in the future to allow the structural optimisation and modelling of bio-composites.

KEYWORDS

Hemp-lime, Hempcrete, Bio-composite, Aggregate, Image analysis, Internal structure.

INTRODUCTION

Currently the world relies heavily on fossil fuels for the production of useful energy; this production is unsustainable and therefore it is increasingly important to use the energy produced efficiently. Burning fossil fuels also produces carbon dioxide (CO_2), the accumulation of which is driving climate change, the effects of which are already being felt(Field et al. 2014).

Buildings are a major contributor to the amount of energy we use and CO_2 we emit; they therefore represent an area of great potential savings(Huovila 2007). Large efficiency gains in the operation of buildings can be made by improving their performance thermally. Ironically however many building insulation products are derived from the very non-renewable fossil fuels that we are trying to preserve and are energy intensive to produce(Harvey 2007). Natural insulation materials often have a very low or even negative embodied carbon and so offer large embodied savings as well as other ecological benefits. Given their potential, many natural insulation materials have become the focus of research including: straw(Alcorn and Donn 2010; Wall et al. 2012), sheep's wool(Zach et al. 2012) and hemp-lime(Benfratello et al. 2013; Murphy et al. 2010).

Hemp is a fast growing and ecologically beneficial break crop that enhances the soil and supresses weeds. It requires minimal fertiliser, pesticides and herbicides and yields multiple products(Allin 2012). The woody internal stalk, or shiv, is a cheap co-product commonly used as animal bedding. When mixed with a lime based binder the shiv forms a low strength composite, hemp-lime, that is most commonly used as a non-load bearing mass infill walling material, cast or sprayed into place(Bevan et al. 2008). The unique porosity of hemp-lime means it buffers humidity and provides both insulation and effective thermal mass through a phase change phenomenon, significantly enhancing thermal efficiency(Arnaud et al. 2013b; Collet and Pretot 2014; Nordby and Shea 2013). As hemp grows it sequesters CO_2 from the atmosphere and thus hemp-lime can be considered carbon negative: effectively removing almost 300kg of CO_2 from the environment per cubic meter used(Boutin et al. 2006; Ip and Miller 2012).

Hemp-lime's application on site is hindered by its variability and a long drying time. Pre-casting and off site drying of hemp-lime components are plausible ways of circumventing these issues(Walker and Thomson 2013). The low strength and poor durability of the material however has restricted this to either high density formulations or as a component in structural insulated panels. This has been at the cost of the thermal performance and design flexibility respectively and has limited application. Refining the production of precast elements to produce stronger and more uniform components is therefore critical in order to improve the uptake of this high potential material.

The internal layout of the shiv particles is unquestionably a contributing factor in the mechanical properties of the composite. This is however a topic which has to date been the subject of little research. In this work a novel analysis and classification method for the internal structure was developed. Data were gathered from 15 specimens using two data collection procedures: computed tomography scanning (CT scanning) and two-dimensional digital imaging of cut sections. Image enhancement and analysis techniques where then implemented to allow the orientation of the shiv to be represented as a frequency distribution to enable classification of the structure. From this analysis, the research aims to discover if hemp-lime should be considered as an anisotropic material in future works relating to the physical testing and theoretical modelling of structural and thermal properties and provide a methodology enabling further investigation.

FACTORS INFLUENCING THE MECHANICAL PROPERTIES OF HEMP-LIME

The mechanical properties of hemp-lime have been studied as part of the fundamental characterisation of this novel material, but few studies have accounted for the impact of orientation on these properties.. What research has alluded to the influence of particle orientation is reviewed in this section.

Compressive Behaviour

The compressive behaviour of hemp-lime is the most widely reported mechanical property and is considered indicative of durability. In addition it is the only mechanical property specified in the world's singular design guide (Lanos et al. 2013).

It is generally considered that the binder is the sole structural element and compressive strength and stiffness are therefore proportional to the amount used(Arnaud et al. 2013a). For common mix designs and construction methods this pattern has indeed been observed widely(Arnaud and Gourlay 2012; Hirst et al. 2010; Murphy et al. 2010). The opposite was observed however by Nguyen et al. (2009) who considered highly compressed materials. This was attributed to a lower free-water content, hindering the hydraulic set of the binder. The formulation of binder has also been considered in respect of compressive behaviour with inconclusive results (Hirst et al. 2010; Magniont et al. 2012).Competition for moisture between the highly hydroscopic shiv and the binder can hinder setting of hydraulic components. As a result "stronger" binders will not necessarily produce composites of higher compressive strength and stiffness(Bevan et al. 2008).

The particle size distribution (PSD)of the shiv has been studied in relation to compressive behaviour by Gourlay, reported in (Arnaud et al. 2013a), and Arnaud and Gourlay (2012) who found that a finer shiv produced material that was slower to acquire strength but obtained higher values after a period of time. This was attributed to a greater degree of natural consolidation occurring with finer particles, providing a stronger geometrical structure but slowing carbonation. Conversely it has been observed elsewhere that in compressed material a coarser shiv will produce higher compressive strength, attributed to an increased overlap and friction between particles(Nguyen et al. 2009).

The manufacturing process has also been found to affect the compressive behaviour. Currently all forms of manufacture involve a degree of consolidation: tamping or vibration in the case of cast material and projection force in the case of sprayed material. The degree of consolidation has been shown to have an impact on the compressive strength and stiffness and this is attributed to increased contact between particles(Nguyen et al. 2009). As both consolidation and binder content directly affect the density, it is often reported simply that compressive strength is proportional to density(Hustache and Arnaud 2008).

It is suggested in many studies that the manufacturing process produces anisotropy in the shiv structure and thus anisotropic mechanical behaviour (Arnaud et al. 2013a; Duffy et al. 2014). This has however, to the authors' knowledge, only been tested by two researchers. The work of Mounanga, reported in Arnaud et al. (2013a), observed that the nature of compressive failure changes with orientation. However no statistically significant difference in capacity was observed. Gross (2013), as part of a wider investigation into the enhancement that hemp-lime can have on timber frames, performed a direct comparison of two casting directions and observed that in compressive tests orientation influenced the result by as much as 50%.

Flexural Behaviour

The flexural behaviour of hemp-lime has been studied considerably less but is relevant to the durability of elongated or flat precast objects. Flexural failure in hemp-lime is reported consistently as a failure of the tensile face and at a much lower stress levels than compressive failure(Benfratello et al. 2013; Gross 2013; Walker et al. 2014). This has been attributed to the lower tensile strength of the binder. Studies byElfordy et al. (2008)and Murphy et al. (2010)however found results for flexural strength comparable to those for compressive strength. Elfordy proposed that a preferable orientation of the shiv was induced in the construction which was perpendicular to the direction of the compacting force and enhanced the flexural properties.

Summary

It can be concluded that whilst several factors that impact the mechanical properties of these materials have been identified, a full understanding of the behaviour is lacking. It is generally considered that the internal structure of hemp-lime is not homogenous and that its formation will be influenced by the production method and consolidation. It is also likely that the mechanical properties are influenced at least as much by particle orientation as they are byother factors such as PSD and binder content.

METHODOLOGY

The aim of this study is to develop a means of numerical classification of the orientation preference of shiv within the material. Two methods for data acquisition, or digitisation, were considered. Both have been successfully applied for similar assessment of other materials and for the assessment of other characteristics of loose hemp particles.

Two dimensional digital image analysis has already been used for accessing the PSD of hemp shiv through imaging samples of loose materials(Nozahic et al. 2012). It has also been used to a lesser extent to analyse the porosity of loose “poured” shiv in consideration of the acoustical properties(Glé et al. 2013). While to the authors’ knowledge this concept has not been used for the assessment of the orientation of shiv in cast material, it has been used to assess the orientation and layout of aggregates in other materials- notably asphalt(Coenen et al. 2012; Yue and Morin 1996) and soil(Shi et al. 1998).

CT scanning produces a volume of 3D pixels (voxels) where assigned value represents the material’s X-ray absorption. CT scanning has been used successfully to classify the distribution of fibre reinforcement in concretes(Liu et al. 2013) and splits in timber (Wehrhausen et al. 2012)amongst other aspects of building materials internal structure. Again itdoes not appear to have been used to classify hemp-lime.

In this study five sets of hemp-lime specimens were produced.Each set comprised three specimens produced to differing mix designs representing an industry standard “wall” mix (mix ID 330), a more compacted mix (mix ID 400) and a lower binder to hemp ratio mix (mix ID 275). The mixes are detailed in table 1. Specimens were produced by initially mixing the binder and water in a pan mixer to form a slurry, the shiv was then incorporated mixed briefly to combine. A predetermined amount of mixture was then weighed into a 150mm cube moulds with a collar and consolidated to 150mm high using a 25mm square tamp. The samples were conditioned at 20°C, 60% relative humidity for a minimum of 28 days prior to analysis.

Table 1 Mix design details

Mix ID	Binder: Tradical HB (% mass)	Hemp: UK sourced (% mass)	Water (% mass)	Quantity of wet mix used (kg)	Target equilibrium density (kg/m^3)	Actual equilibrium density (kg/m^3)
275	36	21	43	1.48	275	284
330	36	16	48	2.00	330	353
400	36	16	48	2.41	400	422

Digitisation

Four sets of specimens were digitised using 2D digital scanning. These were first sectioned using a fine toothed band saw to produce 6 cut faces per specimen; two sets of specimens were sectioned parallel to the tamping direction and two perpendicular to allow for comparison.

When compared to other materials which have been subjected to2D digital image analysis, hemp-lime is more voided and more uniform of colour making reliable identification of particles more difficult. Two physical processes were trailed to enhance the quality of images produced: the addition of a red pigment to the lime to improve definition between the binder and the hemp, and the encasement of the cut faces in a coloured casting resin to fill inter-particle voids. The resin also improves the durability of the cut surface allowing sanding of the surface, removing marks made by the cutting. The resulting four variations of specimen are shown in figure 1. The prepared faces were scanned using a flatbed scanner set to 2400dpi.

The final set of specimens were digitised using a Nikon XTEK, XTH 225 ST computer tomography scanner at 165kV and 165uA. Due to the nature of the scanning process, the data captured was of a central 150mm diameter cylinder within each sample. The scanning process and the reconstructed volume are shown in figure 2. The flow chart, figure 3, summarises the processes used to digitise the specimens and lists the data sets gathered.

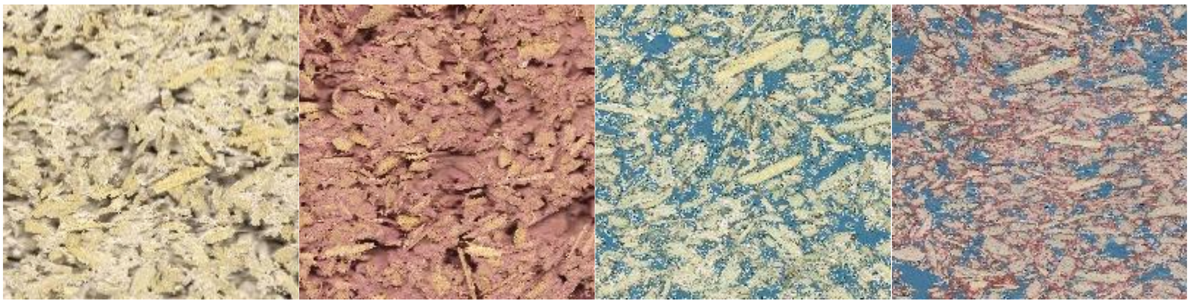

Figure 1 Comparison freshly cut hemp-lime, freshly cut pigmented hemp-lime, resin encased hemp-lime, and pigmented & resin encased hemp-lime

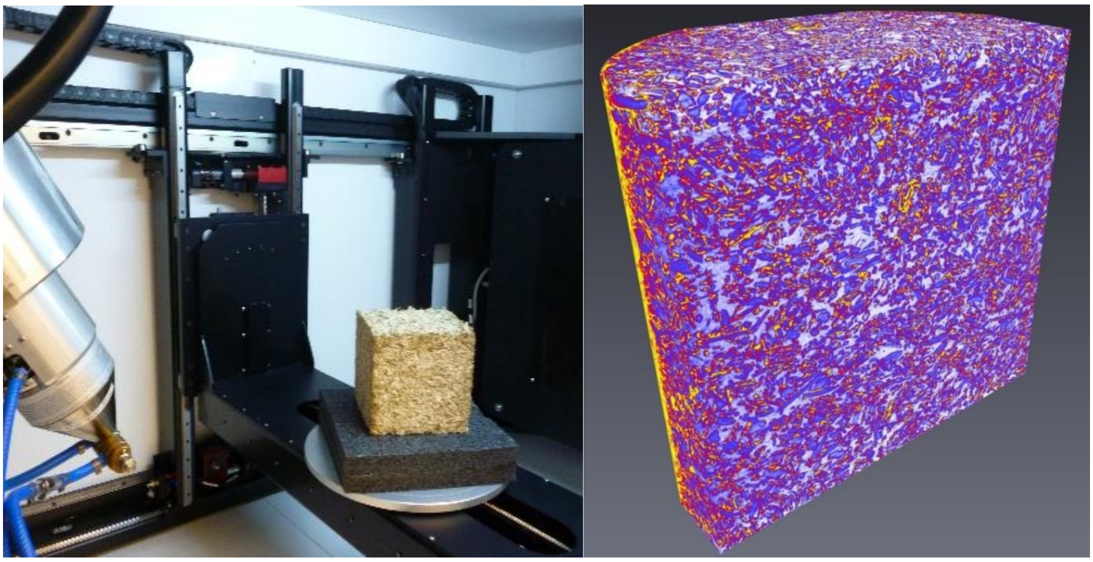

Figure 2 Hemp-lime being scanned in the Nikon XTEK, reconstructed 3D volume in Avizo Fire 8

Data Analysis

To produce usable data the 2D and 3D images were enhanced and filtered to identify the shiv. The enhancement and filtering methods used were based on those used in similar techniques for other materials(Coenen et al. 2012; Yue and Morin 1996) and the PSD analysis of hemp shiv (Nozahic et al. 2012).

The image enhancement of all 2D scans was carried out using the program ImageJ. A median filter (which replaces each pixel with the median of those within a radius) was first applied to remove noise and anomalies. A hue threshold filter was then applied to segregate the shiv and convert the image into a binary form. Finally an opening algorithm(which successively removes and adds pixels from the edge of a binary object) was applied to help clean and separate connected objects. The stages of image enhancement are demonstrated in figure 4. As all these processes are controlled by user selected settings, a range for each setting was trialled giving a total of 288 permutations to be considered. The range of setting used is detailed in table 2. To produce a distribution of particle orientations, ImageJ's particle analysis tool was used to index all discrete binary objects and calculate the orientation of their maximum calliper diameter.

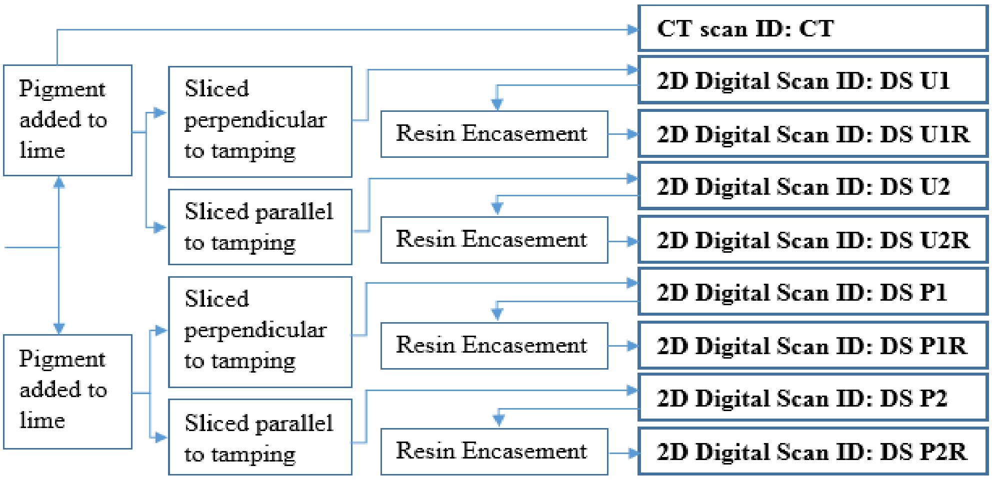

Figure 3 Flow chart of processes and resulting data set IDs

The 3D images were enhanced and analysed using the program Avizo Fire 8 with equivalent 3D versions of the same processes. As the software only allows for a single radius median filter, a varying number of iterations were instead trialled. A brightness threshold filter was used in place of a hue threshold filter as the images are grey scale as opposed to colour. As the overall density of the scans where different, a single range of threshold values was not appropriate and so an individual range of 9 variations was considered for each specimen. As the software only allows one iteration of opening algorithm, various kernel sizes were instead trialled. A total of 81permutations were considered and the range of setting used are summarised in table 2. The Label Analysis Module in Avizo Fire 8 was used to identify and measure the discrete binary objects. For each identified particle the orientation was calculated using the Orientation Theta and Orientation Phi measures. As the particles are considered in 3D space, the orientation is therefore defined by two angles with reference to the horizontal plane, Theta, and vertical axis, Phi.

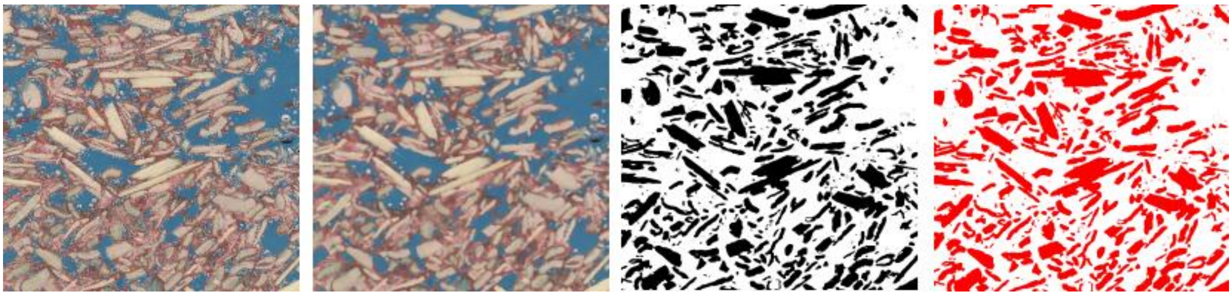
Figure 4Stages of 2D image enhancement: raw image, median filtered, threshold filtered, open algorithm applied

Table 2 Variables used in image enhancement of the 2D and 3D scans

Digitisation method	Range of median filters trailed	Range of thresholds trailed	Range of opening algorithms trailed
2D digital scanning	Radius of 5,10,15,20,25 and 30 pixels	Hue threshold of 10-50, 12-50, 14-50, 16-50, 18-50, 20-50	1, 2, 3, 5, 10, 15, 20, 25 iterations
CT scanning	5, 6 and 7 iterations	Brightness Threshold of 4, 4.5 or 5- 8, 8.5 or 9 (275 mix) 4, 5 or 6- 28, 29 or 30 (330 mix) 6, 7 or 8- 28, 29 or 30 (400 mix)	Radius of 1, 2, 3

RESULTS

Two Dimensional Digital Image Analysis

To assess the effect of the enhancement settings used and to establish the most appropriate settings for correct identification of particles, the frequency distribution of particle orientations for all 288 versions of one image from each data set were produced using 10 degree groupings. A cosine curve (Eq. 1), was then fitted to the distribution by finding the values of α and β that minimise the sum of the squared differences between the modelled and actual distributions. Figure 5 shows the sum of the squared difference plotted for all enhancement variations for the data set DS UR2. If the continuous distribution of any given data set is assumed to follow Eq. 1, the sum of the squared difference represents the effectiveness of the settings used. Using this as a guide the assumed most effective combinations of setting were identified. A visual inspection of these images was then used to confirm their accuracy and assess the most appropriate settings.

$$y = \alpha + \beta \cos(2x) \quad (1)$$

A similar approach was taken to assess the most effective physical processing. Using the settings identified for each data set, the images were assessed visually for their ability to correctly identify individual particles of shiv. From this the most effective combination of physical processes and image enhancements for the identification of shiv particles using 2D scanning was assessed to be as follows: pigment should be added to the binder during forming; the sliced specimen should have the face cast in low viscosity resin and then be sanded to a smooth surface; the image should be median filtered with a radius of 20px; threshold filtered with a 8 bit hue value of 14-50; and an opening algorithm should be applied with 3 iterations. Data sets DS P1R and DS P2R were therefore considered for assessment.

A comparison of the DS P1R and DS P2R data sets was conducted in order to compare the results from two orientations. The individual frequency distributions for all 6 imaged sections for each mix as well as the best fitting cosine curve for all slices are shown for both parallel and perpendicular slices in figure 6.

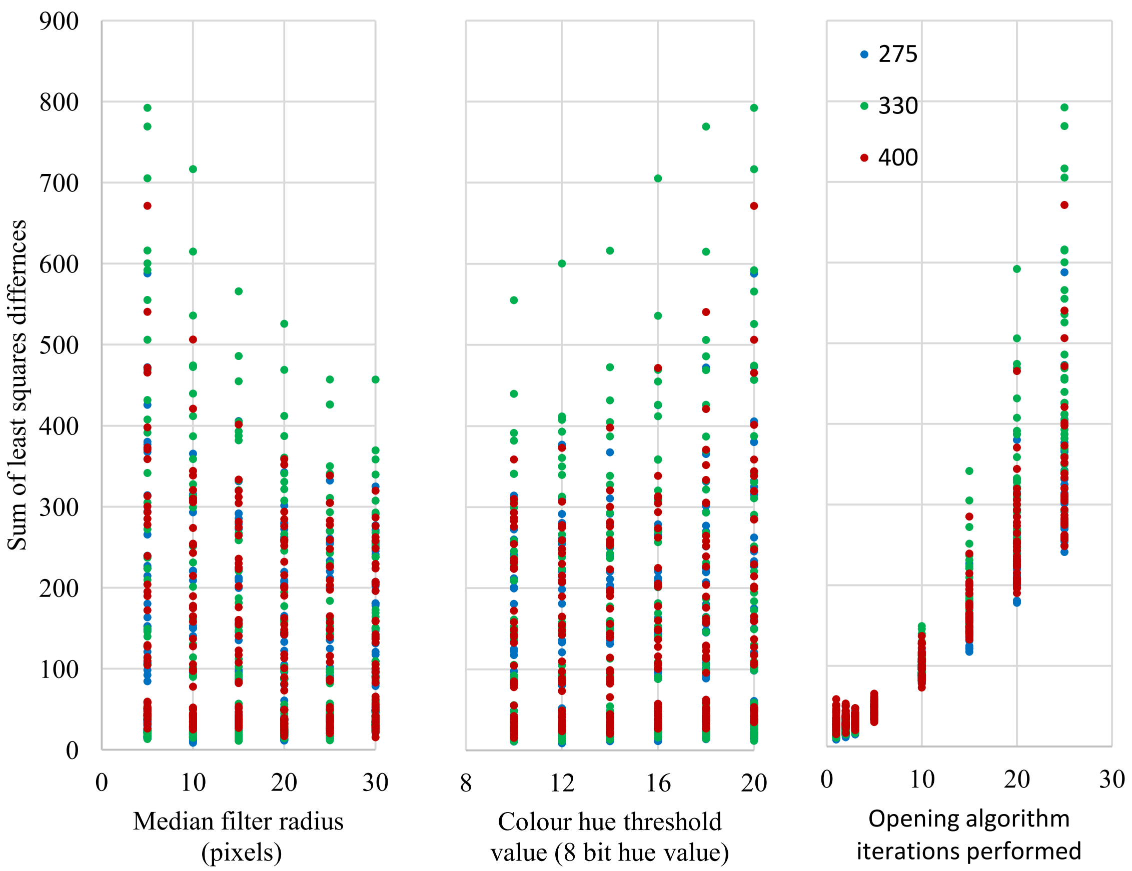

Figure 5 Sum of the least squares differences for the DS UR2 data set

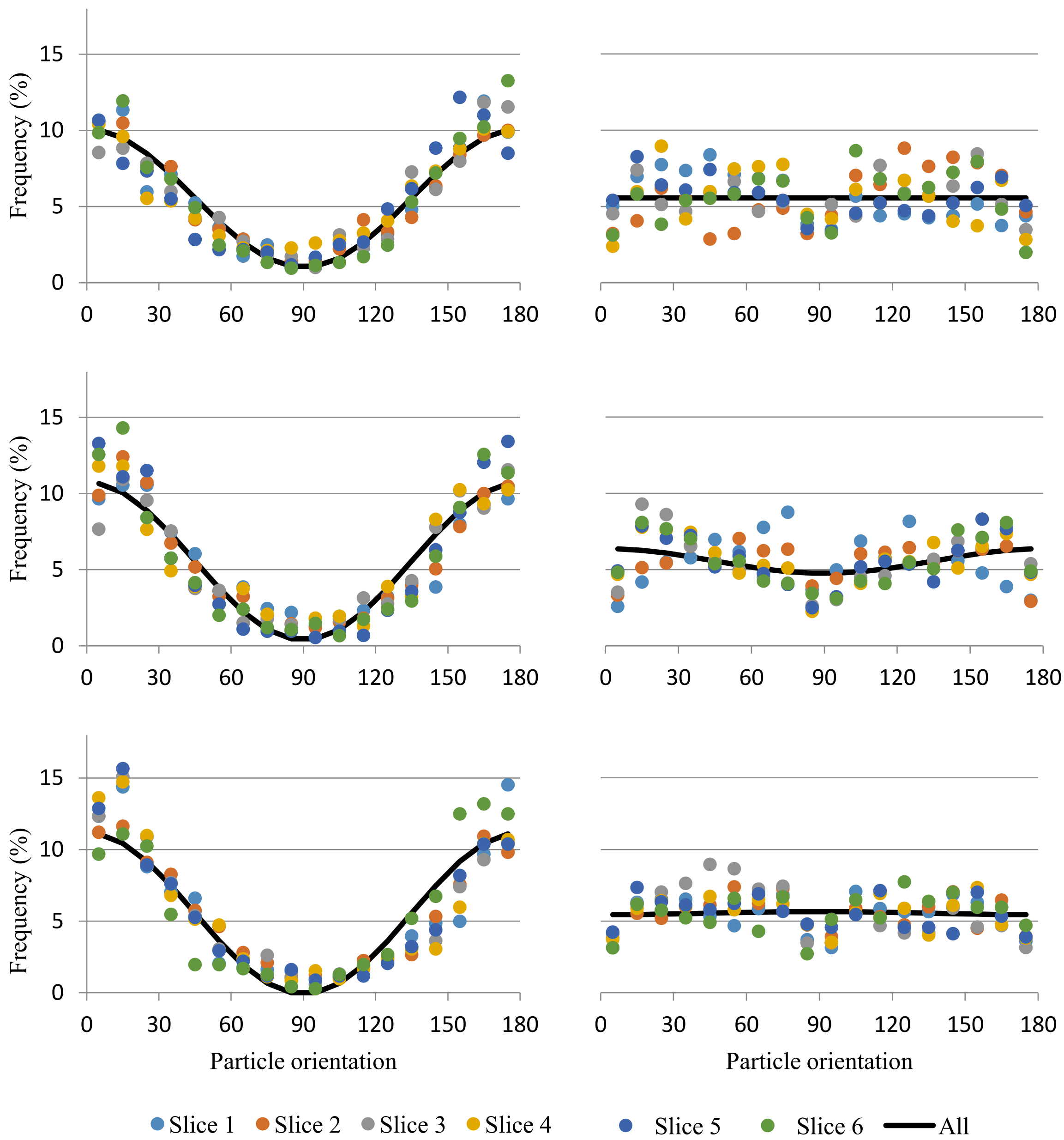

Figure 6 Frequency distributions of DSP1R (left) and DSP2R (right) data sets for the 275 mix (top), 330 mix (middle, and the 400 mix (bottom)

Computer Tomography Scanning

The results from the CT scan data were interpreted using the same frequency groupings. The results from all 81 combinations of enhancement where inspected for perceived accuracy of particle detection by visually inspecting random slices taken from the volume. Six iterations of median filter and opening with a radius of three were the settings perceived to give the most reliable identification of particles for all mix designs. Brightness threshold setting of 5-9.5, 4-29 and 7-29 were perceived to the most appropriate for the 275, 330 and 400 mixes respectively. The frequency distributions of orientation for both directions using these enhancement parameters are given in figure 7.

DISCUSSION

The strong agreement between the results obtained from two dimensional imaging and CT scanning indicates that both methods of data collection are successful way of assessing the orientations of the shiv particle within hemp-lime and could be applied easily to other bio-composite concretes.

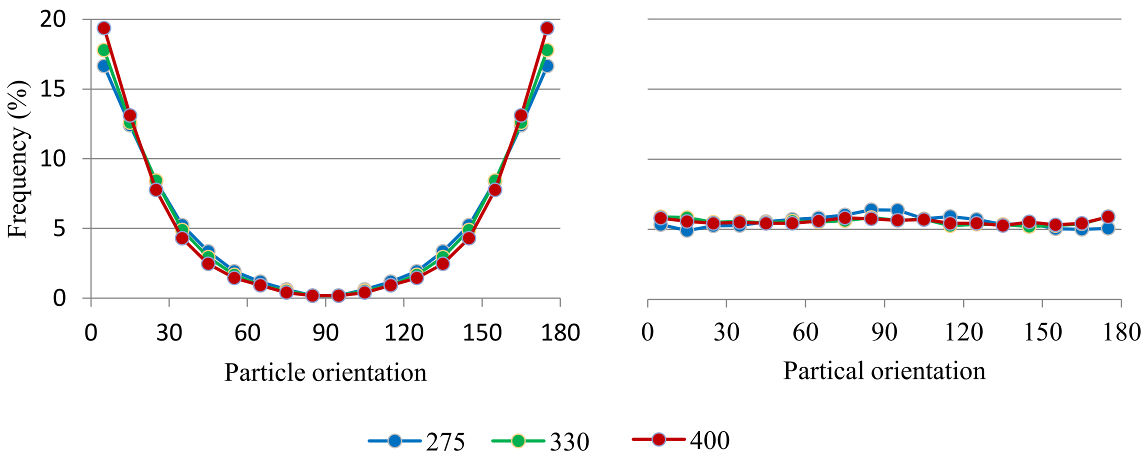

Figure 7 Frequency distributions of particles in the Phi orientation (left) and Theta orientation (right) for the CT data set.

In the case of two dimensional imaging, two physical treatments were identified as essential in order for the technique to be applied accurately: a coloured pigment added to the binder and encasement of the face in coloured resin. Both of these increase the visual contrast between the hemp and the surroundings and enable the software to accurately identify the particles.

For both methods it was observed that accurate identification of a particle is dependent on the enhancement processes applied to the image. In the case of two dimensional imaging, the number of iterations used with the opening algorithm was observed to have the largest single effect in this respect. It is unclear why this might be the case however it was observed that the nature of the algorithm reshapes binary objects towards a circular form that could increase the likelihood of the orientation becoming misinterpreted. This operation should therefore be used with caution in the analysis of these images.

The assumption that the frequency distribution of particle orientation can be modelled by Eq. 1 was useful to enable the easy identification of likely optimal enhancement settings for the 2D images. It is not justifiable to use this method solely however as the true form of the distribution is unknown and there is a high level of natural variation. From the visual inspection of images for both CT scan data and 2D scan data it was possible to identify the most appropriate enhancement parameters and to have a good degree of confidence in the software's ability to correctly identify particles. The comparatively smoother distribution for the CT scan data can be attributed to the larger effective sample size of particles considered.

It is clearly visible from both figure 6 and 7 that there is a distinct difference in the particle orientation distribution of the material when viewed in different directions. When viewed in the direction of compaction force, a relatively flat frequency distribution is observed indicating a random orientation. It is unclear why there should be apparently lower frequencies of orientations around 90° and 0/180° regions in figure 6 and the opposite in figure 7 however this could be in part related to the influences of the mould edges that are aligned in these directions.

When viewed in a direction perpendicular to the direction of compaction there is a very strong indication of directionality within the particles with a strong tendency towards the horizontal. It is a logical assumption, widely mentioned in the literature, that compaction in a given direction will encourage particles to rotate towards planes perpendicular to the force. These results directly support this assumption, providing clear evidence that process of tamping will produce an anisotropic internal structure governed by the direction of force applied. The degree of directionality observed indicates that it is inappropriate to consider the material as homogenous and that future work should clearly state the orientation from which results have been obtained, particularly with reference to mechanical and thermal properties.

From figures 6 and 7 it appears that the specimens of higher density may have higher degrees of orientation. Figure 8 shows the particle distributions for the DS P1R data set and the CT data set (Phi orientations) reduced into a distribution between 0° (horizontal) and 90° (vertical). This increases the effective sample size for the two dimensional image data making trends more obvious. A similar form of distribution is observed for data collected using each method as is a perceived increase in the amount of orientation as density increases. By considering the 330 mix and the 400 mix it is considered likely that as the level of compaction is increased so is the degree of internal orientation. The 275 mix was perceived to have the same compaction level as the 330 mix when produced and so it is unclear why this should have a lower degree of orientation however it is likely that the initial assumption of equivalent compaction is incorrect. The generally lower degree of orientation in the two dimensional data is also unexplained however considered to be a likely result of the different ways the programs assess orientation. The dip in frequency in the lowest value grouping in the two dimensional image analysis is unexplained however considered possibly to be an effect of the calliper diameter orientation being used or the influence of mould edges; not observed in the CT scan data due to the nature of the process only producing an image of a central cylinder. This difference will be studied in greater depth in future work.

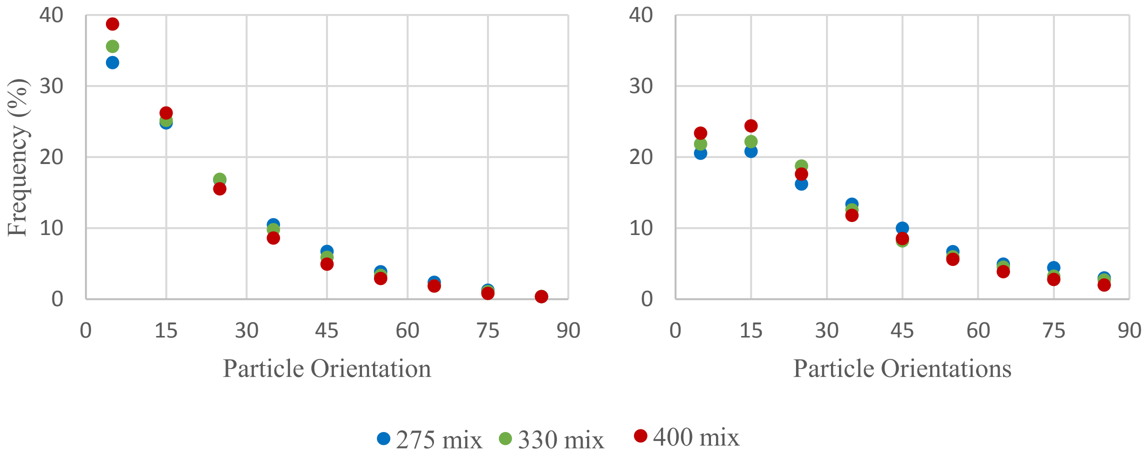

Figure 8 Particle orientation frequency distribution between horizontal (0) and vertical (90) for the DS P1R and CT (Phi orientation) data sets

CONCLUSION

Two methods of producing digital images of the internal structure of the bio-concrete hemp-lime were trialled using a number of image enhancement methods. With the exception of possible edge effects identified by the 2D digital scanning method, both techniques produced very similar frequency distributions. Both CT scanning and the 2D digital scanning methods were able to produce usable data pertaining to the orientation of the hemp particles within the specimens and the optimum methods of image enhancement and specimen processing were established. The results indicate that hemp-lime exhibits a high degree of preferential internal orientation with the shiv tending towards stratified layers perpendicular to the direction of tamping. It is considered that this has a large bearing on the mechanical properties and would explain the anisotropic behaviour of physical properties observed by others. It is therefore important that future research on the mechanical and thermal properties of hemp-lime or other bio-composites should make reference to the direction of compaction.

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