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The influence of constituents on the properties of the bio-aggregate composite hemp-lime

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HIGHLIGHTS

- Directional thermal and mechanical tests conducted on hemp-lime.
- The impact of a range of constituent variables considered.
- Analysis of two dimensional images used to assess the impact on internal structure.
- Anisotropic structure and properties reported determined by the constituents.

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ABSTRACT

Composites made of bio-aggregate particles and lime based binder can be used as a low embodied energy alternative to traditional walling systems and can provide several performance advantages. As the ratio and nature of constituents used in bio-aggregate composites will have bearing on the properties, it is necessary for these to be capable of being optimised to meet specific design requirements. In addition, as these materials are known to be anisotropic, it is required that any impact of constituents is assessed with respect to orientation. In this paper, the influence of the binder to aggregate ratio and aggregate particle size distribution on the compressive strength, flexural strength and thermal conductivity of hemp-lime composites in two directions of loading have been assessed. A newly developed image analysis method was also employed to study the topology of the internal structure. The results show that the material is anisotropic in both behaviour and internal structure and that both binder/aggregate ratio and aggregate particle size distribution affect composite properties. In the case of binder to aggregate ratio, the impact is shown to be directionally dependent and indicative of differing governing factors controlling the failure mode in opposing loading directions.

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1. Introduction

Bio-aggregate composites are formed from a mineral binder and bio-aggregate particles such as hemp [1–3], sun flower [4–6] or rape stalk [7,8]. The wet mixture can be cast or projection formed around a structural frame as an insulating infill [9] with such walls exhibiting lower embodied energy than traditional alternatives [10–12]. In addition composites of hemp and lime have been shown to offer a beneficial compromise between thermal conductivity and thermal inertia, enabling the passive moderation of building climate [13–15]. Despite these advantages the application and utilisation of bio-aggregate composites remains low in construction due in part to the high variability of a bio-sourced product and in part to the conservative nature of the industry. A better understanding of the material's performance, leading to control and optimisation of physical properties, is a necessary step in addressing these issues.

As composite materials, alterations to the ratio and nature of the constituents are logical avenues of material development. The ratio of binder to aggregate and its influence on thermal conductivity and mechanical strength of hemp-lime have been studied extensively [4,16–18] with unanimous agreement that an increase in the binder quantity increases the compressive strength, flexural strength and thermal conductivity. This is attributed to an increasing binder content tending the behaviour of the composite to that of the binder [19,20] and several models for thermal conductivity and compressive strength have been proposed based broadly on this assessment. Mechanical properties and thermal conductivity have been modelled simplistically as a function of density [3,21], considered an indicator of binder content, and more recently, through multi-phase models that specifically accounts for the ratio

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of constituents [18]. While such models are logical, it should be noted that they assume an isotropic relationship in a material that is known to have an anisotropic structure and behaviour [22].

The influence of the particle size distribution of the bio-aggregates used has also been studied previously [23–25]. While in all studies reviewed, particle size distribution has been shown to impact on the physical properties of materials, although there has been limited consensus between studies as to the relationship. It has been observed by some that a finer grade of particles provides an increase in mechanical strength and a smaller increase in thermal conductivity [23,24], attributable to a closer packing of the particles [19]. Contrastingly, others found that a coarser grade of particles yielded better mechanical properties, attributed to a greater overlap of particle [25]. A possible reason for the disagreement of these conclusions may be the small fluctuations in properties reported compared to relatively large natural variation. Alternatively it may also be argued that previous studies tend to express bio-aggregate grades simply as finer or coarser based on average length; other potentially significant factors such as the spread of the distribution or aspect ratio of particles may thus have been overlooked.

Within the body of previous work it is noticeable that the effect of changing these variables is often only reported in one orientation but the observed relationships are assumed to apply globally. It is now known that the internal structure of the bio-aggregate composite hemp-lime is orientated [22] as a result of the production method chosen and the elongated form of the particles. It has also been identified from a number of sources that the mechanical behaviour and thermal conductivity of bio-aggregate composites are anisotropic [19,26–28] that may be attributed to the structure and presumed to apply in all cases where the bio-aggregates are elongated. It is therefore necessary to consider any influence of constituent variables within this context meaning it cannot be assumed that constituent variables have an isotropic effect. To the author's knowledge it has not previously been ascertained if changing the binder concentration or the particle size distribution has a global or directionally dependant influence on physical properties.

This paper considers the thermal conductivity, compressive strength and flexural strength of hemp-lime specimens produced with three ratios of hemp to binder and three distinct grades of hemp aggregate; the particle distribution of the hemp aggregate fully characterised in each instance by means of two dimensional imaging. In order to ascertain if any effects are directionally dependent, thermal and mechanical tests were conducted in two directions: parallel to the direction of casting force and perpendicular to it. A recently developed method for assessment of the internal structure of bio-aggregate composites was also used in each case to provide an insight into the internal topology and to help inform any conclusions drawn about the mechanisms involved.

2. Method

2.1. Specimen production

Five mixtures of hemp-lime were considered in the study covering a range of three distinct grades of hemp aggregate and three hemp to binder ratios, (Table 1). Hemp lime was chosen due to it being the most prominently assessed bio-aggregate composite within the literature and indeed industry. In order to minimise the total amount of material used, single sets of rectangular prism specimens were produced for all mechanical tests as well as the internal structure assessment. The prisms produced were all 400 mm × 150 mm × 150 mm for testing in three point bending. Following the flexural test, one half was resized to a 150 mm cube used for compressive testing and one half sliced into 150 mm × 150 mm × 25 mm slices for the analysis of the internal structure. For thermal conductivity tests, 400 mm × 400 mm × 50 mm specimens were produced of each mixture. In all cases two sets of specimens were cast, one for testing parallel to the casting compaction and one perpendicular.

The specimens were produced by first combining water and the binder in a revolving pan mixer to produce a uniform slurry. Once uniform, the hemp aggregate was added and further mixing conducted until a homogenous mixture was observed. The total mixing time was under 5 min in each case. The binder used throughout the study was a commercially available pre-formulated binder for use with bio-aggregates produced by Tradical®. The hemp aggregate used was grown and processed in France and supplied by the producer in four grades 7, 8, 12 and 14. The three grades used for this study were 7 (referred to herein as fine), 14 (referred to herein as coarse) and 1:1 by mass mixture of 8 and 12 (referred to herein as medium). The rationale of mixing two of the manufactures' grades to produce the medium grade was to ensure a wider distribution of particle sizes in this grade compared to the fine and coarse grades.

The combined mixture was weighed out into the moulds prepared with release oil in 50 mm layers with light tamping between each layer. The amount of material weighed out in each case was predetermined in order to produce a similar compaction state across the specimens. In this study this was set at 45% densification of loose-state density, determined for each mix by weighing a set volume of un-compacted material placed carefully by hand, (Table 1). The specimens were stored after production in a conditioned room at 20 °C and 70% relative humidity, uncovered in the moulds for 6 days and uncovered out of the moulds thereafter.

2.2. Material classification

The three grades of aggregate used in this study: fine, medium and coarse were assessed for particle size distribution by a method of two dimensional image analysis developed by Picandet [29]. This was selected over a simple sieving method in order to provide data about both particle length and width. The analysis was conducted on a 20 g sample of each grade removed from a 20 kg bag by a process of quartering. Scanning was conducted by arranging a small amount of particles with their largest surface face down on the surface of a flatbed scanner by hand in order to segregate them. This was then scanned against a blue background at a resolution of 1200 dpi and the process repeated until the full 20 g was imaged.

All image processing and measurements were conducted using the program ImageJ and the method used follows that described by Picandet [29] and reported here in brief. In each case a colour threshold was applied to the image to produce a binary image of the hemp. The binary images were then enhanced using three iterations of an opening algorithm to remove noise and dust. Assessment of each image was conducted using the particle analysis tool that identifies the primary and secondary axis of each discrete binary object. This is done though equalising the particle's second moments of area to that of an ellipse whose axes are then used to provide a measure of length and width.

To produce a distribution comparable to a sieving analysis, an estimated volume for each particle is calculated based on the area of the particles and an assumption that average thickness is proportional to particle width. Assuming uniform density, this can then provide an estimated mass of the particle allowing for the production of an estimated mass distribution of the sample for both particle length and width. The particle size distributions for the three grades of aggregate are presented in Fig. 1 while bulk density and particle size distribution parameters are presented in

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