PROJECTION FORMED AND PRECAST HEMP-LIME: BETTER BY DESIGN?

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Abstract
Projection forming and off-site pre-casting of hemp-lime panels are alternatives to traditional in-situ casting that can offer several production benefits: minimised on-site time, improved quality assurance and lower drying times. The direction of compacting force applied with these methods is perpendicular to that of traditional on-site cast material and, in the case of projection formed, applied by different means. As a result the internal structure of the material will be aligned and shaped differently with consequent implications for the physical properties that must also be considered when selecting a method of production. This paper reports on the mechanical and thermal properties of hemp-lime produced by projection and by casting in two directions: vertical as per in-situ casting and horizontal as per pre-casting. The internal structure of the material in each case was assessed through image analysis and used to explain the measured differences in properties. The results indicate the importance of the orientated internal structure in determining the performance of this material and show that horizontally precast manufacture can provide inherent performance improvements over traditionally cast material in addition to the logistical benefits while projection forming may allow for thinner wall sections.

Keywords:
Internal structure, image analysis, production process, mechanical properties, thermal conductivity

1 INTRODUCTION

Hemp-lime is a bio-aggregate composite used as an infill walling material offering several advantages over traditional wall build ups: lower embodied energy [Pretot et al. 2014], beneficial thermal inertia [Collet and Pretot 2014, Evrard and De Herde 2010] and passive humidity buffering [Evrard 2006, Osanyintola and Simonson 2006]. Unfortunately, in-situ cast walls of hemp-lime can require a long production and drying time, detrimental to the scheduling of larger projects. To overcome some of these logistical issues, pre-casting and projection application methods have been developed and offer a streamlined onsite process as well as a possibly improved quality control.

A recently acknowledged characteristic of bio-aggregate composites is an anisotropic structure resulting from compaction during material placement. This in turn is known to produce anisotropy in the material properties; the thermal conductivity and compressive behaviour of hemp-lime have both been shown to be directionally dependent with respect to compaction [Amziane et al. 2015, Youssef et al. 2015, Pierre et al. 2014, Nguyen et al. 2010]. With cast in-situ walls, compaction is applied vertically via manual tamping however for projection formed and precast material the compaction is commonly applied horizontally with respect to the wall, altering the orientation of the material's structure. In order to allow fully informed decisions to be made when selecting a production method the impact of this on a wall's physical properties must be considered as well as any logistical benefits.

The directional dependence of the properties of cast hemp-lime have been studied previously. Nguyen assessed highly compacted material and identified a clear anisotropy in the thermal conductivity [Nguyen et al. 2010]; the thermal conductivity perpendicular to compaction was found to be 30% to 50% higher than in the parallel direction. Compressive tests on similar material have indicated that a more brittle failure occurs when loading is applied in a perpendicular direction and that the material exhibits a higher stiffness [Youssef et al. 2015]. The density of material considered in these studies was higher than that standardly used for in-situ casting [Bevan et al. 2008] or found in projection formed material [Elfordy et al. 2008] however more recently it has been confirmed that this behaviour is repeated at lower densities of material. At these densities the difference between the parallel and perpendicular thermal conductivities was found to be approximately 20% [Williams et al. 2016a].

Directional dependence of the properties of projection formed material has been less studied. Pierre assessed the parallel and perpendicular thermal conductivity of projection formed material removed from a larger specimen [Pierre et al. 2014] and found agreement with cast material; an increase in the perpendicular direction as opposed to parallel of 33%. The mechanical performance of projection formed material has been studied parallel to compaction by Elfordy [Elfordy et al. 2008] and while observations are made about an apparent orientation of the material, no data are presented for perpendicular testing. The only known previous comparison of the compressive behaviour of projection formed material in two directions is reported by Hustache [Hustache and Arnaud 2008]. While this report again indicates greater stiffness in perpendicular loading and a more brittle failure manner, limited data are presented.

Compared to the compressive behaviour of hemp-lime, the flexural properties have been studied considerably less despite the requirement for infill materials to transfer horizontal loads to a structural frame. In previously published literature there was one identifiable occurrence where the differing directions of flexural loading has been applied [Gross 2013]. As part of this thesis, cast panel specimens are tested in four point bending with loading either applied perpendicular to compaction and parallel to layers, or, perpendicular to compaction and perpendicular to layers; an arrangement which would involve loading parallel to compaction was not considered. In this case the material was found to have a lower flexural strength when loaded perpendicular to layers, and this can be attributed to the joint between layers providing a weakness.

In consideration of the large number of variables present in the production of hemp-lime, drawing comparisons between existing studies to compare the behaviour of cast and projection formed material is inappropriate. Given the likely increasing use of projection forming and precast manufacturing, it is important therefore that the performance of the material produced can be directly compared to that of comparable cast in-situ material in a way that accounts for the differing orientations of compaction. In this paper experimental results are presented for equivalent hemp-lime produced using projection and casting methods and tested in both loading directions. Three theoretical sections of wall are then considered in order to provide a comparison of walls produced using horizontal projection forming, vertical casting and horizontal casting.

2 METHOD

2.1 Experimental

Specimen production

Specimens were produced using either projection forming by a contractor on an established site or by hand casting in the laboratory but in both cases the binder and hemp used were kept consistent. The specimens produced by casting were of two sizes: 150mm x 150mm x 400mm for flexural, compression and internal structure assessment and 400mm x 400mm x 50mm for thermal conductivity. The specimens produced by projection were 800mm x 800mm x 200mm with a set of specimens of equivalent size to that of casting removed via cutting. In both cases two sets of specimens were produced for testing respectively parallel to and perpendicular to the compacting force.

For production of cast specimens the binder, tradical thermos, and water were first mixed together in a pan mixer for three minutes until a uniform slurry was produced. The hemp shiv, supplied by Cavac, was then added and the mixing continued for another two minutes until the mixture was homogenous and all the particles of shiv coated. The specimens were formed in wooden moulds prepared with a release agent and in 50mm layers with tamping in between. To ensure consistency and provide the desired level of compaction, a predetermined mass of mixture was used for each layer. The specimens were stored within a controlled climate room at 20°C and 50% relative humidity with demoulding conducted at 6 days.

The projection formed specimens were produced by Hemp-Lime Spray at an established building site in Lay Hill, UK. The machine used was comprised of two parts: a slurry mixer with pump and a hemp hopper with auger fed airstream. Together these parts deliver a feed of pressurised slurry and air blown hemp to the operator’s lance where hemp is projected though a central opening, and three small spray nozzles around the perimeter spray the slurry into the stream, Figure 1. The combining of the constituents happens at this point and the individual flows of the hemp air stream and slurry are both controllable by the lance operator. Once produced, the specimens were transported to the University of Bath where they were stored in laboratory conditions. Five sides of the moulds were removed after six days, however to aid handling the base of the mould was retained until the specimens were cut at 27 days.

In the case of the cast material the ratio of the constituents was controlled as presented in table 1. For the projection formed material, while the ratio of water to binder was controlled in the production of the slurry, and kept consistent with the cast specimens, the ratio of hemp to slurry is controlled by the operator of the lance and is thus more approximate. In this instance an effort was made by the operator to try to match the visual consistency during production to a cast reference specimen provided. A subsequent image analysis has been carried out to estimate the actual ratio used, (Table 1).

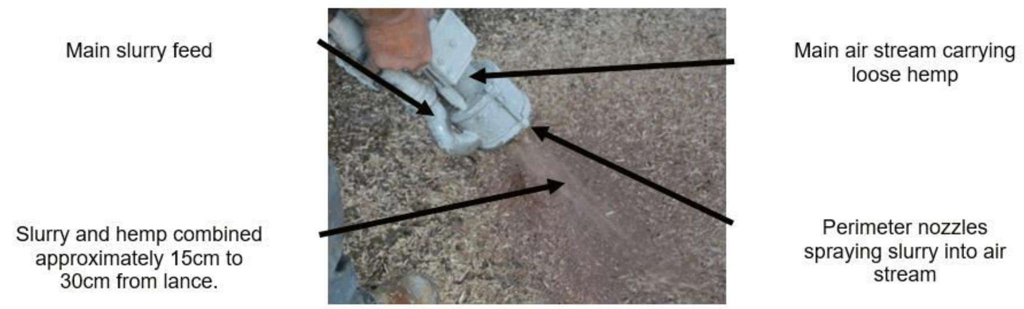

Fig. 1: The projection process and lance.

Tab. 1: The constituent ratios, density and compaction state of material produced by each process. Constituent ratios in the case of cast material are known whereas those for projection formed material have been estimated using subsequent image analysis of the material and the dry density.

	Hemp content in mix (% mass)	Binder content in mix (% mass)	Water content in mix (% mass)	28 day density (kgm-3)	Dry density (kgm-3)	Compaction (%)
Cast hemp-lime	16	36	48	406	348	45
Projection formed hemp-lime	15	36	49	488	374	56

As with the ratio of constituents, the compaction applied by the projection method is also difficult to control and quantify. Based on initial information provided by the contractor, the estimated compaction of their standard projected material was placed at 45% (density increase over uncompacted cast material) and thus this was used for the production of cast specimens. The actual level of compaction in the projection formed specimens was estimated subsequently by image analysis and mass readings, (Table 1), and found to be slightly higher.

Mechanical testing

All mechanical tests were conducted at 28 days after casting in an Instron 50kn testing frame using inbuilt instrumentation and a data sampling rate of 10Hz. The specimens were first tested in three point bending with a span of 300mm and a deflection controlled load rate of 3mm/min. Following completion of the flexural tests, one half of the specimen was resized by sawing to a 150mm cube and tested in compression at the same deflection controlled rate. In each case the tests were repeated over a sample of three specimens and repeated in the two loading directions indicated in Figure 2. For the flexural results, the ultimate stress was taken from the peak load, however in the compressive tests, where there is no peak in parallel loaded material, a yielding point is reported. In this study the failure stress of compressed material is defined as where the instantaneous stiffness falls to 30% of its recorded maximum, referred to herein as compressive rupture stress.

Thermal testing

All thermal conductivity measurements were taken using a Lasercomp Fox 600 heat flow meter. The specimens were mass stable at 20 degrees and 50% relative humidity prior to testing and were wrapped in a single layer of Clingfilm to protect the machine. All tests were run on a temperature gradient of 10°C to 30°. Experiments were conducted both with heat flow parallel to and perpendicular to compaction, (Figure 2).

Image analysis

The internal structure was assessed via two dimensional image analysis of slices taken from the flexural specimens. The process is described fully in previous work [Williams et al. 2016b] but is outlined as follows: six 150mm square slices were removed from each specimen using a band saw. The slices were orientated so that they were imaged in the same axis as the other tests, (Figure 2). Following cutting, each slice was then cast within blue resin to stabilise the cut face and provide visual contrast of voids. The slices were finally sanded and scanned using a desktop scanner. Images were scanned at 1200dpi giving a pixel size equating to 0.000448mm^2.

Analysis of the images was conducted using the program ImageJ. Initially a 10 pixel median filter was applied to smooth irregularities within the image followed by a series of hue thresholds to produce separate binary images of the air, hemp and binder. An opening algorithm was run on each binary image in order to remove fine particles (dust and fibre) and help segregate touching particles. Finally the measure and particle analysis tools were used to measure global properties of the images and individual binary objects respectively. The measurements taken in each case were the respective proportions of hemp, binder and air within the image and the orientations of the hemp particles. These measurements from the six slices were combined to provide an average volumetric breakdown of constituents and particle orientation frequency plots for each specimen.

Theoretical

In normal circumstances three combinations of production method and in-situ versus compaction orientation might be considered for a construction project: in-situ casting - cast vertically; pre-casting of panels - cast horizontally; and projection formation - projection formed horizontally. To compare the performance of these options the data collected from the experimental work was used to predict the performance of three similar wall sections of hemp-lime produced using these combinations. The wall sections considered all have a size of 1m2 and are without timber framing and surface finishes. As the material is primarily an insulation the thickness of hemp-lime in each wall section is specified to give an equivalent U-value of 0.3Wm-1K-1. In each case the flexural loading capacity, compressive loading capacity and embodied energy of the wall section are then predicted based on the experimental results as well as data available in wider literature (Table 2).

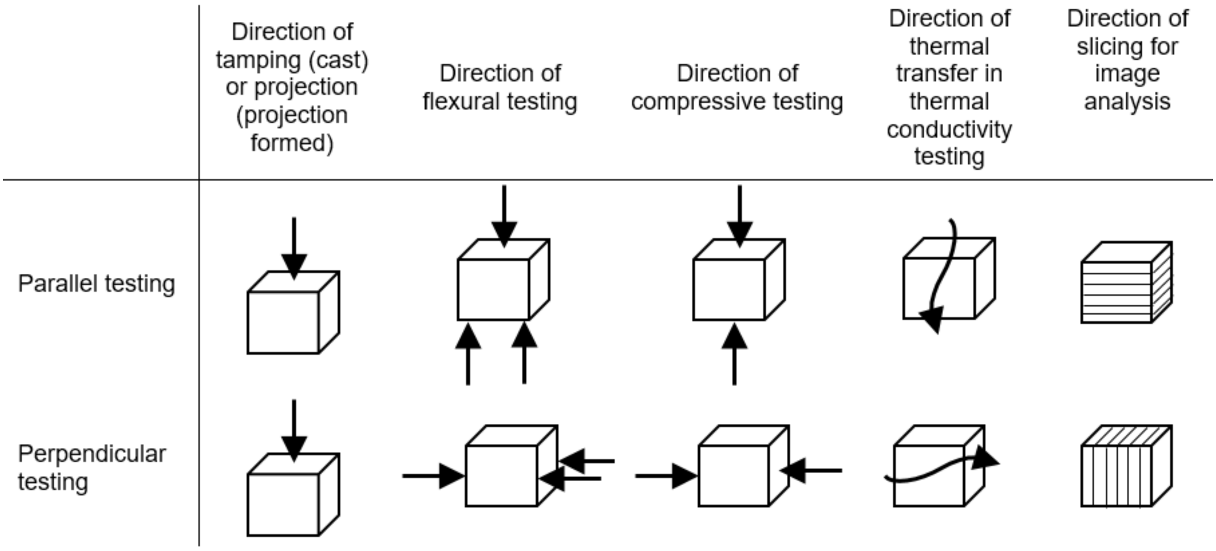

Fig. 2: The casting and loading arrangements for parallel and perpendicular loading.

Tab. 2: Estimated material and process primary energy demands required for the production of hemp-lime as found in wider literature

	Cast hemp-lime	**Projection formed hemp-lime**
Materials	MJ per kg of material	MJ per kg of material
Binder	5.30 [Hammond and Jones 2008]	5.30 [Hammond and Jones 2008]
Hemp	1.67 [Pretot et al. 2014]	1.67 [Pretot et al. 2014]
Water	0.01 [Hammond and Jones 2008]	0.01 [Hammond and Jones 2008]
Manufacture	MJ per kg of dry hemp-lime	MJ per kg of dry hemp-lime
Mixing	0.05 [Ip and Miller 2012]	0.05 [Ip and Miller 2012]
Projection	-	0.02 [Ip and Miller 2012]

3 RESULTS AND DISCUSSION

3.1 Experimental

The stress strain plots of the compressive and flexural tests carried out in both orientations on both projected and cast hemp-lime are presented in Figure 3. In general it can be seen that the projection formed hemp-lime exhibits a less consistent mechanical behaviour irrespective of loading direction. This is considered to be indicative of less consistency in the material structure and directly associated with the projection process used.

Under compression both cast and projection formed hemp-lime are found to behave in an anisotropic way and in accordance with other studies [Nguyen et al. 2010]; the material displays greater stiffness and a more brittle failure mode under perpendicular loading as opposed to a prolonged ductile failure in the parallel direction. In both cases this observation can be attributed to a stratified arrangement of particles dislocating by rotation under perpendicular loading and linearly under parallel loading. This assessment is verified by visual observation of the material under loading, (Figure 4), that indicates localised internal buckling in perpendicular loading.

Under flexure it can be broadly noted that for both cast and projection formed hemp-lime there is no significant difference in behaviour with direction of loading, Figure 3. The cast specimens of hemp-lime particularly are observed to fail in a very consistent manner, confirmed by visual observations as a failure in the tensile face. This is consistent with both results from other studies as well as a general understanding of the low tensile properties of lime mortars. In the projection formed specimens, two separate failure modes were observed and coincide with the two failure zones observed in Figure 3c. Failure below a strain of 0.05 was via expected tensile failure while failure above a strain of 0.05 was observed to be via full depth diagonal cracks. Such diagonal cracks may indicate a shear failure of the material but it is not currently clear why this occurred for these specimens.

The compressive rupture stress, peak flexural stress and thermal conductivity of all the variations of material and loading are presented for comparison in Figure 5. It is broadly apparent that cast material has greater and more consistent mechanical strength despite the similar mixture of constituents and apparently lower compaction. It is thought therefore that inconsistencies in the projection forming process may produce an uneven distribution of binder and thus areas of weakness within the composite. This is supported by observations during production that the flow of hemp and thus mixing ratio fluctuated. In addition it is observed that projection formed material exhibits a greater variance in thermal conductivity between the parallel and perpendicular directions. This greater level of anisotropy, also observed in the compressive rupture strength, is suggestive of a more anisotropic structure.

The orientation analysis of hemp within the internal structure of the specimens is presented in Figure 6. It is observed that in both projection formed and cast material there is an anisotropy in the material's structure that accounts for the anisotropic physical properties. In the case of projection formed hemp-lime specifically, the overall degree of orientation in the perpendicular plane to casting direction is stronger than that for cast material. This verifies the hypothesis that a more orientated structure within projected material manifests in greater anisotropy in the material's properties, Figure 3 and Figure 5. The greater level of orientation in projection formed materials may be linked to the apparent higher compaction of the material implying a greater force however it may also stem from the continuous process applying compaction to each particle as it is placed. More work is required to better understand the mechanics of the projection process.

When considered in a parallel direction, the projection formed material is observed again to show some preference of orientation whereas the cast material does not, Figure 6. This may indicate that the actual direction of casting was not horizontal as assumed; it was noted that the preference of the operator was to generally project the material in a slightly downward direction to aid adhesion and minimise waste. As the direction of projection is controlled by the operator who may alter it around structures and depending on access, it is evident from these results that this may vary the local orientation of the internal structure and thus the performance of the material. Furthermore it can be inferred that the theoretical thermal conductivity of a projection formed wall could be lower than that found in this study, however achieving this may be a practical constraint of the process.

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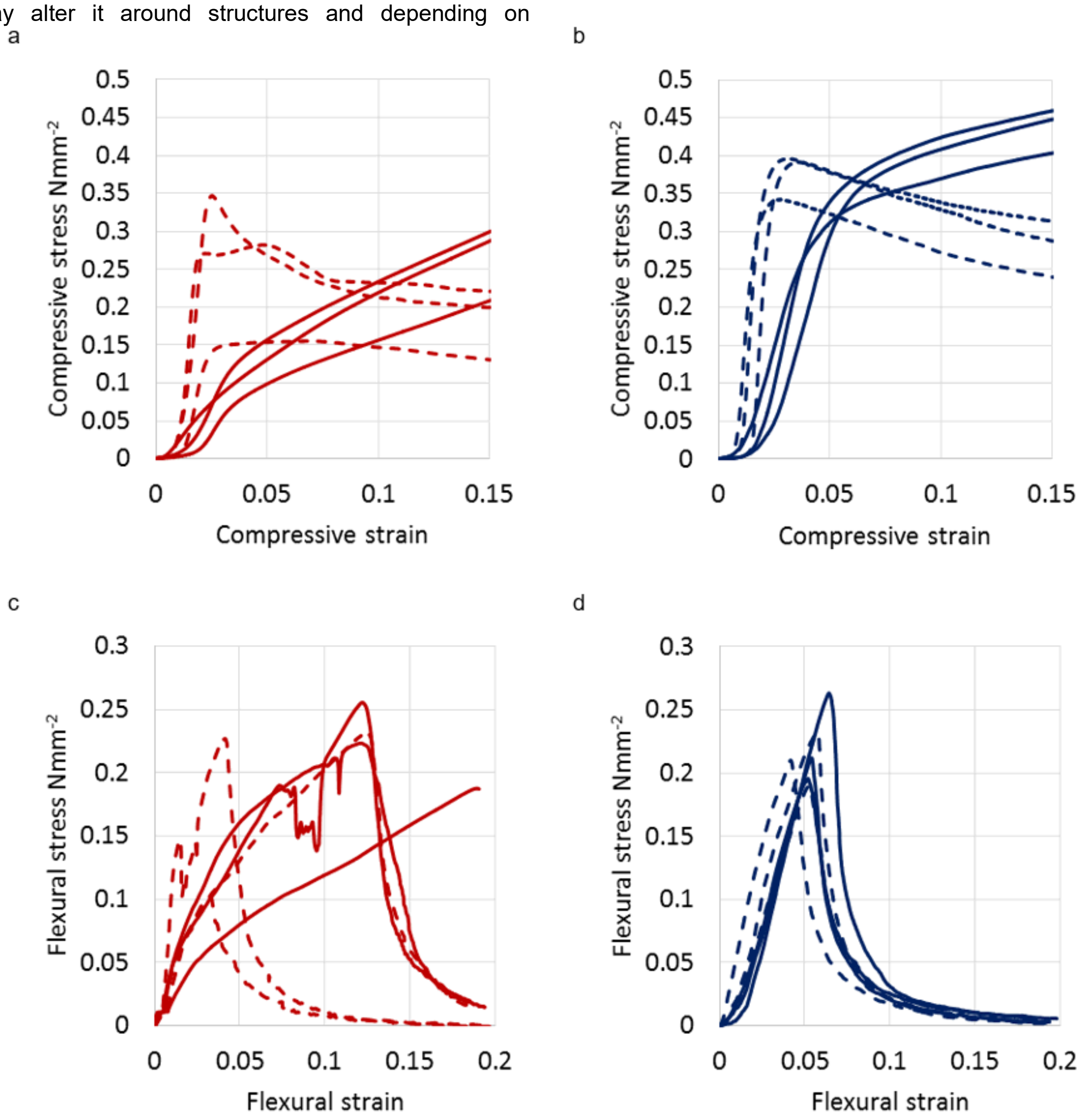

Fig. 3: Compressive and flexural stress/strain plots for hemp lime specimens produced by projection (red, a and c) and casting (blue b and d) with loading applied in the parallel direction (solid line) and perpendicular direction (dashed line).

Fig. 4: Typical compressive failure modes of hemp-lime loaded in the perpendicular and parallel directions, left and right respectively.

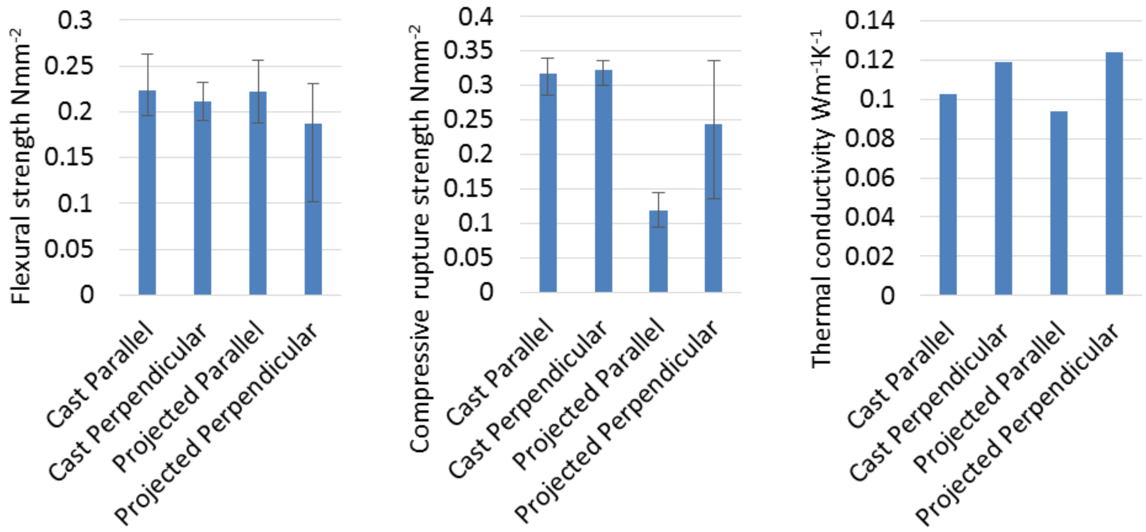

Fig.5: The directional peak flexural strength, compressive rupture strength and thermal conductivity of projection formed and cast hemp-lime.

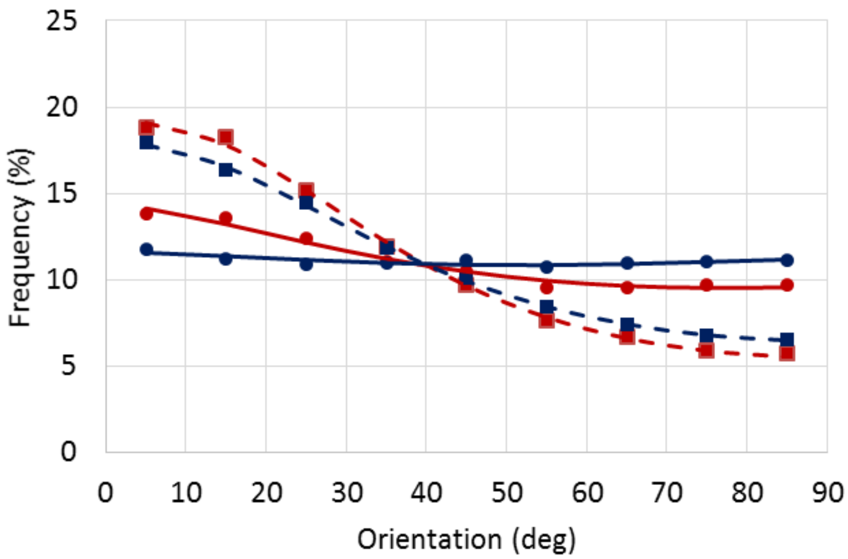

Fig. 6: The frequency distribution of hemp particles in planes viewed in the parallel (solid line) and perpendicular (dotted line) directions, and formed by projection (red) and casting (blue).

3.2 Theoretical

The experimental results identify differences in the parallel and perpendicular behaviour of hemp-lime formed by projection and casting respectively. In order to compare more real world performance however the orientation of the in-situ material must be considered. The three cases identified: cast vertically, cast horizontally and projected horizontally are therefore compared in theoretical wall sections with equivalent thermal conductivity.

In order to estimate an approximate embodied energy of the wall sections in a simple way, data has been used from previous literature, (Table 2). The following assumptions are made for the assessment: the embodied energy of the binder can be taken as that of lime; the embodied energy of hemp that is taken from French data is applicable to an unspecified location; that there is no associated transportation energy for theoretical cases and that the material wastage of the processes are 5% and 10% for cast and projected material respectively based on practitioner observations. The performance data for the theoretical wall sections are presented in Table 3.

It can be seen from Table 3 that the thickness of wall required for onsite casting to have equivalent thermal performance is much higher than that of offsite casting or projection forming. This is attributable to the unfavourable direction of heat transfer compared to the orientation of material structure in this case. The projection formed wall is found to have the lowest thickness and consequently embodied energy however it represents only a small energy saving over offsite casting due to a higher density as well as the more energy intensive process. The offsite cast wall is found to have a lower embodied energy than the onsite cast wall by virtue of being thinner but accordingly lower mechanical capacity via the same reasoning; in the case of projection formed material, the low structural capacity can again be attributed to the width of wall but also the material's intrinsically lower mechanical properties, Figure 5.

For a given thermal requirement it may be inferred that projection formed material may afford the thinnest wall section and lowest embodied energy but a reduced mechanical performance making it well suited to retrofit applications. Onsite cast material will give the best mechanical properties, however as the material is rarely required to resist loading it may not offer other advantages. Horizontally pre-cast material gives a good compromise of wall thickness, embodied energy and mechanical performance and so can be considered to have definite additional advantages over traditional onsite cast material.

Tab. 3: The properties of thermally equivalent wall sections produced by three methods of production

	U-value	Thickness (m)	Ultimate vertical compressive capacity (KN)	Ultimate horizontal flexural capacity (KNm)	Embodied energy (MJ)
Onsite casting: cast vertically	0.300	0.397	126	2.77	586
Offsite casting: cast horizontally	0.300	0.343	111	2.19	506
Onsite projection: projected horizontally	0.300	0.312	76.3	1.81	502

4 CONCLUSION

The experimental aspects of this paper have established that there is a distinct anisotropy in physical properties of both cast and projection formed hemp-lime brought about by an orientated internal structure. This orientation was found to be greatest in projection formed material which afforded it a lower transverse thermal conductivity than cast material despite being of greater density. The mechanical performance of projection formed material was in general found to be lower than that of cast material and was attributed to a less even distribution of the binder within the composite. The results highlight that in order to compare hemp-lime in a meaningful way, the in-situ orientation of the material must be considered.

A theoretical assessment of wall sections that are representative of how material would be produced by three established construction methods: onsite casting, offsite horizontal casting, and projection forming was undertaken. The results identified that projection forming produced the thinnest wall section to deliver a designed level of thermal conductivity, however this was at the cost of reduced loading capacity. This formation method therefore may be considered to be especially suited to retrofitting projects where thickness may be a limiting factor. Offsite cast material was found to have similar mechanical performance to onsite cast material but improved thermal performance due to its orientation,. This method therefore, as well as possible inherent logistical benefits, offers performance benefits over onsite cast material and it is important for this to be considered in specification of material.

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