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Acoustic absorption of hemp-lime construction

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ABSTRACT

Hemp-lime concrete is a sustainable alternative to standard wall construction materials. It boasts excellent hygrothermal properties in part deriving from its porous structure. This paper investigates the acoustic properties of hemp-lime concrete, using binders developed from hydrated lime and pozzolans as well as hydraulic and cementicious binders. To assess the acoustic absorption of hemp-lime walls, as they are commonly finished in practical construction, wall sections are rendered and the resulting impact on absorption is evaluated. Hemp-concretes with lime-pozzolan binders display superior acoustic properties relative to more hydraulic binders. These are diminished when rendered, as the open surface porosity is affected, however hemp-lime construction offers the potential to meet standard and guideline targets for spaces requiring acoustic treatment.

KEYWORDS

Acoustic sound absorption, hemp lime pozzolan concrete, porous materials, sustainability

1 INTRODUCTION

Contemporary building materials and constructions are expected to fulfil a range of functions. As well as having structural integrity, they should insulate from heat loss, weather and noise, manage moisture transport and ensure air tightness. Achieving these functions with materials of low environmental impact aids the effort to cut energy consumption associated with the construction of buildings. In contemporary constructions almost each functional requirement of the facade is fulfilled by a specific layer (e.g. rainscreen, insulation, air and vapour membranes) in the wall buildup. Bio-aggregate based materials offer possible solutions to many of these challenges, in a monolithic construction. An increasing number of performance characterisation studies focussed on bio-aggregate based materials (e.g straw, cork, flax, coconut) is enabling greater confidence in these materials as alternatives to standard construction materials, and more research is needed to ensure their wider usage [1][2].

Hemp based concrete is a bio-aggregate based construction material that enables low energy buildings both in construction and in use [3]. Hemp-based panels have already been investigated as sound-absorbing insulation panels [4], and the use of hemp concretes may offer advantageous acoustic performance compared to traditional concretes. Despite the dubiousness of some of the wilder claims about hemp (*e.g.* ‘hemp crops require virtually no chemicals’, [5]), hemp based concrete offers significant environmental advantages over traditional aggregates. Hemp’s ability to sequester CO_2 during its lifetime to more than offset the CO_2 generated during manufacturing, transport and construction [6], makes it a particularly promising material in the efforts to reduce CO_2 emissions and embodied energy associated with the development of building materials. Accurate and fair assessments of the embodied energy in any building product are difficult to make owing to the influence of various site and manufacturing route specific factors, such as the source of primary energy used in the production process and the transport distances involved. However, it is clear that hemp has a significant advantage over many traditional building materials due to the carbon sequestration that occurs during plant growth [7][8][9]. A commonly-cited estimate of the embodied energy in a hemp concrete wall is a study by Boutin et al [6]. A detailed study of the embodied energy involved in conventional concrete construction was carried out by Goggins et al [10]. Despite the caveats that apply to estimates of the embodied energy and greenhouse gas potential of construction materials, there appear to be significant environmental advantages to the use of hemp based products over traditional cement and hard aggregate concretes. There are also significant drawbacks to hemp as a construction material, notably its low strength and stiffness by comparison with traditional concrete. Its comparatively poor structural properties mean that the use of hemp as a main constituent of high rise and/or long span buildings is unlikely, but it offers many advantages when used in low rise domestic construction. A further key difference between hemp products and stone aggregate concretes is the hygroscopic nature of hemp; while this can have both positive and negative effects, it necessitates the use of alternative techniques and materials, which may present a challenge for widespread adoption – an example is the use of lime binders rather than cement-based binders.

The use of a lime-pozzolan binder mix, in lieu of cement, increases the sustainability further; pozzolans and materials with pozzolanic properties include metakaolin and ground granulated blast furnace slag (GGBS) respectively. Lime (CaO) has a lower firing temperature than cement [11] and hydrated lime (CL90: $Ca(OH)_2$) absorbs CO_2 when hardening through carbonation. Metakaolin ($Al_2Si_2O_7$) is a pozzolanic material, obtained by the calcination of kaolinitic clay, that can enhance the mechanical and durability properties of mortar and concrete [12]. Metakaolin is processed with less energy intensity than cement [13]. GGBS is a by-product of iron and steel manufacture and has long been used with Portland cement (PC) in concrete [14]. Although not a true pozzolan, its suitability as a binder constituent with lime is well established [15]. Hemp concrete with lime-pozzolan binders has demonstrated thermal [16], mechanical [17], durability [17] and moisture transport [18] qualities, and constructed hemp concrete buildings perform well [3][19].

A less emphasised role of walls, is the dissipation of noise produced in the spaces they envelop. Designing for acoustic performance is often an appendum to projects, achieved in post-occupancy by attaching noise absorbing panels to surfaces. Exposure to high levels of noise constitutes a risk to health and well-being [20], and has been related to a range of negative emotions [21][22] and cardiovascular disease [23]. The architectural tendency toward open-plan space, an increase in the specification of glass, smooth and polished hard surface finishes, has exacerbated the problem, with noise discomfort commonly reported in post-occupancy evaluations of buildings [24][25]. Designing for good acoustic performance is particularly pertinent in schools [26][27], where high background noise levels lead to reduced memory, attention span and motivation [28]. Construction methods and building materials that exhibit inherently good sound dissipation properties can offer solutions in environments where excess and reverberated noise is a nuisance such as classrooms [26][27].

Sound absorption coefficients (α) measured in the range 0 to 1 are commonly as low as α=0.04-0.08 for smooth concrete or rendered wall surfaces [29]. A wide range of alternative concretes have been investigated for their acoustic performance, including porous [30] and aerated [31] concretes, and concretes containing crumb rubber [32] and vegetal materials [33] including hemp [34]. All these materials benefit from having a porous structure that enables sound absorption within the material's pores where the sound wave is dissipated via conversion to heat [35]. Hemp-lime composites are characterised by high porosity in the range of 70-80% [36]. Pores of different scales exist including macropores or inter-particle pores between the particles of hemp shiv, mesopores (intra-particle) within shiv and binder and micropores in the binder. Extensive research by the group of Gle, Gourdan and Arnaud has characterised the acoustic advantages, enabled by the porous nature of hemp composites through experimental [34] and modelling [37] investigations. Initially Cezero [38] investigated the impact of binder to shiv ratio showing a significant reduction in sound absorption with increasing binder content. Gle et al. [34][39] investigated the parameters of fabrication including density, particle size distribution, type of binder and water content on the acoustic properties of hemp concrete, with hydraulic and cementicious binders. In the low frequency range, up to 500Hz, hemp concretes were shown to exhibit sound absorption coefficients of 0.2 to 0.5 depending on binder type, with the quick cement binder displaying significantly lower sound absorption capabilities than hydraulic lime binders [34]. Both loose hemp shiv, and hemp-lime concrete, contain pores of multiple scales, varied descriptions of which are incorporated in developed models [34][37].

These acoustic studies have focused on the characterisation of loose hemp shiv or the bulk hemp-lime concrete. However, hemp-lime concrete does not have the necessary surface finish or durability of architectural walls and is often rendered with a lime or lime-hemp binder [3]. These renders ensure the maintenance of the moisture transport advantages of hemp-lime construction [11]. Hemp-lime renders can retain relatively high porosity (52.9% [8]); however, the skim finish results in the closing of surface pores. A smooth or reflective finish significantly affects the sound absorption characteristics of the construction material as exemplified by the wide variance between fair-faced and painted concrete block [41]. With respect to hemp-lime concrete, the addition of excess water during fabrication can result in a binder layer forming close to the wall or sample moulding, resulting in a smooth and closed surface that greatly reduces sound absorption [42].

This paper reports the sound absorption characteristics of rendered and unrendered hemp concrete walls made with lime-pozzolan binders, and compares them with hydraulic and cementitious binders. Hemp-lime construction is assessed with reference to acoustic design guidelines for spaces warranting of attentive acoustic treatment.

2 METHODS

Acoustic absorption was tested on hemp lime wall sections in a laboratory with minimal background noise. Details of the materials and testing procedure are outlined below. The methodology developed by Grimes et. al. (2013) and validated for the in situ measurement of the sound absorption characteristics of building fabrics was used [41]. The procedure adapts ISO standards ISO 10534-2:2001 [43] and ISO 13472-2:2010 [44] enabling in situ testing of constructed walls.

2.1 MATERIALS

2.1.1 HEMP

Hemp varies with climate and harvest conditions amongst other factors [45]. The hemp shiv used in this study is grown in Central France and supplied by La Chanvrière de l’Aube and hence has a growth cycle consistent with those from other hemp concrete acoustic evaluation studies [34]. Given the significance of particle size on inter-pore structure [39] the particle size distribution is evaluated for a sample of hemp used enabling confidence in comparison with these previous studies. The particle size distribution for a sample of hemp is listed in Table 1 and the three primary sizes shown in Figure 1. The hemp shiv aggregate was mixed with six different binders as described in Table 3.

Hemp composite walls were cast in timber shuttering, in panels 1 m by 1 m and 300 mm in thickness. The panels were allowed to cure outside for 1 year with protective covering at 16°C ± 4°C and relative humidity 50% ± 15% as outlined in previous work [16]. This was followed by 12 months at room temperature in the laboratory prior to acoustic testing. Replicating common hemp concrete construction methods, the walls were tamped in plywood shuttering by an experienced practitioner who ensured consistent workability across all hemp-lime concretes. Methods and testing, for example workability measurement tests, are as yet ill-defined for hemp-lime and hence experience is relied upon as recommended by other authors [16][46]. Although the mechanical properties of hemp concretes have been shown to exhibit variability, and to vary according to the dryness of the sample [47][48], this effect is not seen for the acoustic properties: changes in sound absorption properties are not significantly affected by moisture content [49]. Consequently, the hemp was allowed to dry naturally; acoustic testing of the panels was undertaken 24 months after casting when the natural drying process had reduced the material density to levels documented in Table 3.

Table 1. Particle size distribution

Particle Length (mm)	Mass (g)	% quantity	% by mass
Small (≤ 4mm)	0.8	50	17.02
Medium (≤ 8mm)	1.2	28	25.53
Large (> 9mm)	2.7	22	57.45

Figure 1. Three sizes of hemp particles.

2.1.2 *BINDERS*

Six different binders were used for these experiments; they are outlined in Table 3. A hydrated lime (CL90) and a hydraulic lime NHL 3.5 complying with EN 459-1 [50] were used. For comparison purposes, a binder including Portland cement (CEM I) complying with EN197-1:2011 [51] was also used. This binder is a standard, cement-lime, hemp concrete binder typically used on site - termed 'builder's mix' (BM) in this paper. Similarly for comparison, a proprietary commercial mix (CM in Table 3) with significant hydraulic content, specifically developed for use with hemp is evaluated.

Four hemp concrete walls include pozzolans (Table 3). Two pozzolans – metakaolin (M) and GGBS (G) – were identified as having potential for use in hemp-lime concrete on account of their fast setting and high reactivity [52]. The chemical composition of the pozzolans, assessed through spectroscopy as previously outlined [16], are given in Table 2. The pozzolans' chemical composition, amorphousness and surface area are described in other work [17]. Two other hemp concrete walls (M+WR, G+WR) include a water retainer, methyl celulose, to retain water in the binder and reduce the water absorbed by the hemp [53].

Table 2 Chemical composition of GGBS and Metakaolin [16]

Composition	GGBS (%)	Metakaolin (%)
CaO	39.27	--
SiO_2	34.14	51.37
Al_2O_3	13.85	45.26
Fe_2O_3	0.41	0.52
SO_3	2.43	--
MgO	8.63	0.55

2.1.3 HEMP CONCRETE

Six hemp concrete walls with each of the six binder compositions as outlined in Table 3 are tested. Each wall in the sample set can be segregated into two distinct sets; those including cement and hydraulic lime (BM, CM) and those comprising hydrated lime and pozzolan binders (G, M, G+WR, M+WR). SEM images of selected samples are shown in Figure 2.

Table 3. Composition and properties of hemp concrete walls.

Wall Composition	Specimen Notation	Binder composition (% by weight)	Binder: Hemp: Water (by weight)	Density (kg/m^3)
Hemp concrete including hydraulic binders	BM (Builder's Mix)	70% CL90s, 20% NHL3.5, 10% CEM I	2:1:2.9	573
	CM (Commercial Mix)	100% commercial binder	2:1:3.1	583

Hemp concrete made with hydrated lime and pozzolans	G (GGBS)	70% CL90s, 30% GGBS	2:1:3.3	505
	M (Metakaolin)	80% CL90s, 20% metakaolin	2:1:3.1	493
	G+WR (GGBS and water retainer)	70% CL90s, 30% GGBS, 0.5% methyl cellulose	2:1:3.1	522
	M+WR (Metakaolin and water retainer)	80% CL90s, 20% GGBS, 0.5% methyl cellulose	2:1:3.1	469

The density of the concretes bound with hydraulic lime and cement binders (BM, CM) were consistently higher than the densities of samples bound with hydrated lime and pozzolan binders. The porosity was measured by water displacement pycnometry [52], on samples of each mix cast contemporaneously with the panels. The porosity for all the samples was 72%±2%. SEM analysis of the hemp-concrete [17] evidenced their pore structure. Significant hydrates filling pores are evident in the concretes with hydraulic and cementicious binders while the lime-pozzolan binders were largely carbonated with infrequent hydrates [16].

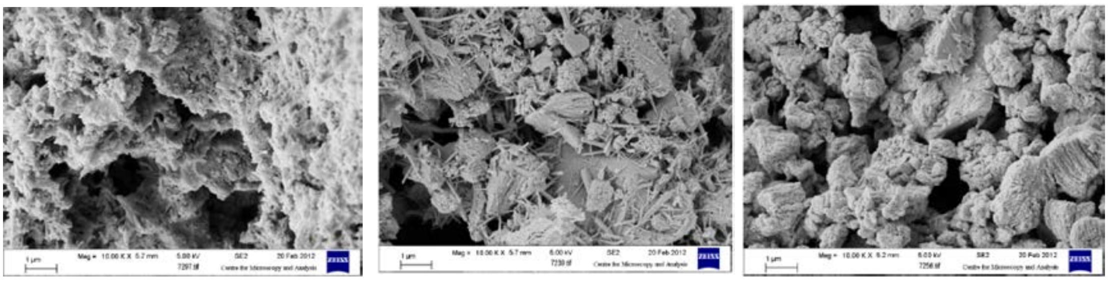

Figure 2. SEM images of (left) BM, (middle) CM, (right) G binder hemp concrete matrices.

2.1.4 Hemp Render

Hemp-lime render mixes have been investigated for the development of a breathable, thermal insulation render for retrofitting [54]. This study investigates renders mixed in two ratios: 2:1 and 1:1.25 (lime to hemp ratio by weight). The former of these is a commonly used mix, and the latter is investigated to assess the impact of a greater proportion of hemp in the mix. 10 and 20mm renders were applied to the hemp lime concrete wall containing hydrated lime, metakaolin and methyl cellulose (M+WR in Table 3) and the sound performance tested.

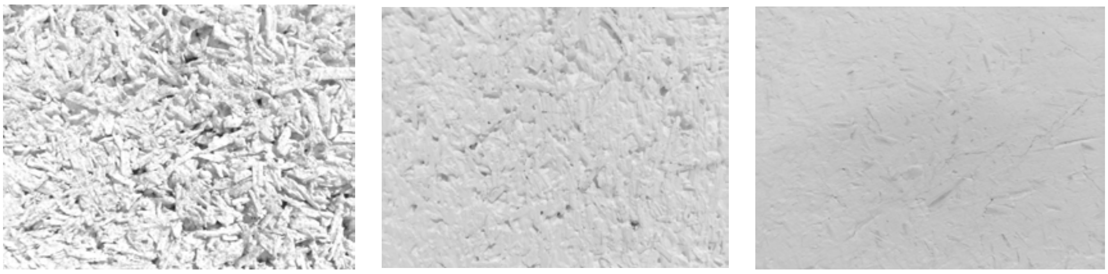

Figure 3. Surface finishes of (left) unfinished hemp-lime concrete, (middle) 1:1.25 lime-hemp render, (right) 2:1 lime-hemp render.

2.2 IMPEDANCE TUBE TESTING

An impedance tube with 70mm diameter is tightly contacted to the wall surface. A white noise signal is generated using a B&K 1405 noise generator, amplified and transmitted through a speaker down the length of impedance tube.

Tests were undertaken at the centre point and repeated in multiple locations in a 300mm radius around the centre. An average value was taken across six tests. For each panel the standard deviation between tests was less than 5%. Acoustic absorption coefficients were calculated in the frequency range 332Hz up to 2865Hz with cut-off frequencies defined in the standards [43] and literature [55], for the distance between the microphones (43mm) and length of tube (963mm). In the BB93 guideline document for acoustics in schools, published by the BRE [26], the reverberation time criteria are set in terms of the average value of the three octave bands, 500 Hz, 1 kHz, and 2 kHz, denoted as mid frequency reverberation time T_{mf}.

3 RESULTS

The acoustic characteristics of hemp-lime concrete were discerned through analysis of the absorption profile across the range of frequencies up to 2500Hz. Results for loose hemp shiv, unrendered and rendered hemp-lime concrete walls are discussed in the context of material density and porosity.

3.1 ACOUSTIC CHARACTERISATION OF LOOSE HEMP

The absorption characteristics are tested on loose hemp, without binder for different levels of compaction and depth of shiv and various sizes of particles similar to the study of Gle et al. [34].

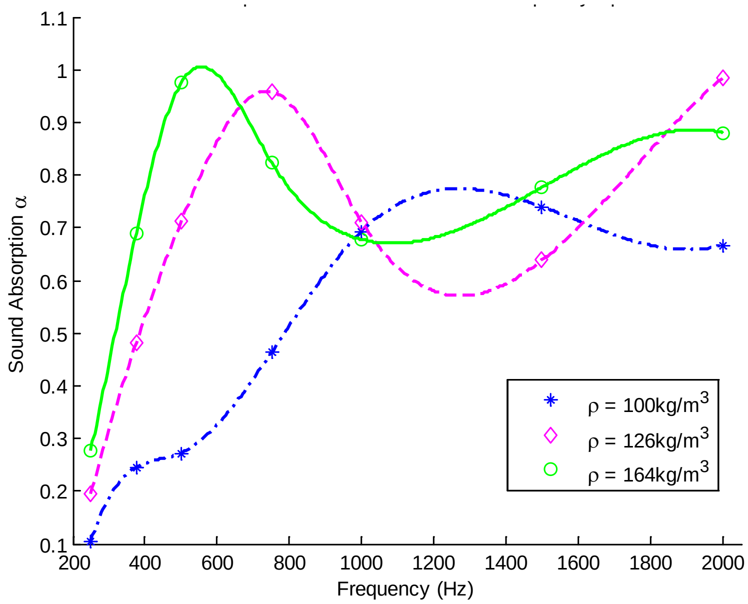

Figure 4. Sound absoption characteristics of loose hemp shiv, for different levels of compaction.

Owing to the porous nature of the loose hemp, sound absorption is high across the range of frequencies, similar to other unbonded bio-based materials [56]. A peak in the 400-600 Hz range is observed as previously reported [34].

Similarly, increasing the depth of shiv shifts the absorption curve to the lower frequencies. However, changing the degree of compaction of loose shiv has the greatest effect on the sound absorption profile across the range of frequencies. Compaction changes the pore size distribution and shifts the acoustic absorption curve, including first and second peaks, toward the low frequencies enhancing the amplitude of the first peak as is shown in Figure 4.

3.2 ACOUSTIC CHARACTERISATION OF HEMP-LIME CONCRETES

Table 4 documents the sound absorption coefficient at the 1/3 octave frequencies 500Hz, 1000Hz and 2000Hz, for all six hemp concretes. The sound absorption frequency in the range 400-2000Hz is plotted in Figure 5.

Table 4. Sound absorption coefficients of unrendered hemp-lime concrete walls with various binders.

Binder	***ρ (kg/m³)***	**α: 500 Hz**	**α: 1K Hz**	**α: 2K Hz**
Builders mix (BM)	*573*	0.32	0.24	0.26
Commercial mix (CM)	*583*	0.45	0.37	0.39
GGBS (G)	*505*	0.49	0.42	0.44
Metakaolin (M)	*493*	0.46	0.39	0.44
GGBS & water retainer (G+WR)	*522*	0.52	0.45	0.53
Metakaolin & water retainer (M+WR)	*469*	0.42	0.37	0.41

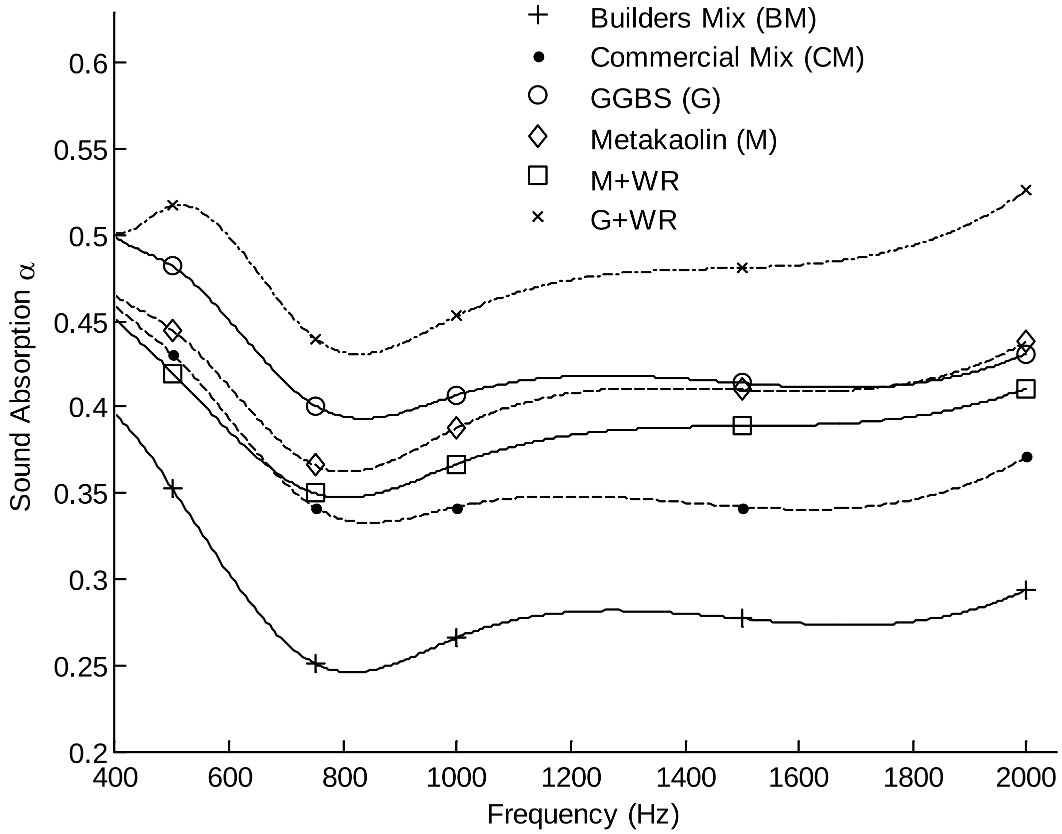

Figure 5. Sound absorption of hemp-lime concrete walls with different binders in the range 500-2000Hz.

The hemp with BM binder, which includes 10% portland cement, has the lowest sound absorption across all frequencies. The hydraulic lime commercial binder (CM) is also lower than both lime-pozzolan binders which exhibit similar characteristic profiles. The densities of the lime-pozzolan concretes are lower, implying an inverse relationship between sound absorption and hemp concrete density. Absorption coefficients for all samples are higher in the low frequencies, dip at approximately 750Hz and reach almost constant values in the 1000-2000Hz range. Density and open porosity are inversely related [37], and this could explain the higher sound absorption coefficients exhibited by the pozzolanic binders across the range of frequencies.

3.3 ACOUSTIC CHARACTERISATION OF RENDERED HEMP-LIME CONCRETE

The change in the acoustic absorption characteristic of hemp-lime concrete walls, when rendered with 10 and 20 mm hemp-lime renders, is documented in Table 5, for 2 different render mixes. The absorption coefficients for the unrendered metakaolin with water retainer (M+WR) bound hemp concrete are plotted in Figure 6. For clarity only the walls with the 10 mm renders are plotted.

Table 5. Sound absorption coefficients of rendered hemp-lime concrete walls.

Binder	α: 500 Hz	α: 1 kHz	α: 2 kHz
Unrendered Control Wall (M+WR)	0.42	0.37	0.41
10mm Hemp-Lime Render 1.25:1	0.31	0.18	0.18
10mm Hemp-Lime Render 1:2	0.28	0.17	0.22
20mm Hemp-Lime Render 1.25:1	0.29	0.16	0.18
20mm Hemp-Lime Render 1:2	0.28	0.15	0.19

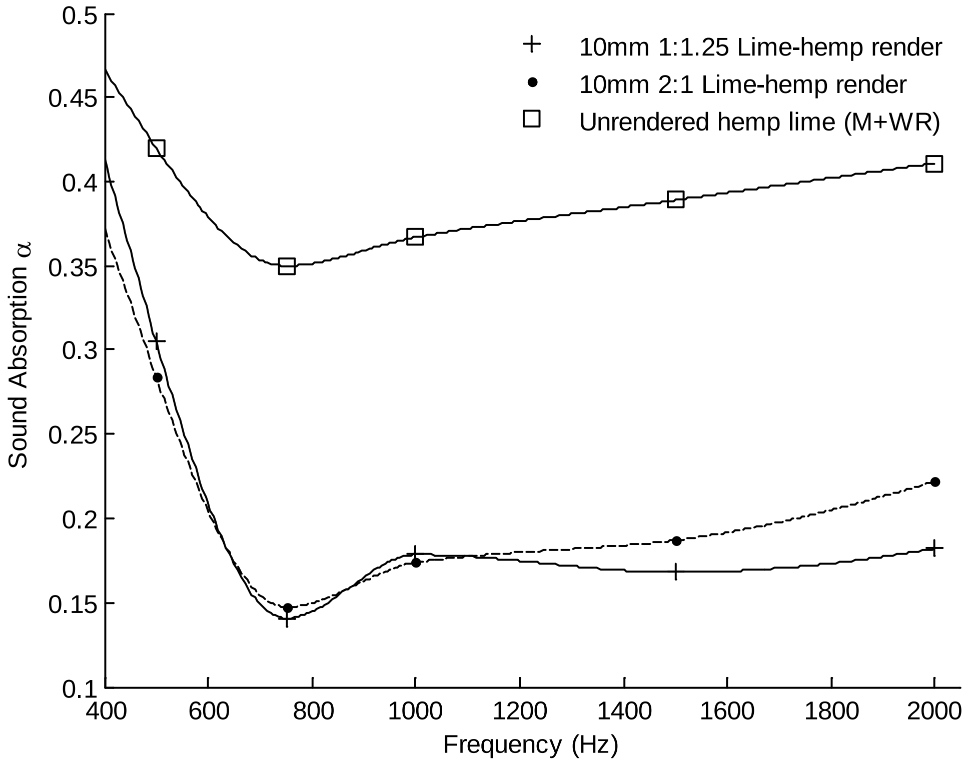

Figure 6. Sound absorption of rendered hemp-lime concrete walls in the range 500-2000Hz.

The sound absorption coefficient is reduced consistently across the range of frequencies examined: over 50% at the majority of frequencies. The 20 mm render (Table 5) produced a slight further reduction in acoustic absorption capability of the hemp-lime walls.

4 MODELLING

Table 6: Table of nomenclature

Symbol	Meaning
α	Absorbance coefficient
α_∞	High frequency tortuosity
Φ	Porosity
ρ	Bulk density
ρ_f	Fibre density
ρ_0	Air density
ρ_{eq}	Equivalent density
ω	Angular frequency
σ	Airflow resistivity
T	Ratio between the first and zeroth order Bessel functions of the first type
γ	Ratio of specific heat capacities for air (with respect to pressure and volume)
P_0	Mean air pressure
k	Wavenumber
K_{eq}	Equivalent stiffness
l	Sample thickness
s	Shape factor
Z	Sample surface impedance
Z_0	Impedance of air
Z_C	Characteristic impedance of the sample

4.1 MODELLING OF HEMP SHIV

Developing a predictive model for the absorbance of media with multi-scale porosity remains a topic of current research. Models for the sound absorption of porous media often use airflow resistance and tortuosity as the model inputs [5]. In [26] Gle et. al. apply the model suggested by Allard et. al. [46] to calculate the absorbance from the porosity and resistivity, and report good agreement between that model and experimental results for loose hemp shiv. The present work follows this approach, using the relationships developed by Gle et al. between density, porosity and resistivity to produce predictions of the absorbance coefficient of loose hemp shiv. The porosity is calculated from the measured densities as:

$$\Phi = 1 - \frac{\rho}{\rho_f}$$

The airflow resistivities are extrapolated from the results from Gle et al. relating density to resistivity, as shown in Figure 7.

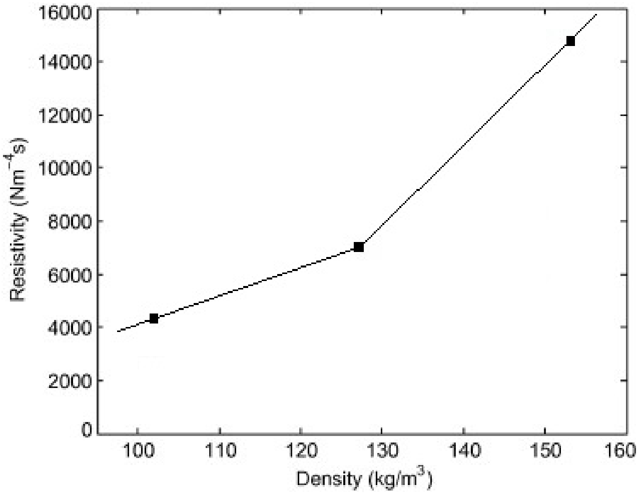

Figure 7 Relationship between density and airflow resistivity from Gle et al. (linear extrapolation lines added).

Both the porosity and resistivity depend more strongly on the degree of compaction than they do on the properties of individual particles. From these relationships, the model parameters for the present shiv samples are shown in Table 7.

Table 7. Calculated porosities for a fibre density of 1083 kg/m^3

Sample	**Density kg / m^3**	**Porosity %**	**Resistivity**
Loose	100	91	4000
Medium	126	88	6600
Dense	164	85	18600

This allows the prediction of the absorbance based on the Allard-Biot model as presented by Gle et al. The high-frequency tortuosity is left as a fitting parameter to be determined. The model is a model for the absorbance coefficient based on the equivalent density and stiffness.

$$\alpha = 1 - \left|\frac{Z - Z_0}{Z + Z_0}\right|^2 \qquad (1)$$

With Z and Z_C calculated as follows:

$$\rho_{eq} = \frac{\rho_0 \alpha_\infty}{\phi} - \frac{i\sigma}{\omega} F(\lambda) \qquad (2)$$

$$F(\lambda) = \frac{-\lambda\sqrt{i}T(\lambda\sqrt{i})}{4 - 8\dfrac{T(\lambda\sqrt{i})}{\lambda\sqrt{i}}} \qquad (3)$$

$$K_{eq} = \frac{\gamma P_0}{\phi}\left(1 + 2(\gamma - 1)\frac{T\left(\lambda\sqrt{iN_{Pr}}\right)}{\lambda\sqrt{iN_{Pr}}}\right)^{-1} \qquad (4)$$

$$\lambda = \sqrt{\frac{8s^2\alpha_\infty\rho_0\omega}{\sigma\phi}} \qquad (5)$$

$$Z_c = \sqrt{\rho_{eq}K_{eq}} \qquad (6)$$

$$k = \omega \sqrt{\frac{\rho_{eq}}{K_{eq}}} \qquad (7)$$

$$Z = -i\, Z_c \cot(kl) \qquad (8)$$

This allows the absorption coefficient to be calculated as shown in Equation 1.

Gle et al. present the graph shown in Figure 8 for a particular sample of loose shiv. Predictions of the absorption for the medium-compaction shiv in the present test are shown in Figure 9 with $\alpha_\infty = 2.3$. This is the high-frequency tortuosity found by Gle et. al.; however, the model provides a much better match to the present data using $\alpha_\infty = 4$ (also shown in Figure 9).

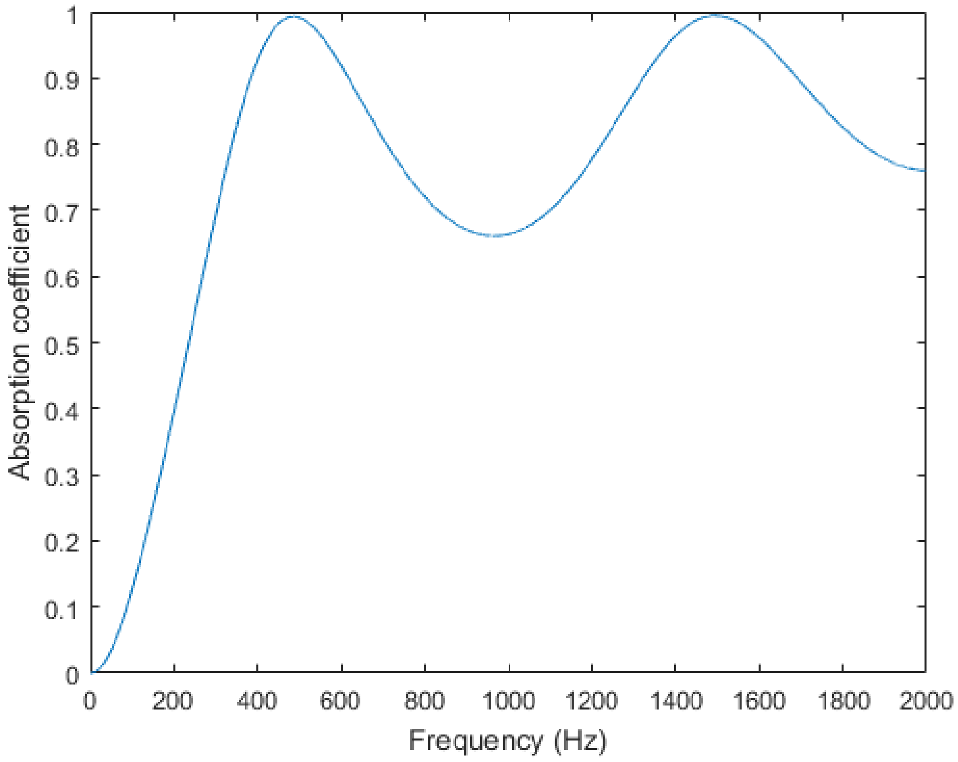

Figure 8 Absorbance of a sample of loose shiv, from Gle et al.

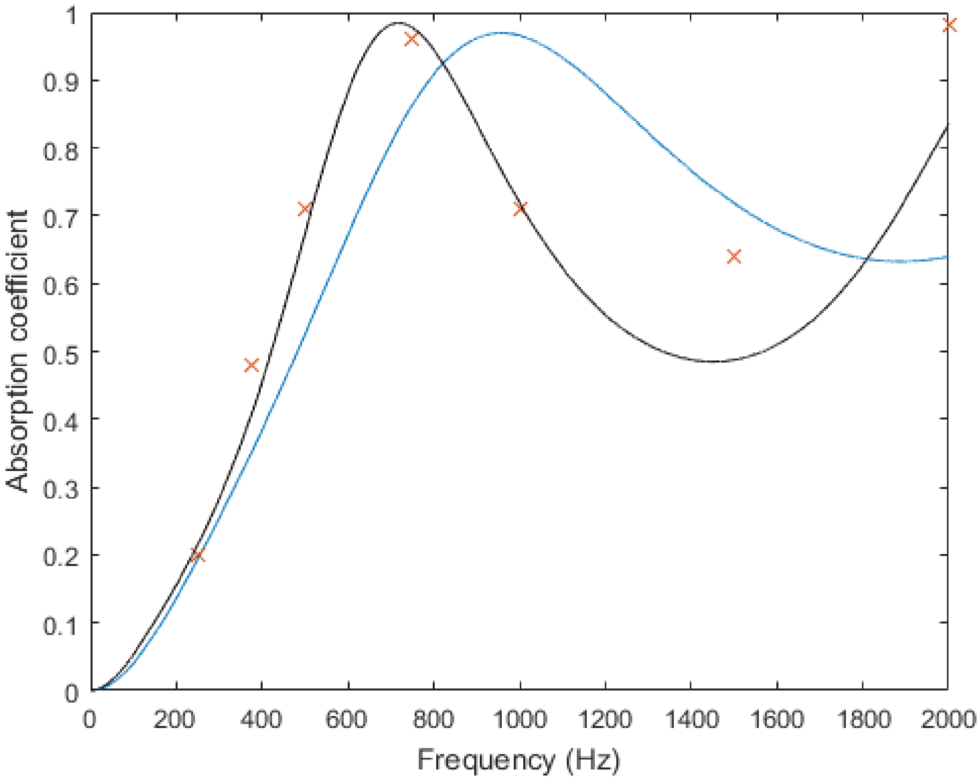

Figure 9 Predicted absorbance for $\alpha_\infty = 2.3$ (blue) and $\alpha_\infty = 4$ (black) with experimental results (red) for medium-density loose shiv.

A similar process is used for each loose shiv sample. The results from the low and high density shives, with the respective model parameters, are plotted in Figure 10.

The parameters used for this figure, and those that follow, are given below:

Φ	As measured (Table 4)
ρ_0	1.2 kg/m^3
σ	25 kN m^{-4} s
γ	1.4
P_0	101 kPa
l	0.3 m
s	1

Z_0	400 Pa s/m

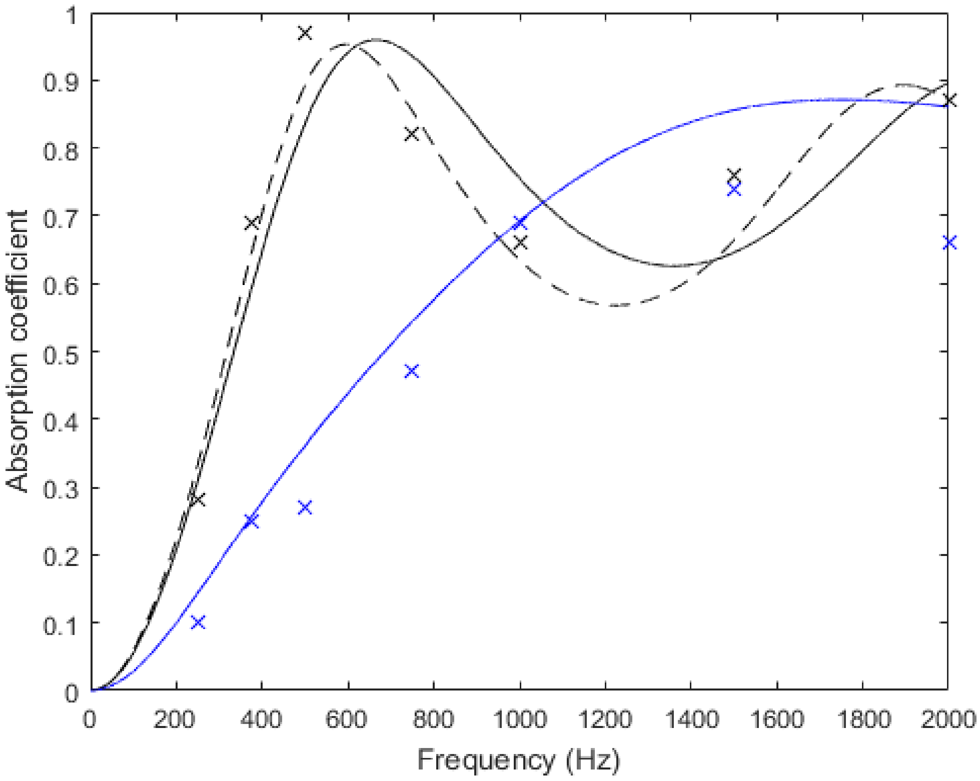

Figure 10 Low-density shiv ($\alpha_\infty = 1$, blue) and high-density shiv ($\alpha_\infty = 4$, solid black, and $\alpha_\infty = 5$, dashed black).

The results above suggest a very high value for the tortuosity is needed to in order for the model to fit the data. The work of Jaouen, Boutin and Geindreau suggests a physical upper limit for the high-frequency tortuosity of around 3. Together with the results, this suggests that the present model perhaps does not accurately capture the true multi-scale nature of the porosity, but more work is needed to clarify this. It is possible that the tortuosity is indeed higher when using a mixture of shiv particle sizes, compared to the more uniform distributions used by Gle et. al. (2013, and also in earlier work), although the low-density case would seem to contradict this. It is possible that the greater degree of compaction in the higher-density cases leads to breaking of some hemp particles, a reduction in average size, and hence an increase in tortuosity.

4.2 MODELLING OF HEMP-LIME CONCRETE

The Biot-Allard model, which provides a good model for hemp shiv, has previously been shown to be a poor model of the acoustic behaviour of hemp-lime concretes [34]. Gle et. al. use Johnson's model, which gives a different form for the dynamic density, and find much better agreement with experimental results. However, the present study could not find physically possible values of the parameters for the Johnson model that are in agreement with the experimental results. The results presented by Gle et al for concrete extend only up to 500 Hz; in the present study, in particular, the results for all the concretes tested show a substantial fall in absorption coefficient from 500 to 750 Hz. The Johnson model does not adequately describe the absorption in this frequency range, and further modelling work is required to identify a suitable model for the acoustic behaviour of hemp-lime concretes in this frequency range.

5 DISCUSSION

5.1 ACOUSTIC ABSORPTION OF HEMP-LIME

The hemp concretes investigated exhibit significant sound absorption across the tested frequency range and are characterized by absorption coefficients between 0.24 and 0.53. Hemp concretes with lime binders exhibit significantly higher sound absorption coefficients than binders including cement. The results also showed that hemp concretes with hydrated lime-pozzolan binders have a greater sound absorption than hemp concretes bound with hydraulic binders. This indicates that there is an inverse relationship between sound absorption and hydraulic content. These results align with those of Gle et al. [34], who showed concretes with quick natural cement binders to be significantly less absorptive than hydraulic lime binders in the frequency range up to 500Hz. This indicates that there is an inverse relationship between sound absorption and hydraulic content although this finding may be influenced by density in this study.

Rendering the hemp concrete wall reduced the open surface porosity resulting in a significant reduction in its sound absorption ability. Greater relative reduction in sound absorption is evident in the higher frequencies. Although the two renders examined varied in quantity of hemp relative to lime, no significant variation in sound absorption is observed between both.

It is difficult to directly compare the sound absorption characteristics of different materials, as the absorption coefficient is not a single-valued, intrinsic material property but depends strongly on frequency and material thickness. Nevertheless, hemp-lime concrete displays good sound absorption when compared to other common building materials [41], although it exhibits sound absorption coefficients slightly lower than porous concrete [30] and fair faced concrete block [41]. When compared to the range of sound absorption materials, the unrendered hemp-lime falls into the absorption class D for building materials [57]. It drops into the absorption class E when rendered which is low with respect to commercial sound absorption panels, but high with respect to standard wall types.

Previous work on the acoustic absorption of plant fibres has generally focussed on the properties of the loose fibres or wool-type insulation products, rather than bound or rendered products as in the present study; and results presented are sometimes questionable. A review article by Asdrubali et al [56] uncritically presents implausible results, such as absorption coefficients significantly greater than 1, indicating imprecise measurement aparatus. Although Asdrubali's review has been cited as a reference for absorption coefficients, their paper simply gives a value of 0.6 for the absorption coefficient of hemp (at 500 Hz), when the present study shows significant variation depending on density. Despite the caveats noted, some typical results for porous concrete and a selection of natural materials are shown in Table 8 for comparison purposes. For ease of comparison, this table shows only the NRC values for each material – these are calculated by taking the mean of the absorption coefficients at 500, 1000 and 2000 Hz, rounded to the nearest 0.05.

Table 8. Sound absorption values for a range of materials. (Berardi and Iannace (new ref at end of list) tested a range of thicknesses for some materials and the highest values are quoted here. NRC values for porous concrete are calculated using the value at 1900 Hz rather than 2 kHz.)

Material	NRC	Data source
Unrendered hemp concrete	0.4	Present study
Rendered hemp concrete (mean value)	0.2	Present study
Porous concrete (sample A)	0.6	[30]
Porous concrete (sample B)	0.25	[30]
Hemp	0.25	[58]
Cork	0.2	[58]
Wood fibres	0.5	[58]
Sheep wool	0.55	[58]
Kenaf	0.6	[58]
Coconut	0.65	[58]

5.2 ASSESSMENT OF CONSTRUCTIONS USING HEMP-LIME

Reverberation time (T_R, the time taken for a sound to decay by 60 dB) is a salient criterion in the acoustic design of spaces. Dependent on room geometry and absorption, it is used to describe the rate at which sound decays, and is described by the Sabine formula[51]:

$$T_R = 0.163\, {}^{V}\!/_{A} \qquad (9)$$

where V is the volume of the room, and $A = \alpha_1 S_1 + \alpha_2 S_2 + \alpha_3 S_3 + \ldots$, where $S_{1\text{-}n}$ are the different room surfaces and $\alpha_{1\text{-}n}$ their corresponding sound absorption coefficients.

Given the propensity for smooth, plastered or glazed wall surfaces in contemporary architecture, acoustic absorption of surfaces is often quite low and T_R can be long, affecting intelligibility of speech and clarity of sound. The tendency is often to concentrate sound absorbing materials on the ceiling; however, this can be of limited impact and ignores the multiple reflections between parallel walls in a rectangular floor plan [29]. Also, exploiting the thermal mass of building construction is often key to passive and low energy strategies for indoor climate control of buildings. Night cooling of extensive thermal mass requires exposure of fair-faced concrete including soffits and floors. Hence the energy/climate concept can conflict with the acoustic concept and prohibit extensive cladding of ceilings for acoustic absorption.

Optimum reverberation times differ depending on the space function ranging from 0.4-0.7 s for classrooms, 0.8-1.2 s for theatres and 1.4 s upwards for churches and cathedrals [29], and hemp-lime walls (whether rendered or unrendered) offer potential to reduce reverberation time to that specified in standard and guideline documents. Taking school classrooms as an example, UK guideline documents specify limits for the average value of octave bands at 500 Hz, 1000 Hz and 2000 Hz, denoted T_{mf} [26]]. German guidelines DIN 18041 [27] specify T_R of 0.5-0.7 s for classrooms with room volume 150-250 m^3 as typical. The unrendered hemp-lime walls evaluated in this study can easily achieve these recommended reverberation times for the typical range of classroom volumes. When considering the room volume range 150-250 m^3, and presuming an exposed masonry/concrete floor and soffit (α around 0.1), hemp lime-pozzolan concrete walls (α in Table 3) can enable a

T_{mf} of 0.5-0.6 s with a good distribution of sound absorbing surfaces and no ceiling or wall appendages. However, rendering of the hemp-lime walls reduces the absorption ability significantly (Table 5). When rendered T_{mf} increases to 1.2-1.7 s. Although this reverberation time is much lower than in rendered or painted walled rooms it is outside the required values for classrooms; consequently, acoustic treatment or additional sound absorbing panels will be required to meet guideline values.

5.3 LIMITATIONS OF THE IMPEDANCE TUBE METHOD

There are some limitations associated with the impedance tube method of calculation, principally that measurements are at normal incidence. Although this condition is not commonly satisfied, characteristic impedance of a porous media can be measured with the impedance tube and used to predict acoustic behavior of the material at oblique incidence. The study is also limited to the range of frequencies defined by the dimensions of impedance tube. The low frequency vowel sounds are generally in the 125Hz (men) – 265Hz (children) range. However, recognition of constants and speech formants whose energy is concentrated in the measured frequencies of the speech spectrum, are key for speech intelligibility [26]. Complex computer simulations using geometrical techniques such as ray tracing and the mirror-source method are required to accurately predict the acoustic characteristics of specifically designed spaces and sound environments. However, the acoustic quality of spaces can be approximated using reverberation time estimates (T_{mf}) when acoustic paramaters of construction materials (α) are characterised.

6 CONCLUSIONS

Unrendered hemp concretes exhibit significant acoustic absorption, with average sound absorption of 40-50% of the normal incident signal, across the tested range of frequencies. Hemp concrete with lime-pozzolan binders exhibit superior sound absorption, compared to more hydraulic binders. Within this group GGBS binders appear to have slightly higher absorption coefficients than metakaolin based binders. These results suggest that the chemical composition of the binders has a greater influence on sound absorption than material density or porosity. Current acoustic models of materials of multi-scale porosity provide a good degree of correlation with experimental results for loose hemp particularly at low frequencies. Further work is required to develop an accurate predictive model for the high frequency acoustic behaviour of hemp-lime concrete.

In practice, the addition of a lime render finish to the hemp-lime composite wall presents a durable wall finish without significantly compromising the hygrothermal qualities of the hemp-lime construction. However, when hemp-lime walls are rendered the absorption coefficient reduces significantly. Buildings and rooms built using hemp concrete enable exposure of high sound absorbing surfaces, and hence low reverberation times, with a reduced need for additional acoustic treatment.

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