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# Acoustic absorption of hemp-lime construction

Authors: Oliver Kinnane<sup>1</sup>, Aidan Reilly<sup>1</sup>, John Grimes<sup>2</sup>, Sara Pavia<sup>2</sup> and Rosanne Walker<sup>2</sup>

Affiliations: (1) Department of Architecture, Queen's University, Belfast, Northern Ireland

(2) Department of Civil, Structural and Environmental Engineering, Trinity College Dublin, Ireland

Corresponding author: Aidan Reilly

E. o.kinnane@qub.ac.uk

**T.** +44 (0) 28 9097 4520

A. Dept. of Architecture, David Keir Building, Belfast BT9 5AG , Northern Ireland.

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Prepared by: Kinnane et al.

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**T** +44(0)28 9097 4520

E o.kinnane@qub.ac.uk

# 1 ABSTRACT

2 Hemp-lime concrete is a sustainable alternative to standard wall construction 3 materials. It boasts excellent hygrothermal properties in part deriving from its 4 porous structure. This paper investigates the acoustic properties of hemp-lime 5 concrete, using binders developed from hydrated lime and pozzolans as well as 6 hydraulic and cementicious binders. To assess the acoustic absorption of hemp-lime 7 walls, as they are commonly finished in practical construction, wall sections are 8 rendered and the resulting impact on absorption is evaluated. Hemp-concretes with 9 lime-pozzolan binders display superior acoustic properties relative to more hydraulic 10 binders. These are diminished when rendered, as the open surface porosity is 11 affected, however hemp-lime construction offers the potential to meet standard and 12 guideline targets for spaces requiring acoustic treatment.

# 13 **Keywords**

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

15 sustainability

# 16 **1** INTRODUCTION

17 Contemporary building materials and constructions are expected to fulfil a range of 18 functions. As well as having structural integrity, they should insulate from heat loss, 19 weather and noise, manage moisture transport and ensure air tightness. Achieving 20 these functions with materials of low environmental impact aids the effort to cut 21 energy consumption associated with the construction of buildings. In contemporary 22 constructions almost each functional requirement of the facade is fulfilled by a 23 specific layer (e.g. rainscreen, insulation, air and vapour membranes) in the wall 24 buildup. Bio-aggregate based materials offer possible solutions to many of these 25 challenges, in a monolithic construction. An increasing number of performance 26 characterisation studies focussed on bio-aggregate based materials (e.g straw, cork, flax, coconut) is enabling greater confidence in these materials as alternatives to 27 28 standard construction materials, and more research is needed to ensure their wider 29 usage [1][2].

30 Hemp based concrete is a bio-aggregate based construction material that enables 31 low energy buildings both in construction and in use [3]. Hemp-based panels have 32 already been investigated as sound-absorbing insulation panels [4], and the use of 33 hemp concretes may offer advantageous acoustic performance compared to 34 traditional concretes. Despite the dubiousness of some of the wilder claims about 35 hemp (e.g. 'hemp crops require virtually no chemicals', [5]), hemp based concrete 36 offers significant environmental advantages over traditional aggregates. Hemp's 37 ability to sequester CO<sub>2</sub> during its lifetime to more than offset the CO<sub>2</sub> generated

during manufacturing, transport and construction [6], makes it a particularly 38 39 promising material in the efforts to reduce CO<sub>2</sub> emissions and embodied energy 40 associated with the development of building materials. Accurate and fair 41 assessments of the embodied energy in any building product are difficult to make 42 owing to the influence of various site and manufacturing route specific factors, such 43 as the source of primary energy used in the production process and the transport 44 distances involved. However, it is clear that hemp has a significant advantage over 45 many traditional building materials due to the carbon sequestration that occurs 46 during plant growth [7][8][9]. A commonly-cited estimate of the embodied energy in 47 a hemp concrete wall is a study by Boutin et al [6]. A detailed study of the embodied 48 energy involved in conventional concrete construction was carried out by Goggins et 49 al [10]. Despite the caveats that apply to estimates of the embodied energy and 50 greenhouse gas potential of construction materials, there appear to be significant 51 environmental advantages to the use of hemp based products over traditional 52 cement and hard aggregate concretes. There are also significant drawbacks to hemp 53 as a construction material, notably its low strength and stiffness by comparison with 54 traditional concrete. Its comparatively poor structural properties mean that the use 55 of hemp as a main constituent of high rise and/or long span buildings is unlikely, but 56 it offers many advantages when used in low rise domestic construction. A further 57 key difference between hemp products and stone aggregate concretes is the hygroscopic nature of hemp; while this can have both positive and negative effects, 58 59 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.

62 The use of a lime-pozzolan binder mix, in lieu of cement, increases the sustainability 63 further; pozzolans and materials with pozzolanic properties include metakaolin and 64 ground granulated blast furnace slag (GGBS) respectively. Lime (CaO) has a lower firing temperature than cement [11] and hydrated lime (CL90: Ca(OH)<sub>2</sub>) absorbs CO<sub>2</sub> 65 when hardening through carbonation. Metakaolin  $(Al_2Si_2O_7)$  is a pozzolanic material, 66 67 obtained by the calcination of kaolinitic clay, that can enhance the mechanical and 68 durability properties of mortar and concrete [12]. Metakaolin is processed with less 69 energy intensity than cement [13]. GGBS is a by-product of iron and steel 70 manufacture and has long been used with Portland cement (PC) in concrete [14]. 71 Although not a true pozzolan, its suitability as a binder constituent with lime is well 72 established [15]. Hemp concrete with lime-pozzolan binders has demonstrated 73 thermal [16], mechanical [17], durability [17] and moisture transport [18] qualities, 74 and constructed hemp concrete buildings perform well [3][19].

75 A less emphasised role of walls, is the dissipation of noise produced in the spaces 76 they envelop. Designing for acoustic performance is often an appendum to projects, achieved in post-occupancy by attaching noise absorbing panels to surfaces. 77 78 Exposure to high levels of noise constitutes a risk to health and well-being [20], and 79 has been related to a range of negative emotions [21][22] and cardiovascular disease 80 [23]. The architectural tendency toward open-plan space, an increase in the 81 specification of glass, smooth and polished hard surface finishes, has exacerbated 82 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].

89 Sound absorption coefficients ( $\alpha$ ) measured in the range 0 to 1 are commonly as low as  $\alpha$ =0.04-0.08 for smooth concrete or rendered wall surfaces [29]. A wide range of 90 91 alternative concretes have been investigated for their acoustic performance, 92 including porous [30] and aerated [31] concretes, and concretes containing crumb 93 rubber [32] and vegetal materials [33] including hemp [34]. All these materials 94 benefit from having a porous structure that enables sound absorption within the 95 material's pores where the sound wave is dissipated via conversion to heat [35]. 96 Hemp-lime composites are characterised by high porosity in the range of 70-80% 97 [36]. Pores of different scales exist including macropores or inter-particle pores 98 between the particles of hemp shiv, mesopores (intra-particle) within shiv and 99 binder and micropores in the binder. Extensive research by the group of Gle, 100 Gourdan and Arnaud has characterised the acoustic advantages, enabled by the 101 porous nature of hemp composites through experimental [34] and modelling [37] 102 investigations. Initially Cezero [38] investigated the impact of binder to shiv ratio 103 showing a significant reduction in sound absorption with increasing binder content. 104 Gle et al. [34][39] investigated the parameters of fabrication including density, 105 particle size distribution, type of binder and water content on the acoustic properties

106 of hemp concrete, with hydraulic and cementicious binders. In the low frequency 107 range, up to 500Hz, hemp concretes were shown to exhibit sound absorption 108 coefficients of 0.2 to 0.5 depending on binder type, with the quick cement binder 109 displaying significantly lower sound absorption capabilities than hydraulic lime 110 binders [34]. Both loose hemp shiv, and hemp-lime concrete, contain pores of 111 multiple scales, varied descriptions of which are incorporated in developed models 112 [34][37].

These acoustic studies have focused on the characterisation of loose hemp shiv or 113 the bulk hemp-lime concrete. However, hemp-lime concrete does not have the 114 115 necessary surface finish or durability of architectural walls and is often rendered 116 with a lime or lime-hemp binder [3]. These renders ensure the maintenance of the 117 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 118 closing of surface pores. A smooth or reflective finish significantly affects the sound 119 120 absorption characteristics of the construction material as exemplified by the wide 121 variance between fair-faced and painted concrete block [41]. With respect to hemplime concrete, the addition of excess water during fabrication can result in a binder 122 layer forming close to the wall or sample moulding, resulting in a smooth and closed 123 124 surface that greatly reduces sound absorption [42].

125 This paper reports the sound absorption characteristics of rendered and unrendered 126 hemp concrete walls made with lime-pozzolan binders, and compares them with 127 hydraulic and cementitious binders. Hemp-lime construction is assessed with

reference to acoustic design guidelines for spaces warranting of attentive acoustictreatment.

# 130 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.

137 2.1 MATERIALS

138 2.1.1 HEMP

139 Hemp varies with climate and harvest conditions amongst other factors [45]. The 140 hemp shiv used in this study is grown in Central France and supplied by La 141 Chanvrière de l'Aube and hence has a growth cycle consistent with those from other 142 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 143 sample of hemp used enabling confidence in comparison with these previous 144 145 studies. The particle size distribution for a sample of hemp is listed in Table 1 and the 146 three primary sizes shown in Figure 1. The hemp shiv aggregate was mixed with six 147 different binders as described in Table 3.

148 Hemp composite walls were cast in timber shuttering, in panels 1 m by 1 m and 300 149 mm in thickness. The panels were allowed to cure outside for 1 year with protective covering at  $16^{\circ}C \pm 4^{\circ}C$  and relative humidity  $50\% \pm 15\%$  as outlined in previous work 150 151 [16]. This was followed by 12 months at room temperature in the laboratory prior to 152 acoustic testing. Replicating common hemp concrete construction methods, the 153 walls were tamped in plywood shuttering by an experienced practitioner who 154 ensured consistent workability across all hemp-lime concretes. Methods and testing, 155 for example workability measurement tests, are as yet ill-defined for hemp-lime and 156 hence experience is relied upon as recommended by other authors [16][46]. 157 Although the mechanical properties of hemp concretes have been shown to exhibit 158 variability, and to vary according to the dryness of the sample [47][48], this effect is 159 not seen for the acoustic properties: changes in sound absorption properties are not significantly affected by moisture content [49]. Consequently, the hemp was allowed 160 161 to dry naturally; acoustic testing of the panels was undertaken 24 months after 162 casting when the natural drying process had reduced the material density to levels 163 documented in Table 3.

## 164 Table 1. Particle size distribution

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



166

167 Figure 1. Three sizes of hemp particles.

## 168 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, cementlime, 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

183 binder and reduce the water absorbed by the hemp [53].

Composition	GGBS (%)	Metakaolin (%)
CaO	39.27	
SiO <sub>2</sub>	34.14	51.37
Al <sub>2</sub> O <sub>3</sub>	13.85	45.26
Fe <sub>2</sub> O <sub>3</sub>	0.41	0.52
SO₃	2.43	
MgO	8.63	0.55

184 Table 2 Chemical composition of GGBS and Metakaolin [16]

185 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.

**191** Table 3. Composition and properties of hemp concrete walls.

Wall	Specimen	Binder composition	Binder: Hemp:	Density
Composition	Notation	(% by weight)	Water (by	(kg/m³)
			weight)	
Hemp	BM	70% CL90s, 20% NHL3.5,	2:1:2.9	573
concrete	(Builder's Mix)	10% CEM I		
including	СМ	100% commercial binder	2:1:3.1	583
hydraulic	(Commercial Mix)			
binders				

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

192 The density of the concretes bound with hydraulic lime and cement binders (BM, 193 CM) were consistently higher than the densities of samples bound with hydrated lime and pozzolan binders. The porosity was measured by water displacement 194 195 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 196 [17] evidenced their pore structure. Significant hydrates filling pores are evident in 197 198 the concretes with hydraulic and cementicious binders while the lime-pozzolan 199 binders were largely carbonated with infrequent hydrates [16].



- 200
- 201 Figure 2. SEM images of (left) BM, (middle) CM, (right) G binder hemp concrete matrices.

## 202 2.1.4 HEMP RENDER

203 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.



210

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

213 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

- 224 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  $T_{mf}$ .

# 226 **3 RESULTS**

- 227 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.
- 231 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].





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

238 Owing to the porous nature of the loose hemp, sound absorption is high across the 239 range of frequencies, similar to other unbonded bio-based materials [56]. A peak in 240 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.

247 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.

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

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





The hemp with BM binder, which includes 10% portland cement, has the lowest 262 263 sound absorption across all frequencies. The hydraulic lime commercial binder (CM) 264 is also lower than both lime-pozzolan binders which exhibit similar characteristic 265 profiles. The densities of the lime-pozzolan concretes are lower, implying an inverse 266 relationship between sound absorption and hemp concrete density. Absorption coefficients for all samples are higher in the low frequencies, dip at approximately 267 268 750Hz and reach almost constant values in the 1000-2000Hz range. Density and 269 open porosity are inversely related [37], and this could explain the higher sound

absorption coefficients exhibited by the pozzolanic binders across the range offrequencies.

272 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.

#### 278 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



280 281 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 283 284 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 285 hemp-lime walls. 286

# 287 4 MODELLING

288 Table 6: Table of nomenclature

Symbol	Meaning
α	Absorbance coefficient
α∞	High frequency tortuosity
Φ	Porosity
ρ	Bulk density
$ ho_{f}$	Fibre density
$ ho_0$	Air density
$ ho_{eq}$	Equivalent density
ω	Angular frequency
σ	Airflow resistivity
Т	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)
Po	Mean air pressure
k	Wavenumber
K <sub>eq</sub>	Equivalent stiffness
I	Sample thickness
S	Shape factor
Ζ	Sample surface impedance
Z <sub>0</sub>	Impedance of air
Z <sub>C</sub>	Characteristic impedance of the sample

289

290 4.1 MODELLING OF HEMP SHIV

291 Developing a predictive model for the absorbance of media with multi-scale porosity

292 remains a topic of current research. Models for the sound absorption of porous

293 media often use airflow resistance and tortuosity as the model inputs [5]. In [26] Gle 294 et. al. apply the model suggested by Allard et. al. [46] to calculate the absorbance 295 from the porosity and resistivity, and report good agreement between that model 296 and experimental results for loose hemp shiv. The present work follows this 297 approach, using the relationships developed by Gle et al. between density, porosity 298 and resistivity to produce predictions of the absorbance coefficient of loose hemp 299 shiv. The porosity is calculated from the measured densities as:

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

301 The airflow resistivities are extrapolated from the results from Gle et al. relating302 density to resistivity, as shown in Figure 7.





- than they do on the properties of individual particles. From these relationships, the
- 307 model parameters for the present shiv samples are shown in Table 7.

Sample	Density kg / m³	Porosity %	Resistivity
Loose	100	91	4000
Medium	126	88	6600
Dense	164	85	18600

309

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.

314 
$$\alpha = 1 - \left| \frac{Z - Z_0}{Z + Z_0} \right|^2$$
(1)

315 With Z and Z<sub>c</sub> calculated as follows:

316 
$$\rho_{eq} = \frac{\rho_0 \alpha_{\infty}}{\phi} - \frac{i\sigma}{\omega} F(\lambda)$$
(2)

317 
$$F(\lambda) = \frac{-\lambda\sqrt{i}T(\lambda\sqrt{i})}{4 - 8\frac{T(\lambda\sqrt{i})}{\lambda\sqrt{i}}}$$
(3)

318 
$$K_{eq} = \frac{\gamma P_0}{\phi} \left( 1 + 2(\gamma - 1) \frac{T(\lambda \sqrt{iN_{Pr}})}{\lambda \sqrt{iN_{Pr}}} \right)^{-1}$$
(4)

319 
$$\lambda = \sqrt{\frac{8s^2 \alpha_{\infty} \rho_0 \omega}{\sigma \phi}}$$
(5)

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

321 
$$k = \omega \sqrt{\frac{\rho_{eq}}{K_{eq}}}$$
(7)

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

## 323 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).



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

331





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.

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

Φ	As measured (Table 4)
$ ho_0$	1.2 kg/m <sup>3</sup>
σ	25 kN m <sup>-4</sup> s
γ	1.4
<i>P</i> <sub>0</sub>	101 kPa
1	0.3 m
S	1

 $Z_0$ 





339

340 Figure 10 Low-density shiv ( $\alpha_{\infty} = 1$ , blue) and high-density shiv ( $\alpha_{\infty} = 4$ , solid black, and  $\alpha_{\infty} = 5$ , dashed 341 black).

342 The results above suggest a very high value for the tortuosity is needed to in order 343 for the model to fit the data. The work of Jaouen, Boutin and Geindreau suggests a 344 physical upper limit for the high-frequency tortuosity of around 3. Together with the 345 results, this suggests that the present model perhaps does not accurately capture 346 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 347 sizes, compared to the more uniform distributions used by Gle et. al. (2013, and also 348 349 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.

353 4.2 MODELLING OF HEMP-LIME CONCRETE

354 The Biot-Allard model, which provides a good model for hemp shiv, has previously 355 been shown to be a poor model of the acoustic behaviour of hemp-lime concretes 356 [34]. Gle et. al. use Johnson's model, which gives a different form for the dynamic 357 density, and find much better agreement with experimental results. However, the 358 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 359 360 presented by Gle et al for concrete extend only up to 500 Hz; in the present study, in 361 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 362 describe the absorption in this frequency range, and further modelling work is 363 364 required to identify a suitable model for the acoustic behaviour of hemp-lime 365 concretes in this frequency range.

## 366 5 DISCUSSION

### 367 5.1 ACOUSTIC ABSORPTION OF HEMP-LIME

The hemp concretes investigated exhibit significant sound absorption across the 368 369 tested frequency range and are characterized by absorption coefficients between 370 0.24 and 0.53. Hemp concretes with lime binders exhibit significantly higher sound 371 absorption coefficients than binders including cement. The results also showed that 372 hemp concretes with hydrated lime-pozzolan binders have a greater sound 373 absorption than hemp concretes bound with hydraulic binders. This indicates that 374 there is an inverse relationship between sound absorption and hydraulic content. 375 These results align with those of Gle et al. [34], who showed concretes with quick 376 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 377 378 relationship between sound absorption and hydraulic content although this finding 379 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.

385 It is difficult to directly compare the sound absorption characteristics of different 386 materials, as the absorption coefficient is not a single-valued, intrinsic material 387 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.

395 Previous work on the acoustic absorption of plant fibres has generally focussed on 396 the properties of the loose fibres or wool-type insulation products, rather than 397 bound or rendered products as in the present study; and results presented are 398 sometimes questionable. A review article by Asdrubali et al [56] uncritically presents 399 implausible results, such as absorption coefficients significantly greater than 1, 400 indicating imprecise measurement aparatus. Although Asdrubali's review has been 401 cited as a reference for absorption coefficients, their paper simply gives a value of 402 0.6 for the absorption coefficient of hemp (at 500 Hz), when the present study shows 403 significant variation depending on density. Despite the caveats noted, some typical 404 results for porous concrete and a selection of natural materials are shown in Table 8 405 for comparison purposes. For ease of comparison, this table shows only the NRC 406 values for each material – these are calculated by taking the mean of the absorption 407 coefficients at 500, 1000 and 2000 Hz, rounded to the nearest 0.05.

408

- 409 Table 8. Sound absorption values for a range of materials. (Berardi and Iannace (new ref at end of list) tested a
- 410 range of thicknesses for some materials and the highest values are quoted here. NRC values for porous
- 411 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]

## 412

## 413 5.2 Assessment of Constructions using Hemp-Lime

414 Reverberation time ( $T_R$ , the time taken for a sound to decay by 60 dB) is a salient 415 criterion in the acoustic design of spaces. Dependent on room geometry and 416 absorption, it is used to describe the rate at which sound decays, and is described by 417 the Sabine formula[51]:

418 
$$T_R = 0.163 V/_A$$
 (9)

419 where *V* is the volume of the room, and  $A = \alpha_1 S_1 + \alpha_2 S_2 + \alpha_3 S_3 + ...$ , where  $S_{1-n}$  are the 420 different room surfaces and  $\alpha_{1-n}$  their corresponding sound absorption coefficients. 421 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, 422 affecting intelligibility of speech and clarity of sound. The tendency is often to 423 424 concentrate sound absorbing materials on the ceiling; however, this can be of 425 limited impact and ignores the multiple reflections between parallel walls in a 426 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 427 428 buildings. Night cooling of extensive thermal mass requires exposure of fair-faced 429 concrete including soffits and floors. Hence the energy/climate concept can conflict with the acoustic concept and prohibit extensive cladding of ceilings for acoustic 430 431 absorption.

432 Optimum reverberation times differ depending on the space function ranging from 433 0.4-0.7 s for classrooms, 0.8-1.2 s for theatres and 1.4 s upwards for churches and 434 cathedrals [29], and hemp-lime walls (whether rendered or unrendered) offer 435 potential to reduce reverberation time to that specified in standard and guideline 436 documents. Taking school classrooms as an example, UK guideline documents 437 specify limits for the average value of octave bands at 500 Hz, 1000 Hz and 2000 Hz, 438 denoted  $T_{mf}$  [26]]. German guidelines DIN 18041 [27] specify  $T_R$  of 0.5-0.7 s for 439 classrooms with room volume 150-250 m<sup>3</sup> as typical. The unrendered hemp-lime 440 walls evaluated in this study can easily achieve these recommended reverberation 441 times for the typical range of classroom volumes. When considering the room 442 volume range 150-250 m<sup>3</sup>, and presuming an exposed masonry/concrete floor and 443 soffit ( $\alpha$  around 0.1), hemp lime-pozzolan concrete walls ( $\alpha$  in Table 3) can enable a

444  $T_{mf}$  of 0.5-0.6 s with a good distribution of sound absorbing surfaces and no ceiling 445 or wall appendages. However, rendering of the hemp-lime walls reduces the 446 absorption ability significantly (Table 5). When rendered  $T_{mf}$  increases to 1.2-1.7 s. 447 Although this reverberation time is much lower than in rendered or painted walled 448 rooms it is outside the required values for classrooms; consequently, acoustic 449 treatment or additional sound absorbing panels will be required to meet guideline 450 values.

451

#### 452 5.3 LIMITATIONS OF THE IMPEDANCE TUBE METHOD

453 There are some limitations associated with the impedance tube method of 454 calculation, principally that measurements are at normal incidence. Although this condition is not commonly satisfied, characteristic impedance of a porous media can 455 456 be measured with the impedance tube and used to predict acoustic behavior of the 457 material at oblique incidence. The study is also limited to the range of frequencies 458 defined by the dimensions of impedance tube. The low frequency vowel sounds are 459 generally in the 125Hz (men) – 265Hz (children) range. However, recognition of 460 constants and speech formants whose energy is concentrated in the measured frequencies of the speech spectrum, are key for speech intelligibility [26]. Complex 461 462 computer simulations using geometrical techniques such as ray tracing and the 463 mirror-source method are required to accurately predict the acoustic characteristics 464 of specifically designed spaces and sound environments. However, the acoustic

- 465 quality of spaces can be approximated using reverberation time estimates  $(T_{mf})$
- 466 when acoustic parameters of construction materials ( $\alpha$ ) are characterised.

# 467 6 CONCLUSIONS

Unrendered hemp concretes exhibit significant acoustic absorption, with average 468 469 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 470 absorption, compared to more hydraulic binders. Within this group GGBS binders 471 appear to have slightly higher absorption coefficients than metakaolin based 472 473 binders. These results suggest that the chemical composition of the binders has a greater influence on sound absorption than material density or porosity. Current 474 acoustic models of materials of multi-scale porosity provide a good degree of 475 476 correlation with experimental results for loose hemp particularly at low frequencies. Further work is required to develop an accurate predictive model for the high 477 frequency acoustic behaviour of hemp-lime concrete. 478

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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