

This item was submitted to Loughborough's Institutional Repository (<https://dspace.lboro.ac.uk/>) by the author and is made available under the following Creative Commons Licence conditions.



For the full text of this licence, please go to:  
<http://creativecommons.org/licenses/by-nc-nd/2.5/>

1 **Analysis of the Hygrothermal Functional Properties of Stabilised Rammed Earth Materials**

2  
3 **Matthew Hall<sup>\*</sup> and David Allinson**

4  
5 *Institute of Sustainable Energy Technology, School of the Built Environment, University of*  
6 *Nottingham, University Park, Nottingham NG7 2RD, UK Tel: +44 (0) 115 846 7873, Fax:*  
7 *+44 (0) 115 951 3159, E-mail: matthew.hall@nottingham.ac.uk*

8 *\*corresponding author*

9  
10 **Abstract**

11 Suitable experimental methodologies for determining the hygrothermal properties of  
12 stabilised rammed earth (SRE) materials have been presented along with comparative  
13 experimental data for three different SRE mix designs with parametric analysis of the  
14 influence of these variables on material function. Higher bulk porosity corresponds to reduced  
15 volumetric heat capacity ( $C$ ), but increased sorptivity ( $S$ ) and vapour permeance ( $W$ ). Since  
16 bulk porosity and void size distribution (VSD) are interdependent variables, it follows that for  
17 constant particle size distribution (PSD) and compaction energy an increase in porosity results  
18 in an increase in the mean pore radius,  $\bar{r}$  for a material. This explains why the magnitude of  
19 liquid/vapour transfer ( $S$  and  $W$ ) terms are inversely related to the hygroscopic moisture  
20 capacity,  $\zeta$  since the capillary potential,  $\Psi$  will increase when the mean pore diameter  
21 decreases. The implications are that the hygrothermal properties of SRE materials can be  
22 designed and predicted by manipulating particle size distribution and compaction energy.

23  
24 **Keywords:** hygrothermal; porous materials; stabilised rammed earth; heat & mass transfer  
25 and storage

27 **Nomenclature:**

28  $V_T$  = total volume

29  $V_s$  = volume of solid

30  $V_v$  = volume of void

31  $V_a$  = volume of air

32  $V_m$  = molar volume

33  $p_v$  = vapour pressure

34  $p_{sat}$  = saturation vapour pressure

35  $p_{sat}^*$  = saturation vapour pressure above a flat surface

36  $P_a$  = total air pressure

37  $P_w$  = total water pressure

38  $r$  = pore radius

39  $r_{crit}$  = critical pore radius

40  $\bar{r}$  = mean pore radius

41  $T$  = thermodynamic temperature (K)

42  $\eta$  = viscosity

43  $\gamma$  = surface tension

44  $\phi$  = relative humidity ( $0 \leq \phi \leq 1$ )

45 RH = relative humidity % ( $\phi * 100$ )

46  $\theta$  = relative moisture ( $0 \leq \theta \leq 1$ )

47  $\theta_r$  = residual moisture content

48  $\theta_c$  = capillary saturation moisture content

49  $\theta_{AEV}$  = air entry value moisture content

50  $\theta_s$  = saturation moisture content

51  $\rho_w$  = density of water ( $\text{kg/m}^3$ )

- 52  $\rho_v$  = density of water vapour ( $\text{kg/m}^3$ )
- 53  $g$  = gravitational constant
- 54  $h$  = height
- 55  $g_{v, air}$  = rate of water vapour diffusion through air
- 56  $D$  = diffusion coefficient for water vapour in still air ( $\text{m}^2/\text{s}$ )
- 57  $C_v$  = mass concentration of water vapour ( $\text{kg/m}^3$ )
- 58  $M_w$  = molar mass of water ( $\text{kg/kg mol}$ )
- 59  $R_o$  = the universal gas constant ( $\text{J/kg mol K}$ )
- 60  $m_w$  = mass of water ( $\text{kg}$ )
- 61  $A$  = area
- 62  $G$  = water vapour flow rate ( $\text{kg/s}$ )
- 63  $W$  = water vapour permeance ( $\text{kg/m}^2 \text{ s Pa}$ )
- 64  $i$  = cumulative volume of absorbed water per unit inflow surface area ( $\text{mm}^3/\text{mm}^2$ )
- 65  $t$  = time
- 66  $S$  = sorptivity ( $\text{mm}/\text{min}^{-0.5}$ )
- 67  $\xi$  = hygroscopic moisture storage function
- 68  $\Psi$  = capillary potential
- 69  $\lambda$  = thermal conductivity ( $\text{W/m K}$ )
- 70  $\lambda^*$  = moisture content-dependent thermal conductivity ( $\text{W/m K}$ )
- 71  $q_{sens}$  = sensible heat flow ( $\text{W/m}^2$ )
- 72  $q_{lat}$  = latent heat flow ( $\text{W/m}^2$ )
- 73  $w$  = reference moisture content ( $\text{kg/m}^3$ )
- 74  $g_v$  = rate of water vapour transfer ( $\text{kg/s m}^2$ )
- 75  $h_e$  = specific latent enthalpy of evaporation/condensation ( $\text{J/kg}$ )
- 76  $S_r$  = degree of saturation (or saturation ratio)
- 77  $m_f$  = moisture factor

78  $c_p$  = specific heat capacity at constant pressure (J/kg K)

79  $c_p^*$  = moisture content-dependant specific heat capacity at constant pressure (J/kg K)

80  $\varpi$  = relative mass fraction

81

## 82 **1 Introduction**

83 Approximately one half of the world's population are said to live or work in an earth building [1] and  
84 it has long been mooted that earth materials have the ability to provide superior levels of indoor  
85 thermal comfort, e.g. [2, 3, 4]. Stabilised rammed earth (SRE) is the modern practice of a traditional  
86 construction technique and is typically achieved by the addition of  $\leq 10\%$  Portland cement to subsoil  
87 and dynamic compaction (ramming) of the mixture into temporary formwork. It provides a low  
88 embodied energy material for rapid construction on-site. Its modern day use is widespread across  
89 Australasia, North America, Asia, and parts of mainland Europe such as Spain, Germany and France  
90 and increasingly Great Britain. Since earth is a porous, hygroscopic material that contains active clay  
91 minerals, it is expected that the walls absorb water vapour from the air when relative humidity  
92 increases and release this moisture when the humidity falls. As it is usual practice to leave earth walls  
93 exposed to the interior of the building, the availability of combined thermal and hygric buffering (i.e.  
94 passive air conditioning) will be maximised when compared with other materials such as brick, timber  
95 or concrete that are often covered over with more insulating and less permeable coverings, e.g. varnish  
96 and paints.

97

98 The functional properties of SRE that can be used to describe its hygrothermal behaviour are  
99 the moisture storage function, vapour permeability, liquid conductivity, thermal conductivity,  
100 and specific heat capacity. Samples of three SRE mix designs were manufactured and tested  
101 to determine these functional properties and the results compared.

102

103 The objective of this paper is to investigate how the hygrothermal properties of SRE materials  
104 can be experimentally measured and how these functional properties are influenced by the

105 variable mix design parameters of the material. The aim is to test the hypothesis that  
106 hygrothermal properties can then be predicted and designed through correspondence with mix  
107 design parameters. SRE materials can be characterised as multiphase granular composites  
108 whose particle size distribution (PSD) and particle packing efficiency largely determine the  
109 geometry of their matrix structure. The term stabilisation refers to the application of a process  
110 and/or additive component that enhances the cohesion, Young's modulus or another physical  
111 property [5-7]. By far the most common forms of stabilisation are i) dynamic compaction and  
112 ii) addition of hydraulic binders, e.g. cementitious materials. As with most granular soils,  
113 dynamic compaction close to the Proctor optimum moisture content increases the inter  
114 particle friction/interlock whilst reducing the bulk porosity. The addition of hydraulic binders  
115 (commonly  $\leq 10\%$  Portland cement) increases the internal cohesion of the material and  
116 enhances durability and toughness [5-9]. Since hardened cement paste bonds particles  
117 together by surface adhesion between the paste and particle surfaces (interfacial transition  
118 zone), cement stabilisation is most effective on granular soils [8-10] where the specific  
119 surface area per unit mass is lower and the greater absence of cohesive materials is less able to  
120 interfere with the interfacial transition zone.

121

## 122 **2 Specimen Preparation**

123 The characterisation of SRE material composition can easily be approximated using the  
124 geotechnical soil model. The particle size distribution for SRE must normally fall within  
125 designated upper and lower limits resulting in a wide range of achievable particle packing  
126 efficiencies and associated bulk porosity/dry density and void size distribution (VSD), as  
127 explained extensively in the authors' previous research [11-13]. By using an established  
128 technique of blending characterised soil constituents (14-6.3mm gravel, 5mm down medium  
129 grit sand, silty clay) and matching the net PSD to the defined upper/lower limits, the authors  
130 can maintain the parameters of aggregate mineralogy, particle angularity and clay mineralogy

131 as constants whilst keeping PSD as the single variable. SRE specimens were prepared as one  
132 litre cylinders (3 compaction layers), 1/3 litre discs (1 compaction layer), and 300 x 300mm  
133 slabs (1 compaction layer). All were stabilised by compacting at OMC using a constant  
134 energy of  $596 \text{ kJ/m}^3$  and the addition of 6% wt CEM IIa class Portland cement, followed by  
135 air curing for a minimum of 28 days at  $20^\circ \text{ C} (\pm 2^\circ \text{ C})$  and 75% RH ( $\pm 5\%$ ) in an  
136 environmental chamber.

137

### 138 **3 Moisture Sorption and Storage**

139 The assumption here for hygrothermal materials is that a representative microstructure of  
140 porous media has a total volume ( $V_T$ ) which consists of solid state matter ( $V_s$ ) and fluid-filled  
141 void ( $V_v$ ), where  $V_T = V_s + V_v$ . Under atmospheric conditions, when the material is dry the  
142 voids are filled with air ( $V_v = V_a$ ) and when saturated the voids are filled with water ( $V_v = V_w$ ).  
143 Clearly, when moisture enters a dry or unsaturated continuum it must displace air from the  
144 moment it crosses the boundaries defined by  $V_T$ ; a process referred to as ‘absorption’.  
145 Absorbed moisture vapour may also be ‘adsorbed’ to the internal surfaces by van der Waals  
146 forces. Absorbed moisture may be classified into one of three domains (hygroscopic,  
147 capillary, and gravitational) depending upon i) its phase when it enters  $V_T$ , and ii) its strength  
148 of electrostatic attraction. Hygroscopic moisture is absorbed in the vapour phase, capillary  
149 moisture is absorbed in the liquid phase, and gravitational moisture is liquid that is absorbed  
150 when the capillary potential in the pore network is zero (i.e. super saturation).

151

152 Although the classification of absorbed moisture (determined by its phase upon entry) cannot  
153 change, its phase once inside  $V_T$  can change, e.g. condensing from vapour to liquid. This is  
154 chiefly governed by internal void geometry and electrostatic surface charge for a given  
155 temperature and partial vapour pressure. Theoretically, the saturation vapour pressure above a  
156 flat surface of liquid water ( $p_{\text{sat}}^*$ , when  $r = \infty$ ) is dependent upon the pressure applied ( $\Delta P_a$ ) to

157 that liquid by a surrounding gas, in this case air. For a given  $\Delta P_a$ , the saturation vapour  
 158 pressure becomes  $p_{sat} = p_{sat}^* e^{V_m \Delta P / R_o T}$  [14]. Furthermore, by curving the surface of the water  
 159 to a known radius,  $r$  a pressure change (negative for water) occurs where  $\Delta p_{sat} = 2\gamma/r$ .  
 160 Therefore, we can see that the saturation vapour pressure of liquid water held inside a pore of  
 161 radius  $r$  (and having a contact angle  $\alpha$ ) is greater than that of a flat surface, i.e.  $p_{sat} > p_{sat}^*$ .  
 162 This of course leads to Kelvin's Equation,  $p_{sat} = p_{sat}^* e^{-2\gamma V_m / r R_o T}$  where molar volume of water  
 163  $\sim 18$  ml at STP [14]. In the case of hygroscopic moisture (vapour phase) of known partial  
 164 pressure,  $p_v$  that has been absorbed by a pore, Kelvin's equation can simply be rearranged to  
 165 find the 'critical pore radius' ( $r_{crit}$ ) assuming  $p_v = p_{sat}$ . At this point moisture vapour condenses  
 166 inside the pore to restore thermodynamic equilibrium. Obviously, where radii vary within  
 167 complex pore structures it follows that vapour condenses to fill the pore with liquid when  $r <$   
 168  $r_{crit}$ , and visa versa.

169  
 170 Figure 1 shows the wetting/drying sorption isotherms for a typical hygrothermal material,  
 171 correlating relative moisture content,  $\theta$  with absorbed moisture domains. As with liquid  
 172 sorption, hysteresis typically occurs between the relative moisture content,  $\theta$  at a given  
 173 humidity,  $\phi$  due to the influence of electrostatic potential on the porous material inside  
 174 surfaces. As relative humidity increases from zero, single layer adsorption and then multi  
 175 layer adsorption of water vapour molecules occurs within the pore structure of the material.  
 176 Metastable groups of adsorbed water vapour molecules can spontaneously nucleate into a  
 177 liquid water meniscus that is in equilibrium with the relative humidity for a given pore radius,  
 178 as predicted by the Kelvin equation. In this way, hygroscopic moisture can be stored in liquid  
 179 phase inside the porous material. Kelvin's equation can be used to calculate the theoretical  
 180 critical pore radius in which water vapour condenses in relation to the relative humidity. The  
 181 validity of Kelvin's equation applies to the portion of a sorption isotherm where capillary  
 182 condensation will occur in pore radii sufficient to permit thicknesses greater than multi



183 molecular layers, i.e. droplets. This typically occurs at  $\varphi \approx 0.5$ , although the occurrence of  
184 capillary potential-induced liquid moisture flow is typically not considered until  $\varphi > 0.8$  [15]  
185 (refer to value  $\theta_{80}$ , Figure 1). At the hypothetical point when  $\varphi \rightarrow 1$ , the transition from  
186 hygroscopic to capillary domain occurs and is defined as the residual moisture content,  $\theta_r$ . For  
187 modelling purposes, however, a ‘kick point’ moisture content can be specified to indicate the  
188 maximum hygroscopic moisture content since that can be readily determined experimentally,  
189 e.g. normally 95 or 98% RH [15, 16]. Above this level pressure plate apparatus can be used  
190 for relative humidity at saturation. When  $\theta$  is in the capillary domain, moisture transport is  
191 dominated by capillary potential,  $\Psi$  and the microstructure is referred to as ‘unsaturated’ (as  
192 in soil mechanics), refer to Figure 2. During wetting, absorption will continue until capillary  
193 saturation  $\theta_c$  at which point the ambient air pressure  $P_w = P_a - (2 \gamma / r + \rho_w g h)$ , for the  
194 supported mass of water inside the pore structure (where  $g$  is the gravitational constant) [14].  
195 Obviously, if  $\theta_c \ll \theta_s$  (fully saturated) then additional moisture can be absorbed without  
196 capillarity (e.g. pressure differential, gravity etc), some of which can be supported by  
197 remaining net surface charge in the pore network surfaces. Thus, on the drying curve the  
198 maximum capillary moisture content is determined by the air entry value to find  $\theta_{AEV}$ . At  
199 ‘super saturation’ ( $>\theta_{AEV}$ ) the force of gravity on the additional mass of the non-capillary (or  
200 gravitational) moisture is greater than the attraction of the remaining net surface charge inside  
201 the pore structure.

202

203 The sorption and desorption isotherms were determined for representative samples of each  
204 rammed earth mix recipe. SRE disc specimens were split into large fragments ( $V_T \approx 15\text{ml}$ )  
205 and oven dried to constant mass at  $105^\circ \text{C}$ . An array of five sealed desiccators was prepared,  
206 each containing a different saturated salt solution and stored at an ambient air temperature of  
207  $23^\circ\text{C} \pm 0.5^\circ\text{C}$  in order to provide a wide range of stable relative humidity environments (see  
208 Table 1). The dry specimens were progressively placed in each of the desiccators, in order of

209 increasing humidity, and permitted to absorb moisture vapour until constant mass was  
210 achieved (normally > 3 days), defined as <0.1%  $\Delta$ wt/day [17]. Samples were then fully  
211 immersed in distilled water for 24 hours and the saturated mass recorded to find  $\theta_c$ , but  $\theta_r$  can  
212 only be interpolated since it occurs at  $\varphi \rightarrow 1$ . The capillary saturated specimens were then  
213 progressively placed in each of the desiccators in order of decreasing humidity. In this manner  
214 both the sorption and desorption isotherms were determined. The relationship between the  
215 moisture content of a porous material and the relative humidity of the surrounding  
216 environment is described by the moisture storage function (MSF). It is used to calculate the  
217 partial pressure of a water vapour gradient for water vapour diffusion as well as the capillary  
218 potential gradient for liquid water conductivity (see part 1).

219

#### 220 **4 Water Vapour Transport**

221 It is apparent that the fluid transport mechanism in porous materials is not simply defined by  
222 its domain classification. Once fluid has entered the porous medium  $V_T$ , the intrinsic  
223 conditions of the pore network will determine i) fluid phase, and ii) its associated transport  
224 mechanism(s). To elucidate, absorbed hygroscopic moisture (from vapour) will subsequently  
225 be adsorbed by internal surfaces, condense, or diffuse. Adsorbed capillary moisture (from  
226 liquid) will either flow or vaporise. The intrinsic properties that determine these conditions  
227 include pore radius, pore geometry, surface charge, and surface temperature.

228

229 Water vapour can enter porous materials through pore openings at the surface and liquid water inside  
230 the material can evaporate. The material's granular skeleton reduces the available cross-sectional area  
231 of air for vapour diffusion and the complex spatial connectivity of the pore spaces increases path  
232 lengths, providing additional resistance. For pores with smaller diameter, the mean molecular free path  
233 of the water vapour molecules approaches or exceeds the pore diameter. In this case, pore wall  
234 collisions and van der Waals forces between the water vapour and pore surface dominate molecular  
235 movement, i.e. Knudsen diffusion. Also, water vapour molecules that are adsorbed to the walls of the

236 pores inside the material, either in a single layer or as multiple layers, can move along the surface by  
237 surface diffusion. These phenomena are illustrated in Figure 3.

238

239 The rate of water vapour diffusion in still air can be described by Fick's law:

$$240 \quad g_{v,air} = -D \frac{\partial C_v}{\partial x} \quad (1)$$

241 This equation can be expressed in terms of water vapour partial pressure using the ideal gas law:

$$242 \quad C_v = \rho_v = \frac{p_v M_w}{R_0 T} \quad (2)$$

243 The rate of water vapour flow through a porous specimen can be determined using the wet  
244 cup/dry cup method [18] in a temperature and humidity controlled environmental chamber,  
245 see Figure 4. By using a saturated salt solution for the 'test' vessel, a vapour pressure gradient  
246 was imposed across the sample thickness thus inducing diffusive mass transfer. The  
247 specimen sides were coated with a 2-part epoxy resin and sealed into the cups using silicone  
248 sealant to ensure vapour tightness. For the SRE specimens a 'test' solution of Potassium  
249 Nitrate  $\text{KNO}_3$  (94.0% RH) was used in the cup (i.e. a 'wet' cup) and the climate chamber set  
250 to 23°C and 53.5% RH, see Table 1. The actual air temperature and relative humidity were  
251 logged for the duration of the test using Tiny Tag sensors with an accuracy of  $\pm 0.4$  °C and  $\pm$   
252 3 %RH. Specimen mass increase was determined gravimetrically, and the quantity of 'test'  
253 solution was sufficient to permit test periods of between 2 and 3 weeks. The absorbed mass  
254 ( $\Delta m_w$ ) increased linearly against the elapsed time ( $t$ ), and the slope  $\Delta m_w/t$  gave the water  
255 vapour flow rate,  $G$  through the specimen in kg/s, see Figure 5. The water vapour permeance  
256 was then calculated from:

$$257 \quad W = \frac{G}{A \cdot \Delta p_v} \quad (3)$$

258 Where  $A$  = specimen inflow surface area ( $\text{m}^2$ ), and  $\Delta p_v$  = water vapour pressure difference  
259 across the specimen (Pa) which was calculated from the mean of the measured temperature  
260 and relative humidity over the course of the test.

261

## 262 **5 Liquid Water Transport**

263 Previous research has shown that bricks, stone, and SRE materials have been found to obey  
264 the  $i/t^{0.5}$  linearity rule demonstrating dependence upon the  $\gamma/\eta^{0.5}$  relationship [13, 19-21], i.e.  
265 capillary potential is the motivational force for flow in the unsaturated state. Theoretically, the  
266 sharp wet front approximation can be used to model absorption and desorption of capillary  
267 moisture and the associated transfer rates [13, 20]. Experimentally, the gravimetric  
268 measurement of absorbed volume per unit inflow surface area,  $i$  ( $\text{mm}^3/\text{mm}^2$ ) is measured  
269 using test specimens that are partially immersed to a constant a depth of  $5\text{mm} \pm 1\text{mm}$ . Pre-test  
270 conditioning and actual testing of the specimens were performed by the authors in a large  
271 environmental chamber at  $23^\circ\text{C} \pm 1^\circ\text{C}$  and  $50\% \pm 5\%$  relative humidity. In SRE materials,  
272 increasing the cementitious binder content resulted in an increase in bulk porosity and hence  
273 an increase in the sorptivity,  $S$ . More interestingly this was found to give higher initial rates of  
274 suction but which decreased very sharply over time due to the moisture-content dependent  
275 nature of the capillary potential [13]. It is hypothesised that since  $n$  and  $\bar{r}$  are interdependent  
276 in porous granular media, then a reduction in both (caused by changing PSD and/or  
277 compaction energy) would increase  $\Psi$  (due to smaller  $\bar{r}$ ) but reduce  $\xi$  (due to lower porosity).  
278 Hence, the rate of flow reduction over time, as a result of  $\Psi(\theta)$ , is higher when changes to  
279 material pore structure result in  $\Delta\theta_c$  being negative. The experimental data for SRE materials  
280 has been presented elsewhere [13, 21], and partly in Table 2 for comparison.

281

## 282 **6 Heat Transfer and Storage**

283 Within a porous building material, heat transfer can occur through a number of mechanisms  
284 (see Figure 6). Firstly, there is conduction, which occurs primarily through the material's  
285 granular skeleton, which in the case of SRE consists of hydraulically-bound mineral aggregate  
286 particles and clays. Heat transfer will be enhanced by the introduction of water into the voids

287 between particles as the thermal conductivity of water is an order of magnitude higher than  
 288 air, and conduction at inter-particle contact points is augmented by menisci formation.  
 289 Localised radiative and convective heat transfer will also occur between particles within the  
 290 matric structure and these are assumed to be included within the continuum-level moisture  
 291 content dependent thermal conductivity,  $\lambda^*$  (W/m K) [11]. The dry state and moisture-  
 292 dependant thermal conductivity ( $\lambda^*$ ) were measured using a heat flow meter apparatus to ISO  
 293 8301 [11]. Moisture factor ( $m_f$ ) the slope of the  $\lambda:S_r$  graph and was determined by linear  
 294 regression, such that:

$$295 \quad \lambda^* = \lambda(1 + S_r m_f) \quad (4)$$

296 The moisture content-dependant specific heat capacity,  $c_p^*$  was calculated as the sum of the  
 297 heat capacities of the constituent parts, weighted by their relative mass fractions,  $\varpi$ , as shown  
 298 in Equation 2 [12, 22].

$$299 \quad \rho_{bulk} c_p^* = \rho_{dry} (\varpi_{sand} c_{sand} + \varpi_{gravel} c_{gravel} + \varpi_{clay} c_{clay} + \sigma_{cem} c_{cem}) + w c_w \quad (5)$$

300 The results from these tests have previously been presented [11, 12] and are shown in Table 2  
 301 for direct comparison of all hygrothermal properties between each of the materials.

302

## 303 **7 Parametric analysis of hygrothermal properties**

304 Table 2 shows the hygrothermal functional properties for each of the three SRE materials. The  
 305 parametric difference between each material is the particle size distribution which, since  
 306 compaction energy and solid phase properties are constant, results in variation in packing  
 307 efficiency and hence i) bulk porosity and, ii) void size distribution. Clearly dry density and  
 308 bulk porosity are inversely related and so higher porosity results in reduced volumetric heat  
 309 capacity ( $C$ ), but increases sorptivity ( $S$ ) and vapour permeance ( $W$ ). These broad trends are  
 310 somewhat predictable, and the new data presented here can be used by other researchers in  
 311 transient hygrothermal modelling of SRE materials. Interesting trends occur when one  
 312 considers the intricacies of inter-particle contact, void size distribution and pore network

313 tortuosity brought about by particle packing efficiency. Moisture factor  $m_f$ , for example,  
314 represents the sensitivity of a material's thermal conductivity to increasing degree of  
315 saturation and is not simply related to porosity [11, 12]. Much more research is needed to  
316 understand how heat transfer occurs in porous granular materials.

317

318 Whilst the uncertainty in the measurements made for the tests were small (balance accurate to  
319 +/- 0.01g, stop watch accurate to 1s) and the test environments were closely controlled and  
320 monitored (temperature better than +/- 1°C and RH better than +/-3%), simply propagating  
321 these errors may underestimate the uncertainty of the results. Galbraith [23] has shown that,  
322 for identical materials, different laboratories can produce results that vary in excess of +/-20%  
323 of the mean vapour permeability result for particle board. This was attributed to systematic  
324 error in the tests as evidenced by the large bias between individual laboratories. Assuming  
325 that the tests are carried out carefully, a confidence interval of +/-5% should be achievable  
326 [23], however the properties of rammed earth specimens are known to vary between samples  
327 and wider variation may be expected (authors have found strength tests to typically vary by  
328 +/-20%). Further testing is therefore required to determine the accuracy of the results,  
329 however, while the moisture storage function for the three materials described here may be  
330 deemed similar, it is reasonable to attribute significant differences in the permeability results.

331

332 The sorption isotherm in Figure 7 shows the wetting and drying curves for each of the three  
333 SRE materials. The point  $\theta_r$  is difficult to measure experimentally since by definition it occurs  
334 at  $\phi \rightarrow 1$ . Therefore, the important transitional point  $\theta_c$  has been found and the portion of the  
335 isotherm shaded in grey (between >95% RH - 100% RH) is interpolated for completeness.  
336 Although at scale the moisture storage curves are very similar a degree of hysteresis occurs  
337 between wetting and drying as a result of changes to the net capillary potential as described  
338 previously. The gradient of the linear section of the moisture storage curves is used to

339 determine the hygroscopic moisture capacity for absorption (wetting),  $\xi_a$  and for desorption  
340 (drying),  $\xi_d$ , the values for which are given in Table 2. A particular portion of the isotherm  
341 that is of interest in relation to building physics is that which occurs in the RH range that is  
342 defined as the indoor comfort zone, i.e. between 40 and 70% RH [24].  
343  
344 Figure 8 highlights disparities that occur between the wetting/drying moisture storage curves  
345 for respective SRE materials where the indoor comfort range (above) is shaded. The total  
346 hygroscopic moisture storage capacity of SRE materials appears to vary by a small amount in  
347 relative terms. Interestingly, in terms of material functional properties the moisture storage  
348 capacity across the range appears to inversely relate to porosity. The 433 material, for  
349 example, exhibits the highest hygroscopic moisture storage capacity (across the range) and  
350 correspondingly the highest  $\Psi(\theta)$ , however this material also has the lowest porosity and  
351 vapour permeability. It is assumed that the surface properties of the solid phase material  
352 components are constant and since  $\theta$  never approaches  $\theta_r$  (always hygroscopic domain), the  
353 capacity for moisture vapour storage across a given RH range must be determined by the  
354 overlap between VSD and critical pore radii, as defined by Kelvin's equation. This simple  
355 relationship, however, relies upon the significant assumption that porosity is a constant. In  
356 porous granular materials, PSD and compaction energy effectively determine the particle  
357 packing efficiency. Crucially this suggests that bulk porosity and mean pore radius  $\bar{r}$  are  
358 interdependent variables for porous granular media; increasing packing efficiency will  
359 increase the vapour storage function whilst decreasing transfer rates (sorptivity and vapour  
360 permeability) and visa versa. The implications are that since VSD and  $\bar{r}$  can be controlled by  
361 compaction energy and PSD, the hygrothermal functional properties of SRE materials can be  
362 designed using this technique, e.g. a 703 mix would sacrifice moisture storage capacity in  
363 favour of increased moisture transport rates.

364

365 When considering the use of hygrothermal materials for relative humidity buffering in  
366 buildings it is important to consider the response rates of the material to changes in ambient  
367 relative humidity. Previous research has drawn direct comparisons between water vapour  
368 absorption rates ( $\text{g/m}^2 \text{ s}$ ) for different materials [25] with the premise that higher values  
369 indicate superior buffering ability. The fundamental weakness with this approach is that rather  
370 than buffering, this data provides the maximum rate since as moisture is absorbed i) the  
371 vapour pressure differential decreases (the driving force for absorption rate) towards zero as  
372 equilibrium is approached, and ii) the internal mass transfer rates slow down as  $\theta$  increases.  
373 This relationship produces the characteristic  $w:t$  curve where  $\Delta w \rightarrow 0$  as  $\Delta P \rightarrow 0$   
374 (thermodynamic equilibrium). Whilst it is not possible to use experimental data of individual  
375 functional properties to directly compare moisture buffering capacity between materials,  
376 hygrothermal transient models such as WUFI can simulate the effects of moisture buffering  
377 by coupling mass storage and diffusion functions, and then solving the mass balance  
378 equations.

379

## 380 **8 Conclusions**

381 Suitable experimental methodologies for determining the functional hygrothermal properties  
382 of SRE materials have been identified. Comparative experimental data has been presented for  
383 three different SRE mix designs enabling parametric analysis of the influence of these  
384 variables on hygrothermal properties. Higher bulk porosity corresponds to reduced volumetric  
385 heat capacity ( $C$ ), but increased sorptivity ( $S$ ) and vapour permeance ( $W$ ). Since bulk porosity  
386 and VSD are interdependent and are largely controlled by PSD and compaction energy, it  
387 follows that decreased porosity results in a decrease in  $\bar{r}$  for a given material (constant PSD  
388 and particle geometry). This is consistent with experimental observations of increased  
389 capillary potential coupled with decreased permeability. The variation in vapour absorption  
390 capacity is consistent with the latter observation since capacity appears to increase with



391 capillary potential and is inversely related to bulk porosity. However, at total hygroscopic  
392 storage capacity appears to vary little as a result of SRE mix parameters whereas response  
393 rates can vary significantly. This is perhaps the key to understanding the use of hygrothermal  
394 materials for relative humidity buffering in buildings because the fabric vapour storage  
395 capacity will typically be more than sufficient in relation to the volume of air inside a room.  
396 The opportunity for SRE materials to perform well in this regard is related to optimising their  
397 response rate to match the anticipated fluctuations in vapour pressure gradients. A  
398 fundamental understanding of hygrothermal behaviour can be combined with an  
399 understanding of the functional properties of hygrothermal materials, including experimental  
400 approaches to quantifying these properties. The next step is to verify this predictive approach  
401 by numerically simulating the hygrothermal behaviour of SRE walls under known  
402 indoor/outdoor climatic conditions and then comparing the predicted material responses with  
403 experimental measurements.

404

#### 405 **Acknowledgements**

406 The authors wish to acknowledge the support of the Engineering and Physical Sciences  
407 Research Council.

408

#### 409 **References**

- 410 1. Eartharchitecture.org. 2008. *Earth Architecture*. [online] Available at <http://www.eartharchitecture.org/>  
411 [accessed 13 November 2008]
- 412 2. Building Research Institute of the University of Kassel. 2008. *Facts*. [online] Available at  
413 <http://www.asl.uni-kassel.de/~feb/index.html> [accessed 13 November 2008]
- 414 3. Mortenson N. 2000. *The naturally air conditioned house*. [online] Available at  
415 [http://www.dab.uts.edu.au/ebrf/research/air\\_conditioned.html](http://www.dab.uts.edu.au/ebrf/research/air_conditioned.html) [accessed 13 November 2008]
- 416 4. Taylor P & Luther MB. 2004. Evaluating rammed earth walls: a case study. *Solar Energy*, 76(1), pp. 79-84.
- 417 5. Jayasinghe C & Kamaladasa N, 2007, 'Compressive strength characteristics of cement stabilized rammed  
418 earth walls', *Construction and Building Materials* 21 [11] pp. 1971-1976

- 419 6. Hall M, 2006, 'Assessing the Environmental Performance of Stabilised Rammed Earth Walls using a  
420 Climatic Simulation Chamber', *Building and Environment*, 42 [1] pp.139-145
- 421 7. Heathcote KA, 1995, 'Durability of Earth Wall Buildings', *Construction and Building Materials*, 9[3]  
422 pp.185-189
- 423 8. Bryan AJ, 1988, 'Criteria for the Suitability of Soil for Cement Stabilisation', *Building and Environment*  
424 23[4] pp.309-319
- 425 9. Bryan AJ, 1988, 'Soil/Cement as a Walling Material - I: Stress/Strain Properties', *Building and Environment*  
426 23[4] pp.321-330
- 427 10. Innovative Pavement Research Foundation, 2005, Effects of Coarse Aggregate Clay-Coatings on Concrete  
428 Performance', *Technical Report IPRF-01-G-002-01-4.2*, Skokie, Illinois
- 429 11. Hall M & Allinson D, 2008, 'Assessing the Effects of Soil Grading on the Moisture Content-Dependent  
430 Thermal Conductivity of Stabilised Rammed Earth Materials', *Applied Thermal Engineering*, 29 pp. 740 -  
431 747
- 432 12. Hall M & Allinson D, 2008, 'Assessing the Moisture-Content Dependent Parameters of Stabilised Earth  
433 Materials Using the Cyclic-Response Admittance Method', *Energy and Buildings* 40 [11] pp. 2044 - 2051
- 434 13. Hall M & Allinson D, 2009, 'Influence of Cementitious Binder Content on Moisture Transport in Stabilised  
435 Earth Materials Analysed using 1-D Sharp Wet Front Theory', *Building and Environment* 44 pp. 688 - 693
- 436 14. Atkins P & De Paula J, 2006, *Atkins' Physical Chemistry - 8<sup>th</sup> Edition*, Oxford University Press
- 437 15. Kunzel H, 1995, 'Simultaneous heat and moisture transport in building components', Report based on PhD  
438 thesis, Fraunhofer Institute of Building Physics
- 439 16. Valen MS, 1998, Moisture Transfer In Organic Coatings On Porous Materials - The Influence Of Varying  
440 Environmental Conditions, PhD Thesis, Norwegian University of Science and Technology, Trondheim
- 441 17. BSI, 2000, BS EN ISO 12571:2000 Hygrothermal performance of building materials and products.  
442 Determination of hygroscopic sorption properties, British Standards Institute, London
- 443 18. BSI, 2001, BS EN ISO 12572:2001 Hygrothermal performance of building materials and products.  
444 Determination of water vapour transmission properties, British Standards Institute, London
- 445 19. Hall C & Hoff WD, 2002, *Water Transport in Brick, Stone and Concrete*, Taylor & Francis, London
- 446 20. Hall C & Yau MHR, 1987, 'Water Movement in Porous Building Materials - IX: The Water Absorption and  
447 Sorptivity of Concretes', *Building and Environment* 22[1], pp. 77-82
- 448 21. Hall M & Djerbib Y, 2005, "Moisture Ingress in Rammed Earth: Part 3 – The Sorptivity and the Surface  
449 Inflow Velocity", *Construction and Building Materials*, 20 [6] pp.384-395

- 450 22. Campbell GS & Norman JM, 1998, *An Introduction to Environmental Biophysics - 2nd Edition*, Springer,  
451 New York
- 452 23. Galbraith GH, 1993, 'Vapour permeability: suitability and consistency of current test procedures', *Building*  
453 *services engineering research and technology* 14 [2] pp. 67-70
- 454 24. CIBSE, 2006, *Guide A: Environmental design – 7<sup>th</sup> Edition*, Chartered Institute of Building Services  
455 Engineers, London
- 456 25. Minke G, 1995, "Materialkennwerte Von Lehmstoffen", *Bauphysik*, 17 pp. 124-130  
457

458 **Figure Captions**

459

460 Fig 1 - Water vapour sorption isotherm illustrating relative moisture contents and Kelvin

461 Equation critical pore radii

462 Fig 2 - Capillary potential: relative moisture content graph with corresponding moisture

463 domains

464 Fig 3 - Mechanisms of vapour diffusion in porous granular materials

465 Fig 4 - Experimental apparatus for determining water vapour permeability (left) and water

466 vapour absorption (right)

467 Fig 5 - Graph showing upper/lower range of mass transfer rates for each SRE material in a

468 vapour permeability test

469 Fig 6 - Heat and mass transfer in porous granular materials

470 Fig 7 - Sorption isotherm showing wetting (sorb) and drying (desorb) curves for the three

471 SRE materials

472 Fig 8 - Indoor thermal comfort portion of the sorption isotherm for comparative analysis of

473 wetting/drying curves between SRE materials

474

**Table 1 - Saturated salt solutions and associated partial pressure variables**

<b>Salt solution</b>	<b>RH (%) at 23°C</b>
Magnesium chloride	$32.90 \pm 0.17$
Potassium carbonate	$43.16 \pm 0.36$
Magnesium nitrate	$53.49 \pm 0.22$
Sodium bromide	$58.20 \pm 0.42$
Sodium chloride	$75.36 \pm 0.13$
Potassium nitrate	$94.00 \pm 0.60$

475

476

477 **Table 2 - Hygrothermal properties of SRE mix recipes**

mix	Thermal Properties						Hygic Properties				
	$\rho_{dry}$	$n$	$C$	$\lambda$	$m_f$	$\lambda^*$	$S$	$W$	$\xi_a$	$\xi_d$	
	kg/m <sup>3</sup>	-	MJ/m <sup>3</sup> K	W/m K	-	W/m K	mm/min <sup>0.5</sup>	kg/m <sup>2</sup> sPa	kg/kg	kg/kg	
						$S_r = 0$	$S_r = 1$				
433	2120 <sup>a</sup>	0.239 <sup>a</sup>	1.754	1.010 <sup>a</sup>	0.802	1.010	1.820	1.487 <sup>b</sup>	1.56E <sup>-10</sup>	23.20	31.56
613	2020 <sup>a</sup>	0.273 <sup>a</sup>	1.728	0.833 <sup>a</sup>	0.643	0.833	1.369	2.117 <sup>b</sup>	3.23E <sup>-10</sup>	28.71	19.19
703	1980 <sup>a</sup>	0.302 <sup>a</sup>	1.719	0.866 <sup>a</sup>	0.955	0.866	1.693	2.700 <sup>b</sup>	4.79E <sup>-10</sup>	13.93	21.30
478	<sup>a</sup> [8]										
479	<sup>b</sup> [10]										