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

2

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4

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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, ζ since the capillary potential, Ψ 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

26

- 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 η = viscosity
- 43 γ = surface tension
- 44 ϕ = relative humidity ($0 \leq \phi \leq 1$)
- 45 RH = relative humidity % ($\phi * 100$)
- 46 θ = relative moisture ($0 \leq \theta \leq 1$)
- 47 θ_r = residual moisture content
- 48 θ_c = capillary saturation moisture content
- 49 θ_{AEV} = air entry value moisture content
- 50 θ_s = saturation moisture content
- 51 ρ_w = density of water (kg/m^3)
-

- 52 ρ_v = density of water vapour (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 (m^2/s)
- 57 C_v = mass concentration of water vapour (kg/m^3)
- 58 M_w = molar mass of water (kg/kg mol)
- 59 R_o = the universal gas constant (J/kg mol K)
- 60 m_w = mass of water (kg)
- 61 A = area
- 62 G = water vapour flow rate (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 (mm^3/mm^2)
- 65 t = time
- 66 S = sorptivity ($\text{mm}/\text{min}^{-0.5}$)
- 67 ξ = hygroscopic moisture storage function
- 68 Ψ = capillary potential
- 69 λ = thermal conductivity (W/m K)
- 70 λ^* = moisture content-dependent thermal conductivity (W/m K)
- 71 q_{sens} = sensible heat flow (W/m^2)
- 72 q_{lat} = latent heat flow (W/m^2)
- 73 w = reference moisture content (kg/m^3)
- 74 g_v = rate of water vapour transfer (kg/s m^2)
- 75 h_e = specific latent enthalpy of evaporation/condensation (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 ϖ = 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 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_{sat}^* , when $r = \infty$) is dependent upon the pressure applied (ΔP_a) to

157 that liquid by a surrounding gas, in this case air. For a given ΔP_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 α) 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 ~ 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.

170 Figure 1 shows the wetting/drying sorption isotherms for a typical hygrothermal material,
 171 correlating relative moisture content, θ with absorbed moisture domains. As with liquid
 172 sorption, hysteresis typically occurs between the relative moisture content, θ at a given
 173 humidity, ϕ 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 θ_{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, θ_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 θ is in the capillary domain, moisture transport is
191 dominated by capillary potential, Ψ 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 θ_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 θ_{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°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% $\Delta\text{wt}/\text{day}$ [17]. Samples were then fully
211 immersed in distilled water for 24 hours and the saturated mass recorded to find θ_c , but θ_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 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 ± 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 (Δm_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 (m^2), and Δp_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 (mm^3/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 Ψ (due to smaller \bar{r}) but reduce ξ (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, λ^* (W/m K) [11]. The dry state and moisture-
 292 dependant thermal conductivity (λ^*) 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, ϖ , 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 θ_r is difficult to measure experimentally since by definition it occurs
334 at $\phi \rightarrow 1$. Therefore, the important transitional point θ_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), ξ_a and for desorption
340 (drying), ξ_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 θ never approaches θ_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 θ 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

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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 [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 - 8th 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 – 7th 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

Salt solution	RH (%) at 23°C
Magnesium chloride	32.90 ± 0.17
Potassium carbonate	43.16 ± 0.36
Magnesium nitrate	53.49 ± 0.22
Sodium bromide	58.20 ± 0.42
Sodium chloride	75.36 ± 0.13
Potassium nitrate	94.00 ± 0.60

475

476

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

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