



Analysis of the hygrothermal functional properties of stabilised rammed earth materials

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ABSTRACT

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

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1. Introduction

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

more insulating and less permeable coverings, e.g. varnish and paints.

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

The objective of this paper is to investigate how the hygrothermal properties of SRE materials can be experimentally measured and how these functional properties are influenced by the variable mix design parameters of the material. The aim is to test the hypothesis that hygrothermal properties can then be predicted and designed through correspondence with mix design parameters. SRE materials can be characterised as multiphase granular composites whose particle size distribution (PSD) and particle packing efficiency largely determine the geometry of their matrix structure. The term stabilisation refers to the application of a process and/or additive component that enhances the cohesion, Young's modulus or another physical property [5–7]. By far the most common forms of stabilisation are (i) dynamic compaction and (ii) addition of hydraulic binders, e.g. cementitious materials. As with most granular soils, dynamic compaction close to the Proctor optimum moisture content increases the inter-particle friction/interlock whilst reducing the bulk porosity. The addition of hydraulic binders (commonly $\leq 10\%$ Portland cement) increases the

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Nomenclature			
V_T	total volume.	D	diffusion coefficient for water vapour in still air (m^2/s).
V_s	volume of solid.	C_v	mass concentration of water vapour (kg/m^3).
V_v	volume of void.	M_w	molar mass of water ($\text{kg}/\text{kg mol}$).
V_a	volume of air.	R_o	the universal gas constant ($\text{J}/\text{kg mol K}$).
V_m	molar volume.	m_w	mass of water (kg).
p_v	vapour pressure.	A	area.
p_{sat}	saturation vapour pressure.	G	water vapour flow rate (kg/s).
p_{sat}^*	saturation vapour pressure above a flat surface.	W	water vapour permeance ($\text{kg}/\text{m}^2 \text{ s Pa}$).
P_a	total air pressure.	i	cumulative volume of absorbed water per unit inflow surface area (mm^3/mm^2).
P_w	total water pressure.	t	time.
r	pore radius.	S	sorptivity ($\text{mm}/\text{min}^{-0.5}$).
r_{crit}	critical pore radius.	ξ	hygroscopic moisture storage function.
\bar{r}	mean pore radius.	Ψ	capillary potential.
T	thermodynamic temperature (K).	λ	thermal conductivity ($\text{W}/\text{m K}$).
η	viscosity.	λ^*	moisture content-dependent thermal conductivity ($\text{W}/\text{m K}$).
γ	surface tension.	q_{sens}	sensible heat flow (W/m^2).
ϕ	relative humidity ($0 \leq \phi \leq 1$).	q_{lat}	latent heat flow (W/m^2).
RH	relative humidity % ($\phi \times 100$).	w	reference moisture content (kg/m^3).
θ	relative moisture ($0 \leq \theta \leq 1$).	g_v	rate of water vapour transfer ($\text{kg}/\text{s m}^2$).
θ_r	residual moisture content.	h_e	specific latent enthalpy of evaporation/condensation (J/kg).
θ_c	capillary saturation moisture content.	S_r	degree of saturation (or saturation ratio).
θ_{AEV}	air entry value moisture content.	m_f	moisture factor.
θ_s	saturation moisture content.	c_p	specific heat capacity at constant pressure ($\text{J}/\text{kg K}$).
ρ_w	density of water (kg/m^3).	c_p^*	moisture content-dependant specific heat capacity at constant pressure ($\text{J}/\text{kg K}$).
ρ_v	density of water vapour (kg/m^3).	ω	relative mass fraction.
g	gravitational constant.		
h	height.		
$g_{v, \text{air}}$	rate of water vapour diffusion through air.		

internal cohesion of the material and enhances durability and toughness [5–9]. Since hardened cement paste bonds particles together by surface adhesion between the paste and particle surfaces (interfacial transition zone), cement stabilisation is most effective on granular soils [8–10] where the specific surface area per unit mass is lower and the greater absence of cohesive materials is less able to interfere with the interfacial transition zone.

2. Specimen preparation

The characterisation of SRE material composition can easily be approximated using the geotechnical soil model. The particle size distribution for SRE must normally fall within designated upper and lower limits resulting in a wide range of achievable particle packing efficiencies and associated bulk porosity/dry density and void size distribution (VSD), as explained extensively in the authors' previous research [11–13]. By using an established technique of blending characterised soil constituents (14–6.3 mm gravel, 5 mm down medium grit sand, silty clay) and matching the net PSD to the defined upper/lower limits, the authors can maintain the parameters of aggregate mineralogy, particle angularity and clay mineralogy as constants whilst keeping PSD as the single variable. SRE specimens were prepared as 11 cylinders (3 compaction layers), 1/31 discs (1 compaction layer), and 300 × 300 mm slabs (1 compaction layer). All were stabilised by compacting at OMC using a constant energy of 596 kJ/m^3 and the addition of 6% wt CEM IIa class Portland cement, followed by air curing for a minimum of 28 days at 20 °C (± 2 °C) and 75% RH ($\pm 5\%$) in an environmental chamber.

3. Moisture sorption and storage

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

Although the classification of absorbed moisture (determined by its phase upon entry) cannot change, its phase once inside V_T can change, e.g. condensing from vapour to liquid. This is chiefly governed by internal void geometry and electrostatic surface charge for a given temperature and partial vapour pressure. Theoretically, the saturation vapour pressure above a flat surface of liquid water (p_{sat} , when $r = \infty$) is dependent upon the pressure applied (ΔP_a) to that liquid by a surrounding gas, in this case air. For a given pressure differential at the liquid/gas interface, ΔP_a , the saturation vapour pressure becomes $p_{\text{sat}} = p_{\text{sat}}^* e^{V_m \Delta P / R_o T}$ [14]. By curving the surface of the water, as in a meniscus in a capillary or pore, to a known radius, r

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