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Propiedades térmicas e hídricas de materiales aislantes apropiadas para fábricas históricas

Thermal and hygric properties of insulation materials suitable for historic fabrics

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***Resumen*— Mejorar el rendimiento térmico de los edificios mediante la adaptación del aislamiento puede reducir la pérdida innecesaria de calor y energía minimizando el impacto ambiental. El aislamiento térmico interior es a menudo el elegido en los edificios históricos para preservar sus características. Sin embargo, el aislamiento interior puede aumentar la acumulación de humedad en paredes que socavan su durabilidad. Hay una falta de conocimiento sobre la eficacia de sólidos muros históricos y el impacto del aislamiento interno en su comportamiento higrotérmico. Este artículo investiga las propiedades térmicas e hídricas de siete opciones de aislamiento internos, incluyendo la pintura térmica, aerogel (AG), corcho-cal (CL), cal-cáñamo (HL), silicato de calcio bordo (CSB), tablero de fibra de madera (TFB) y placa de polisocianurato (PIR). Sus propiedades se comparan con un enlucido de cal tradicional. El PIR y el aerogel AG muestran extraordinarias propiedades térmicas que contribuyen a la comodidad y ahorro de energía, y la CL y HL son permeables al vapor y a la capilaridad. Estos tienen aproximadamente el doble de la masa térmica de los otros aislantes. Además, la CL tiene una buena inercia térmica (segunda difusividad más baja) y, a pesar de su contenido orgánico, una adsorción de baja a alta RH.**

Palabras clave— Aislamiento; conductividad térmica; capacidad calorífica específica; difusividad; masa térmica; permeabilidad al vapor de agua; capilaridad ; humedad de referencia; porosidad abierta; nanoporosidad..

***Abstract*- Improving the thermal performance of buildings by retrofitting insulation can reduce unnecessary heat loss and building operational energy minimising environmental impact. Internal thermal insulation is often favoured for historic buildings to preserve their features. However, internal insulation may increase moisture accumulation in walls undermining their durability. There is a lack of knowledge on the performance of historic solid walls and the impact of internal insulation in their hygrothermal behaviour. This paper investigates the thermal and hygric properties of seven internal insulation options including thermal paint, aerogel (AG), cork lime (CL), hemp lime (HL), calcium silicate board (CSB), timber fibre board (TFB) and polyisocyanurate (PIR) board. Their properties are compared with a traditional lime plaster. The PIR and aerogel AG show outstanding thermal properties that contribute towards indoor thermal comfort and energy savings and the CL and HL are vapour permeable and capillary active. They have approximately double the thermal mass of the other insulations. In addition, the CL has a good thermal inertia (2nd lowest diffusivity) and, in spite of its organic content, a low adsorption at high RH.**

Index Terms— Insulation; thermal conductivity; specific heat capacity; diffusivity; thermal mass; water vapour permeability; capillarity; reference moisture; open porosity; nanoporosity.

I. INTRODUCTION

The sector is one of the key consumers of energy in Europe using approximately 450Mtoe per annum of which space heating accounts for around 70% of the total energy use (BPIE, 2011). This contributes to climate change, recognised as one of the most significant global problems of the 21st century. Retrofitting insulation to buildings lowers the energy requirement for heating and cooling reducing both emissions and energy consumption thus lowering environmental impact. Applying external insulation is often preferred however, this is not usually appropriate for historic buildings on account of the significance of their facades.

There are risks associated with retrofitting insulation, primarily the accumulation of moisture within the wall and consequent structural and material damage such as frost damage, timber decay and biological growth.

Insulation can increase moisture accumulation in a wall on account of two primary reasons. First, the reduced permeability of an insulation can impede the wall drying towards the interior. In addition, lowering of the wall temperature by the insulation can reduce the drying capacity of the wall increasing moisture condensation. Moisture can negatively affect the occupants by reducing thermal comfort and risk human health (the critical moisture content for mould growth is a surface RH below 80% or wood moisture content below 20% -Straube 2009).

Moisture degrades the thermal performance of the wall and insulation. Rhee-Duverne & Baker (2013) observed a clear relationship between moisture content and poor thermal insulation, with the thermal conductivity of water saturated bricks 1.5 to 3 times higher than dry ones. This is due to the higher thermal conductivity of water when compared to air.

Historic buildings form a large proportion of the building stock in Europe. They are often of architectural and historic interest and it is essential that any thermal upgrading does not undermine their special character. A balance needs to be found between protecting heritage values and appropriate interventions that lessen adverse environmental impact, reduce energy costs and improve occupant comfort to ensure the long term viability of historic buildings.

Moisture transfer and accumulation in building materials

The ability of moisture storage and transfer depends on the characteristics of the material including hydrophillicity/ hydrophobicity and pore structure (pore size distribution, quantity and connectivity). Diffusion typically occurs in larger pores while capillarity is active in smaller pores (Künzel, 1995) of which the greater ones have lower flow resistance allowing water to flow (absorption) and the smaller ones show higher tractive forces (Krus, 1996). Benavente (2011) identifies that liquid water is transported by capillary forces in pores sized up to 0.1 μm with high water absorption rates in the size interval between 1 μm and 1 mm.

Liquid water can enter the building by means of rainfall, rising damp, cracks, construction work or vapour condensation when wall temperatures drop below the dew point. It travels by capillary action and follows the moisture content gradient.

TABLE I
INSULATION MATERIALS STUDIED

MATERIAL	COAT/THICKNESS	COMPOSITION
Lime plaster (control) (LP)	Floating coat c.12mm	3:1:0.60 sand:NHL3.5:water
	Skim coat 3mm	1:1:0.5 sand:NHL2:water
Paint on control lime plaster (P)	Floating coat c.12mm Skim coat 3mm 3 coats of paint	3:1:0.60 sand:NHL3.5:water 1:1:0.5 sand:NHL2:water Emulsion+ceramic additives
Aerogel (AG)	19.5mm aerogel and plasterboard	As per manufacture's spec using mechanical fixings
Lime and hemp (HL)	2*20mm layers	Hemp:NHL2:water 1:2.9:3.5 (by weight)
Lime and Cork (CL)	2*20mm layers	2.15:1 (by weight) Cork/lime:water
Calcium silicate board (CSB)	30mm	As per manufacture's spec- adhesive to affix board
	proprietary skim coat 6-7mm	Basecoat (4-5mm) -mesh imbedded-; finish coat (2mm)
Timber fibre board (TB)	40mm	As per manufacture's spec using mushroom fixings
	proprietary skim coat 6-7mm	Basecoat with mesh imbedded (4-5mm) and finish coat (2mm)
PIR with foil	37.5mm	As per manufacture's spec using mechanical fixings

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Liquid water transport has the ability to transfer considerable more moisture than diffusion (Kunzel and Holm, 2009).

Methods of internal insulation: dealing with moisture when internally insulating solid walls

There is no agreement on the most appropriate method to deal with water when internally insulating solid walls. Broadly, two approaches are used: vapour tight systems (that prevent moisture entering the wall from the interior) and capillary active/vapour permeable systems that facilitate the drying of wall moisture. The moisture behaviour of these systems reported by different authors is inconsistent probably due to the variety of materials, walls and moisture sources.

In vapour tight systems, a vapour retarder is installed on the interior side of the insulation to prevent moisture entering the wall. These systems prevent drying towards the interior, they do not allow moisture buffering of room humidity and perforations can result in substantial under performance. Vapour tight systems use insulators such as polyisocyanurate (PIR), polyurethane (PUR), mineral wool and others. Nielsen et al. (2012), Browne (2012) and Klõšeiko et al (2015) report that vapour tight systems are not particularly efficient to control wall humidity and can result in moisture accumulation at the insulation/wall interface.

Pavlik and Cerny (2009) investigated a capillary active system of hydrophilic mineral wool incorporating a water vapour retarder on the wall interface (as opposed to the interior wall surface in vapour tight systems). They observed no liquid moisture and low RH in the insulation which they attributed to its active water transport. In agreement, in-situ testing of the same insulation showed no water condensation within the wall Toman et al. (2009). Therefore, capillary active systems seem more appropriate than vapour tight systems for facades sensitive to damage by moisture accumulation.

This paper investigates the thermal and hygric properties of a number of insulating materials (table 1) to try to ascertain whether they would be suitable for traditional and historic fabrics.

II. MATERIALS

Thin insulation materials (<45mm) are investigated to minimize adverse visual impact on historic features. A traditional lime plaster was compared with the insulation materials. Lime plaster is not considered an insulator although it has good thermal properties (Stefanidou and Assael, 2010). Researchers report thermal conductivity and specific heat capacity of 0.73W/mK and 970J/KgK (Cerny et al., 2006) and 0.83W/mK and 867J/KgK (Vejmelková et al., 2012) for 1:3 (hydrated lime: aggregate) mixes.

The thermal paint investigated incorporates hollow ceramic microspheres which are supposed to reflect the radiant energy from heated objects thereby reducing energy transfer through the wall. Several authors report that paint coatings can reduce heat transfer (Shen et al., 2011; Azemati et al., 2013 and Sheikhzadeh et al., 2014) but others conclude that they are largely ineffective (Petrie and Childs, 1998).

Aerogel is an innovative material in the building insulation industry with very low thermal conductivity. It is a silica based gel in which the liquid component has been replaced by gas (Cuce et al. 2014). When used as wall insulation, it is typically bonded to a facing such as plasterboard. Little research has been undertaken on its performance to date.

Cork lime is a sustainable insulation made with cork, hydraulic lime and cement. Its thermal properties vary depending on composition and density. Bras et al. (2014) measured thermal conductivity of 0.4-0.8W/mK for density between 1600 and 2100Kg/m^3.

Hemp lime is a sustainable material consisting of lime and hemp shiv. Its thermal properties vary depending on composition and density. Conductivity values range from 0.05 to 0.12 W/mK (Daly et al. 2012)] and specific heat capacity between 1000 J/kgK (Tran Le (2011) referring to Collet (2004)) and 1560 ± 30 J/kgK (Evrard, 2008).

Calcium silicate board is a mixture of portland cement, fine silica, cellulose fibers and fillers cured in an autoclave. Its thermal conductivity is slightly higher than other insulations but it is a popular choice for historic structures as a capillary active material that wicks away water accumulation in walls (Kunzel and Holm, 2009).

Wood fibre insulation is made from defibrated softwood. Vololonirina et al. (2014) observed an average thermal conductivity of 0.0045 W/mK for the dry material, increasing linearly with moisture content.

Polyisocyanurate (PIR) board is a good thermal insulator often retrofitted to walls. Concerns have been raised on account of its vapour impermeability and thus potential moisture accumulation.

III. RESULTS

A. Specific heat capacity of the insulation materials

It was measured in an adiabatic surrounding. The specimens (200*200 mm) were heated at 100 °C for 24 hours and then placed into insulated containers filled with water at c.13 °C. The temperature rise of the water was monitored and the heat capacity was then measured according to 1.

$$\Delta T_{im} m_{im} C_{im} = \Delta T_w m_w C_w \qquad (1)$$

ΔT_{im}: temperature of insulation from oven – temperature of water after sample is immersed (K).

m_{im}: mass of insulation (kg).

C_{im}: specific heat capacity of insulation to be calculated (J/kgK).
ΔT_w: temperature of water before sample is immersed – temperature of water after sample is immersed.
m_w: mass of water in container (kg).
C_w: specific heat capacity of water (4181 J/kgK).

B. Bulk density (ρ) [kg/m^3] and open porosity [m^3/m^3]

The specimens were immersed in water for 28 days. The saturated (Ms) and hydrostatic weights (Mi) were measured (kg). The samples were then dried and their dry weight (Md) measured. The bulk density and open porosity were calculated according to equations (2) and (3):

$$\rho = Md/(Ms-Mi) \tag{2}$$

$$\text{open porosity} = (M_s-M_d)/(M_s-M_i) \tag{3}$$

C. Pore size distribution (nanoporosity)

It was analysed by gas sorption with a Quantachrome Nova 4200e. Samples were degassed under vacuum at 100 °C for 16 hours and the weight of gas adsorbed at different pressures measured. The resulting desorption isotherm was used to determine mean pore sizes using the Barrett-Joyner-Halenda (BJH) method.

D. Moisture adsorption at 80% RH (reference water content)

The moisture content of the insulation in 75.5, 85.1 and 97.6% RH environments was determined by placing samples in sealed containers with saturated solutions of sodium chloride, potassium chloride and potassium sulphate (ISO 12571:2013). The samples were weighted at intervals until equilibrium was achieved. They were dried at 105°C and their dry weight recorded. The reference moisture content is the moisture adsorption at 80% RH [kg/m^3] and was deduced by extrapolation between the 75.5 and 85.1% RH environments.

E. Water vapour diffusion resistance factor [μ]

Dry and wet cup test were undertaken (table 2) EN 12086:1997. Water vapour travels through the specimen from the humid to the dry environment. The water vapour transfer was measured by weighing the test assembly (specimen and dish) weekly. The resistance factor was calculated by dividing the water vapour diffusion coefficient of air by the moisture permeability of the material. Variations in room temperature were accommodated using the Magnus Tetens equation.

F. Water absorption coefficient by capillarity

The insulation and facing (plaster/plasterboard) were measured individually. The specimens were placed on a wire grill in a container so that water covered the bottom 10mm EN1925:1999. At intervals, they were removed and allowed to drain prior to weighing. A graph of the mass of water absorbed divided by the immersed area (kg/m^2) as a function of the square root of time (hours) was plotted. The slope of this line is considered the water absorption coefficient by capillarity. Testing AG, PIR and TB was difficult as capillary water did not strongly adhere and, despite vertical draining, water loss occurred during weighing. In addition, the materials absorbed small quantities of water (<1.5 g for the AG and PIR and 14 g for the TB) resulting in measurement inaccuracies.

TABLE II
WET AND DRY CUP TESTS

Test	Dry state conditions		Wet state conditions	
Dry cup- test conditions A	0% RH	75g of calcium chloride in cup	50% RH	Curing room
Wet cup	50% RH	Curing room	75% RH	75g NaCl sat sol. in cup

G. Water absorption coefficient (vertical tube)

A vertical tube was affixed to the surface of the insulation using mastic adhesive in accordance with RILEM recommendations (Shen et al. 2011). The bulk materials and facing (plaster/plasterboard) were measured together. The tube was filled with water and the quantity of absorbed water measured at regular intervals.

IV. RESULTS

A. Thermal properties of insulation materials

Thermal mass, diffusivity and effusivity were calculated with the density and specific heat capacity laboratory results (table 3). The thermal conductivity was calculated in-situ by comparing the u-value of a wall with and without insulation.

All the insulation materials have low thermal conductivity and relatively low thermal mass compared to the lime plaster (fig 1). The aerogel and PIR have particularly low thermal conductivity, followed by the timber board and cork lime and then the CSB and hemp lime. As expected, the lime plaster has the greatest density and thus the highest thermal conductivity being therefore the poorest insulator. The lime plaster also shows the highest thermal mass and greatest diffusivity (followed by the CSB with less than half). Therefore, even if able to store a considerably superior amount of heat, the plaster changes temperature faster than the other insulators. The thermal paint (covering lime plaster) does not make a measureable contribution towards either the thermal conductivity or thermal mass compared to the control plaster.

The cork lime and hemp lime have approximately double the thermal mass of the other insulations which is a valuable attribute for attenuating fluctuating external temperatures. The hemp lime is less dense than the cork lime however, it has a greater specific heat capacity resulting in a comparable thermal mass. However the cork lime has a greater thermal inertia (2nd lowest diffusivity) which would contribute towards indoor thermal comfort.

TABLE III
THERMAL PROPERTIES OF INSULATION MATERIALS

material	Thick-ness	density	thermal conductivity	specific heat capacity	thermal mass	diffusivity	effusivity
		P	Λ	C_P	C_P P	Λ/(C_P P)	√ Λ C_P P
	mm	Kg/m^3	W/mk	J/Kgk	Kj/K m^2	m^2/S (X10¯8)	J/m^{2}ks$^{1/2}$
LP	40	1820	0.800*	863.90	62.89	50.88	1121.53
P	40	1820	0	866.80	63.10		
AG	19.5	509.4	0.016	1233.50	12.25	2.61	101.54
CL	40	806.2	0.065	866.50	27.94	9.26	212.54
HL	40	602.6	0.090	1068.00	25.74	14.06	241.33
CSB	35	402.0	0.089	819.40	11.53	27.08	171.39
TB	45	231.3	0.050	1217.80	12.68	17.61	118.23
PIR	37.5	233.4	0.034	1421.10	12.44	10.33	106.59

* value from EN ISO 10456:2007

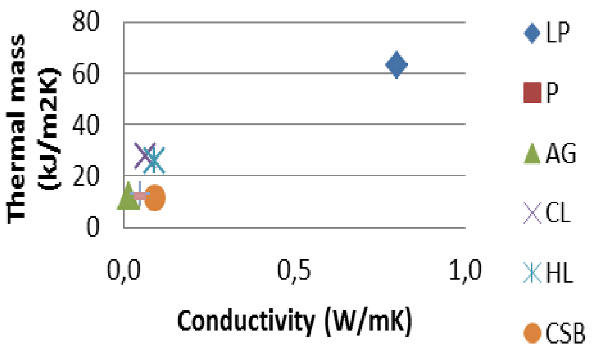

Fig. 1. Relationship between thermal mass/heat capacity and thermal conductivity of the insulation materials.

The calcium silicate board (CSB) has higher thermal conductivity than most of the insulations and does not benefit from the good thermal mass seen in the hemp and cork lime. It also has a higher diffusivity and effusivity than the other insulators and so it changes temperature faster. The timber board (TB) has reasonably low thermal conductivity and high specific heat capacity. The aerogel (AG) shows outstanding thermal properties including a low effusivity coupled to a high specific heat capacity that result in a very low diffusivity therefore, even though its thermal mass is low, the material has high thermal inertia like a high thermal mass material. Similarly, the PIR also has high specific heat and low effusivity but a much greater diffusivity therefore it changes temperature faster. The very good insulating properties of the aerogel (AG) with low thermal diffusivity and effusivity, should positively contribute towards thermal comfort of the indoor environment.

B. *Moisture storage and transfer properties*

As it can be seen from Table 4, no strong correspondence exists between pore sizes and moisture storage/transfer properties, probably due to the strong effect of the hydrophilic/ hydrophobic nature of the materials in their moisture behaviour. This the case of the hydrophobic PIR and AG, with low capillary action despite a large quantity of pores in the size range active to capillary transport (<100nm).

From the results, we can conclude that CL, HL and in particular CSB are capillary active insulation systems and the PIR and AG are vapour tight systems with low liquid water transport. The TB is an exterior system that is mistakenly applied internally. It allows vapour transport but appears to have been treated to inhibit liquid moisture transfer as appropriate for an external insulation system.

TABLE IV
MOISTURE STORAGE AND TRANSFER PROPERTIES OF THE INSULATION

	Bulk density	Open Porosity	Water vapour diffusion resistance (cup tests)	adsorption t 80%RH- reference water content	Water absorp. coeff capillarity	Water absorp. coeff. vertical tube
	kg/m^3	m^3/m^3		kg/m^3	kg/m²√s	kg/m²√s
LP	1820.0	0.29	11.7 - 10.3	20.6	0.127	0.233
P	1820.0	0.29	17.2 - 17.9	N/A	0.011	0.001
AG	140.8	0.34	28.1 - 17.5	2.5	0.002	0.003
CL	806.1	0.44	8.7 - 5.1	19.7	0.229	0.130
HL	602.6	0.66	9.2 - 6.1	37.6	0.318	0.315
CSB	272.7	0.89	8.5 - 4.3	5.4	0.800	0.085
TB	110.5	0.55	9.1 - 3.2	15.2	0.018	0.054
PIR	32.6	0.05	75.9 - 87.8	0.0	0	0.020
AGP	897.3	0.67	-	128.0	0.056	-
CSBP	1177.0	0.45	-	14.0	0.197	-
TBP	1197.0	0.34	-	24.6	0.077	-
PIRP	634.9	0.75	-	89.9	0.244	-

The postfix p indicates the plasterboard finish on the insulations.

C. *Open porosity and nanoporosity*

The results evidenced that the lime plaster has a lower open porosity than the insulations (except PIR) (table 4) and a relatively low proportion of nanopores compared to the insulations (Fig. 2). Notably, the lime based materials (CL, HL) and CSBp have a smaller proportion of small pores (<10nm). It was also noted that the porosity of the lime plaster and paint coated lime plaster are the same as the bulk material predominates.

The PIR and AG have a low open porosity but a large quantity of small pores (<10nm) while conversely, CSB, HL and CL have higher open porosity but a reduced quantity of small pores (>10nm) compared to the other insulation (AG, TB and PIR). The TB has a middle range open porosity and quite a large quantity of small pores.

D. *Moisture adsorption at varying RH*

Hydrophillic building materials facilitate moisture storage and transfer while conversely hydrophobic materials repel water. Hydrophobic materials typically show a low water absorption which suddenly increases at high RH. Building materials are typically hydrophilic with a high sorption capacity at low and medium RH (Karamanis 2015). The moisture contents at 75.5, 85.1 and 97.6% RH (Fig. 3) do not provide enough data points to allow a proper classification of the type of isotherm which would indicate the hydrophobicity/ hydrophillicity of the insulation. However, the strong hygroscopic nature of the organic materials in the timber board, hemp lime and calcium silicate board is evident at these relative humidities. The cork lime, in spite of its organic content, has a low moisture content at 97.6% RH. Similarly, Hansen (1986) measured a low moisture content for cork at 90% RH. The hydrophobic nature of the aerogel is evidenced with his low moisture content and a characteristic steep gradient moisture content rise between 90 and 95% RH (the points between 85.1% and 97.6% are not joined for this reason). In the PIR, also a hydrophobic material, accurate low moisture contents were not measured due to its lightweight.

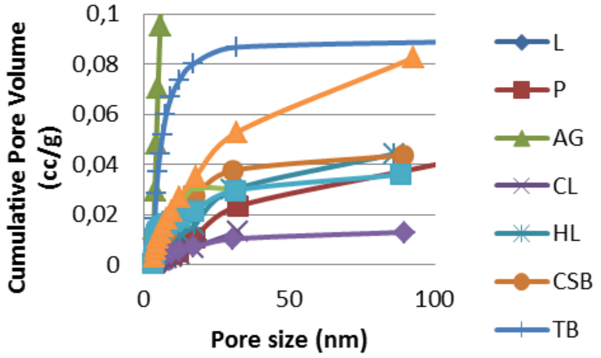

Fig. 2. Volume of nanopores in the lime plaster and insulation materials by gas sorption.

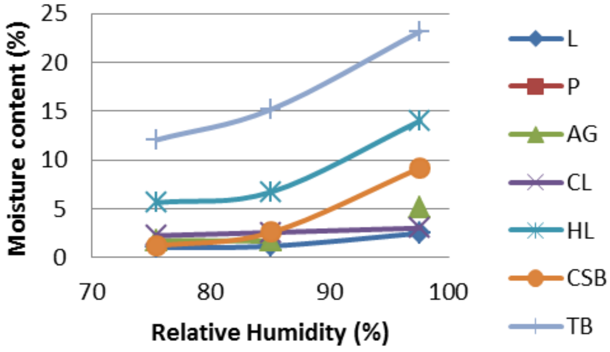

Fig. 3. Moisture content of the lime plaster and insulation materials at 75.5, 85.1 and 97.6% RH.

E. Water *vapour diffusion/ vapour permeability (cup tests)*

A characteristic trend is observed between the dry and wet cup tests in which the wet cup tests suggest an increased vapour permeability. This is attributed to capillary condensation in the pores during the wet cup test increasing liquid transport and shortening diffusion paths among water islands which result in increased vapour permeability. The results suggest that lime plaster which has a lower open porosity than the insulation materials (excluding PIR and AG with vapour barriers) has a corresponding lower vapour permeability. It was also evidenced that the paint layer reduces the vapour permeability of the lime plaster (μ increases from 11.7 to 17.2). The CL, HL, CSB and TB have a high vapour diffusion (8.7, 9.2, 8.5 and 9.1 respectively) which is characteristic of large pore materials (Künzel 1995). The plaster coating on the CSB and TB is probably reducing the vapour permeability of the insulation on account of its lower open porosity. The PIR and AG show a high vapour resistance of 75.9 and 28.1 respectively probably due to their vapour control layers.

F. *Liquid transport coefficient by capillary action*

As aforementioned, this was measured with two methods. There is disparity between the two sets of results on account of the test set-up including: direction of absorption (vertical vs horizontal) and water pressure (none vs height of water in tube c. 1177.2 Pa).

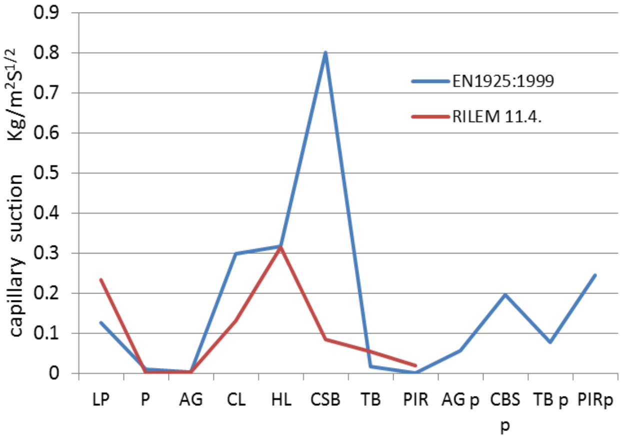

Fig. 4. Capillary suction of the lime plaster and insulation materials.

According to the results, there is a linear relationship between the open porosity and capillarity liquid transport of the bulk materials (Fig. 4). Benavente (2011) states that liquid water is transported by capillary forces in pores sized under 100nm however, no clear relationship was found between the nanoporosity (pores up to 100nm) and the capillarity liquid transport. This is likely due to the hydrophocity/ hydrophillicity of the materials.

It was also noted that the lime plaster had a water absorption coefficient of 0.127/0.233 kg/m²√s (depending on the measurement technique) and that the paint reduces liquid transfer by impeding the entry of liquid water into the bulk material, dropping the coefficient from 0.127 to 0.011kg/m²√s. Both the cork and hemp lime show greater capillarity than the lime plaster which is attributed to the high water absorption of their organic components.

The CSB is exceptionally capillary active (0.873kg/m²√s), allowing large liquid moisture transfer. This is widely considered an advantageous property which enables to wick liquid moisture accumulations through the material to facilitate drying. The CSBp has a slower capillary coefficient of 0.197kg/m²√s. The reduced coefficient observed for the RILEM test (0.085kg/m²√s) on the surface plaster suggests liquid transfer may be delayed at the CSB / plaster interface. This phenomena is commonly observed between brick and mortar (Derluwn et al. 2008). It is known as the hydraulic interface resistance and is likely on account of imperfect contact between the CSB and plaster causing a reduction in flow through the interface.

Timber fibre board is considered a capillary active material although the liquid transfer coefficients are low at 0.018kg/m²√s. This is attributed to the hydrophobic treatment resulting in low capillary liquid transfer (it was an outdoor insulation that was mistakenly applied indoor). A capillary active version of the board would be suitable for the interior.

The AG and PIR bulk materials have porosity in the range suitable for capillary transfer although this is inhibited by their hydrophobic nature and vapour barriers (0.002 and 0 kg/m²√s respectively). The plasterboard facing of both materials allows a small amount of liquid transfer by capillary (0.063 and 0.272kg/m²√s) but their vapour barrier should prevent water ingress into the bulk insulation.

V. CONCLUSIONS

The hydrophilic/ hydrophobic nature of the materials has such a strong effect on their moisture behavior that there is little correspondence between pore sizes and moisture storage/ transfer properties.

The polyisocyanurate (PIR) and aerogel (AG) are hydrophobic, vapour-tight systems with low liquid water transport. The bulk materials have low capillarity (despite having porosity in the capillary transfer range) due to their hydrophobic nature and their vapour barriers. They both show outstanding thermal properties that contribute towards indoor thermal comfort and energy savings. In particular, the AG with low thermal conductivity and effusivity coupled to a high specific heat capacity that result in a very low diffusivity. Therefore, even with a low thermal mass, the AG has high thermal inertia like a high thermal mass material. PIR has a much greater diffusivity so it changes temperature faster and therefore does not protect the interior from fluctuating external temperature.

The lime plaster shows the highest thermal conductivity, thermal mass and diffusivity so it is able to store a superior amount of heat than the insulation but changes temperature faster. It is capillary active but has a lower open porosity, nanoporosity and lower vapour permeability than the insulations (except PIR).

The thermal paint does not make a measureable contribution towards either thermal conductivity or thermal mass and reduces the vapour permeability and the capillary liquid transfer of the lime plaster.

The cork lime (CL) and hemp lime (HL) have approximately double the thermal mass of the other insulations, a valuable attribute for attenuating fluctuating external temperatures. In addition, the CL has a good thermal inertia (2nd lowest diffusivity) which would contribute towards indoor comfort. CL and HL are vapour permeable and capillary active, with a greater capillarity than the lime plaster probably due to the absorption of their organic components. The CL, in spite of its organic content, has a low adsorption at high RH.

The thermal performance of the calcium silicate board (CSB) is inferior as it has higher thermal conductivity, diffusivity and effusivity than most of the insulations and does not benefit from the good thermal mass of the hemp and cork lime. However, it is vapour permeable and exceptionally capillary active, an advantageous property which enables to wick liquid moisture accumulations facilitating drying; but liquid transfer is greatly reduced by its plaster coating interface.

The timber board (TB) has reasonably low thermal conductivity and high specific heat capacity. It is vapour permeable and considered capillary active although the liquid transfer coefficients are low probably due to its hydrophobic treatment (it was an outdoor insulation that was mistakenly applied indoor). A capillary active version of the board would be suitable for the interior. The plaster coating on the TB is reducing the vapour permeability of the insulation.

The CL is the capillary active system that shows more outstanding thermal properties and a lower adsorption at high RH.

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