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# Experimental investigation of thermal inertia properties in hemp-lime concrete walls

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## Abstract

Hemp-lime concrete is a sustainable alternative to standard building wall materials, with low associated embodied energy. It exhibits good hygric, acoustic and thermal properties, making it an exciting, sustainable building envelope material. When cast in temporary shuttering around a timber frame, it exhibits lower thermal conductivity than concrete, and consequently achieves low U-values in a primarily mono-material wall construction. Although cast relatively thick hemp-lime walls do not generally achieve the low U-values stipulated in building regulations.

However assessment of its thermal performance through evaluation of its resistance to thermal transfer alone, underestimates its true thermal quality. The thermal inertia, or reluctance of the wall to change its temperature when exposed to changing environmental temperatures, also has a significant impact on the thermal quality of the wall, the thermal comfort of the interior space and energy consumption due to space heating. With a focus on energy reduction in buildings, regulations emphasise thermal resistance to heat transfer with only less focus on thermal inertia or storage benefits due to thermal mass.

This paper investigates dynamic thermal responsiveness in hemp-lime concrete walls. It reports the influence of thermal conductivity, density and specific heat through analysis of steady state and transient heat transfer, in the walls. A novel hot-box design which isolates the conductive heat flow is used, and compared with tests in standard hot-boxes. Thermal diffusivity and effusivity are evaluated, using experimentally measured conductivity, based on analytical relationships.

Experimental results evident that hemp-lime exhibits high thermal inertia. They show the thermal inertia characteristics compensate for any limitations in the thermal resistance of the construction material. When viewed together the thermal resistance and mass characteristics of hemp-lime are appropriate to maintain comfortable thermal indoor conditions and low energy operation.

**Key words:** hemp, hemp-lime concrete, thermal mass, thermal diffusivity, hot-box testing, pozzolan

## 1. Introduction

Advanced building skins of contemporary architecture are often characterised by materials of high embodied energy that result in significant carbon emissions in their production. In an effort to reduce these Greenhouse gas emissions, to levels below 1990 levels and thereby mitigate climate change, energy related to the operation and construction buildings has risen in prominence in research and policy. Due research focus is being given to the evaluation of alternatives to common building materials as we aim to progress towards a more sustainable built future. Bio-aggregate based materials offer the potential to considerably reduce the embodied energy related to the construction of buildings. During their lifetime they absorb atmospheric $CO_2$

through photosynthesis, and lock it in to the material that forms the product for building construction [1]. Bio-based materials can often be recycled or composted reducing their waste impact after demolition. Hemp is a particularly promising material that grows up to 4m in 4 months [1]. It grows with low fertilizer and irrigation demand and the woody core, a by-product after harvesting of seeds, fibres and stem, can be used as aggregate in a composite formulation. Cement, hydraulic lime or natural hydrated lime can be used as the binder. Lime offers a sustainable alternative to cement. Lime recarbonises when exposed to moisture and $CO_2$. When combined with cement replacements such as GGBS [2] the embodied impact can be further reduced relative to purely cementicious bound composites.

Advanced building skins of contemporary architecture are often characterised by multiple layers each performing a different function. This is particularly true for non-glazed wall sections that include, rainscreens, weather, thermal and air tightness barriers. Hemp-lime in comparison is a bio-aggregate based composite material that forms a predominantly homogenous wall when cast around surrounding structural timbers and rendered off. Hemp-lime has been shown to provides thermal [2], mechanical [3], durability [3] and moisture transport [4] qualities. Constructed hemp concrete buildings perform well [1][5] with the composite having a proven ability to buffer moisture and temperature changes.

Thermal parameters of hemp-lime are increasingly well characterised with a proliferation of studies in recent years publishing performance results for a range of binder types [2], densities [6], moisture contents, and construction/application methods [7]. Recent studies of standard [8] and hemp based buildings [9] have shown that assessment of performance based on U-values alone is unrepresentative of true performance. A material with a high thermal inertia is one in which dynamic effects are prevalent, and one for which steady-state analysis could prove inaccurate. It is a bulk material property related to thermal conductivity and volumetric heat capacity and can modulate the impact of varying environmental conditions. Constantly varying external environment conditions continuously impact the building envelope and don’t regularly allow for prolonged steady-state operation.

With respect of thermal performance characterisation, studies have shown that hemp-lime exhibits high moisture buffering capacity and a good balance between low mass and storage capacity [10]. A recent salient study of whole hemp-building performance presents insightful evidence of the ability of hemp to attenuate oscillations in the external environment [1]. Other studies have undertaken simulation based investigation of dynamic whole hemp-building performance [11][10]. The majority of laboratory-based studies however have focused on steady state thermal characterization with less focusing on non-steady state situations. Transient behavior appears after an imposed change in temperature at a boundary of the material, as occurs during changing climate conditions or indoor environmental conditions. In an oft cited study, Evrard and de Herde (2005) investigated the transient response of 250mm hemp-lime walls through simulation study carried out in WUFI 4.0 software due to sudden cooling [12][13].

This paper is focused on the response of a dry hemp-lime composite to thermal input step changes. We investigate both the steady-state and transient behavior of hemp-lime panels. The transient thermal response of hemp-lime is investigated using a novel hot-box configuration that isolates heat flow due to conduction and minimises convection and radiation effects. Parameters that characterize the thermal inertia capability of hemp-lime walls are documented.

## 2. Thermal Performance Review

Hemp concretes are characterised by high levels of porosity enabling thermal, hygric and acoustic advantages [14]. Recent research investigations have characterised material parameters related to these phenomena.

The thermal response of a material during the transient period of heat transfer through the material can be defined by its thermal diffusivity and thermal effusivity [15]. These parameters are pertinent to understand the scientific analogy of thermal inertia in building envelopes. Maalouf et al. (2014) describe two types of thermal inertia in hemp-lime walls, based on the nature of the thermal action on the wall [10]. They propose the thermal inertia under varying outdoor conditions is appropriately characterised by the thermal diffusivity and, under indoor thermal actions, by the thermal effusivity [10]. The subsequent section reviews a selection of recent studies that have investigated and measured these and other relevant thermal parameters.

| **Parameter** | **Thermal conductivity** | **Thermal transmittance** | **Volumetric heat capacity** | **Thermal effusivity** | **Thermal diffusivity** |
|---|---|---|---|---|---|
| **Equation** | $k = R.l$ | $U = \frac{1}{R}$ | $VHC = \rho C_P$ | $\varepsilon = \sqrt{k\rho C_p}$ | $\alpha = \frac{k}{\rho C_P}$ |
| **Units** | W/m.K | $W/m^2K$ | $J/K.m^3$ | $J/m^2K\sqrt{s}$ | $mm^2/s$ |
| **Values from literature** | 0.129 [2], (0.05 - 0.16 for $\rho$ 220–550 $kg/m^3$) | 0.43 [2], (0.37-0.23 for $l$ 300-500mm) | $\rho$=220–550 $kg/m^3$<br>$C_p$=900-4700 J/kg.K | 231 [10], ($C_p$=1100J/kg.K, $k$ =0.11) | 0.14 [12], (0.27-0.3 for $k$ ~0.1, $C_p$ 3000-4690) |

Table 1: Thermal property relationships and examples of values documented in the literature.

### 2.1.1 Thermal conductivity

Thermal conductivity ($k$) is a measure of how fast heat will flow in the material. Shea et al (2011) recommend prudence when analyzing the conductivity of hemp-lime due to uncertainty in its true value arising from variations in density and moisture content [1]. Localised compaction, and the resulting increase in density, lowers porosity between the shiv particles, thus increasing the thermal conductivity.

Conductivity remains the focus of many studies of thermal properties of hemp composites and values reported in the literature range from 0.05 to 0.16 W/(m·K) depending primarily on the density [6], but also on moisture content and composition. Conductivity increases in a linear fashion with density. Low density mixes (220-275 $kg/m^3$) correspond to 0.05-0.06 W/(m·K), and higher density mixes (450-550 $kg/m^3$) to 0.11-0.16 W/(m·K) [6].

Conductivity also depends on the moisture content [4] and increases in a linear manner in relation to it [11]. Moisture content increases the thermal conductivity of the composite on account of the higher conductivity of water [16]. The binder element of the hemp-lime composite has a higher conductivity that the shiv and an increase in binder content in the composite increases thermal conductivity [17]. Thermal conductivity also varies with the type of binder used and lime based binders exhibit lower conductivities, primarily due to lower density [2].

### 2.1.2 Volumetric heat capacity

Specific heat and volumetric heat capacity (VHC), represent the ability of a material to store heat while undergoing a given temperature change. The VHC defines the 'per unit volume' ($J/m^3$°C) measure while the specific heat is a 'per unit mass' (J/kg°C) measurement.

Despite being a light-weight material, lime-hemp composites are claimed to exhibit high thermal mass. Previous research has identified thermal heat capacities ranging between 1000 J/kgK (for a density of 413Kg/m3) and 1560 ± 30 J/kgK (for a a density of 480 kg/m3) [11][13]. According to Evrard (2008) thermal capacity increases with relative humidity due to the high heat capacity of the water in the composite.

### 2.1.3 Thermal diffusivity

Thermal diffusivity appears in transient heat conduction analysis and represents how fast heat diffuses through a material. It is defined by the ratio between heat conducted (*k*) and that stored (*ρCp*). Maalouf et al. show that hemp concrete has a lower diffusivity than cellular concrete, earth block, solid brick and concrete [10]. Evrard and de Herde, (2005 & 2006), document thermal diffusivity via WUFI simulations, as an average of approximately 1.4 x $10^{-7}$ $m^2/s$, with a range from 1.48 to 0.98 $m^2/s$ for a relative humidity range of 0% to 100%. Higher values of 0.274 to 0.3 $mm^2/s$ are reported by other authors for hemp-lime composites with low conductivity (0.094-0.105 W/m.K) and high specific heat capacity (3000-4690 J/kg.K) [4]. Referencing Collet (2004) and El Hadj (2010), Maalouf [18] documents similarly high values of thermal diffusivity (0.266 $mm^2/s$), for hemp with relatively low specific heat capacity, high density (570 $kg/m^3$) and conductivity (0.15 W/m.K). The low thermal diffusivity of a 250mm hemcrete wall enables almost complete (98.5%) dampening of a sinusoidal change in external temperature of 20°C to 0°C over a 24 hour cycle [12].

### 2.1.4 Thermal effusivity

The material's thermal effusivity (ε) measures its ability to exchange heat with its surroundings. Materials with low effusivity are warm to the touch and can improve thermal comfort. Manufacturers of commercial binders claim that "experience of Hemcrete® buildings in France shows that sub-conscious feelings of thermal comfort are achieved at an air temperature of 1 to 2 degrees lower than in conventional masonry structures" [19]. Thermal effusivity is not extensively reported in the literature. Maalouf et al (2014) document values of 231 $J/m2K\sqrt{}s$ and warn of significant risks of overheating in hemp-lime buildings due to this low value.

Thermal inertia may be understood in terms of thermal effusivity [20]. The temperature of a material with low thermal inertia changes significantly during the day, while the temperature of a material with high thermal inertia does not change as drastically.

## 3. Methods and Materials

### 3.1.1 Materials

Hemp aggregate is mixed with a binder containing calcium lime (70% by weight) and GGBS (30% by weight) and water retainer of 0.5% methyl-cellulose. Binder:Hemp:Water ratio is 2:1:3.1.

Hemp composite walls were cast in timber shuttering and allowed to cure outside for a year, and in the laboratory for 6 weeks as outlined in previous work [21]. The hemp-lime composite was tamped in the shuttering as in standard practice. At 13.5 months porosity was measured at 73.3% porosity using water displacement pycnometry [22].

The panel measures 790mm high, 950mm wide and 300mm deep. The wall had significantly dried by time testing. At time of testing the panel weighed 115 kg. 2 years 10 months passed since initial testing, (at 13.5 months after casting), which has seen a reduction in mass of 20 kg from 135 kg to 115 kg, primarily due to drying and the resulting loss of moisture. The wall density is therefore calculated as 511 $kg/m^3$ a reduction from 569 $kg/m^3$ previously calculated [2]. The specific heat capacity of the hemp-lime concretes was measured as outlined in Walker and Pavia [2].

### 3.1.2 Experimental set-up

A novel hot-box configuration is developed to investigate the transient and steady-state thermal properties of hemp-lime. The rig comprises a hot and cold side. The cold side is exposed to the ambient and the wall sample is contacted directly to the heat plate. The hot side comprises a heat plate, heated by a hot water source supplying water at a specified temperature (40-60°C) to a capillary network of tubing in the plate. A guard plate is set up behind the hot plate to limit the heat transfer in the direction away from the wall sample.

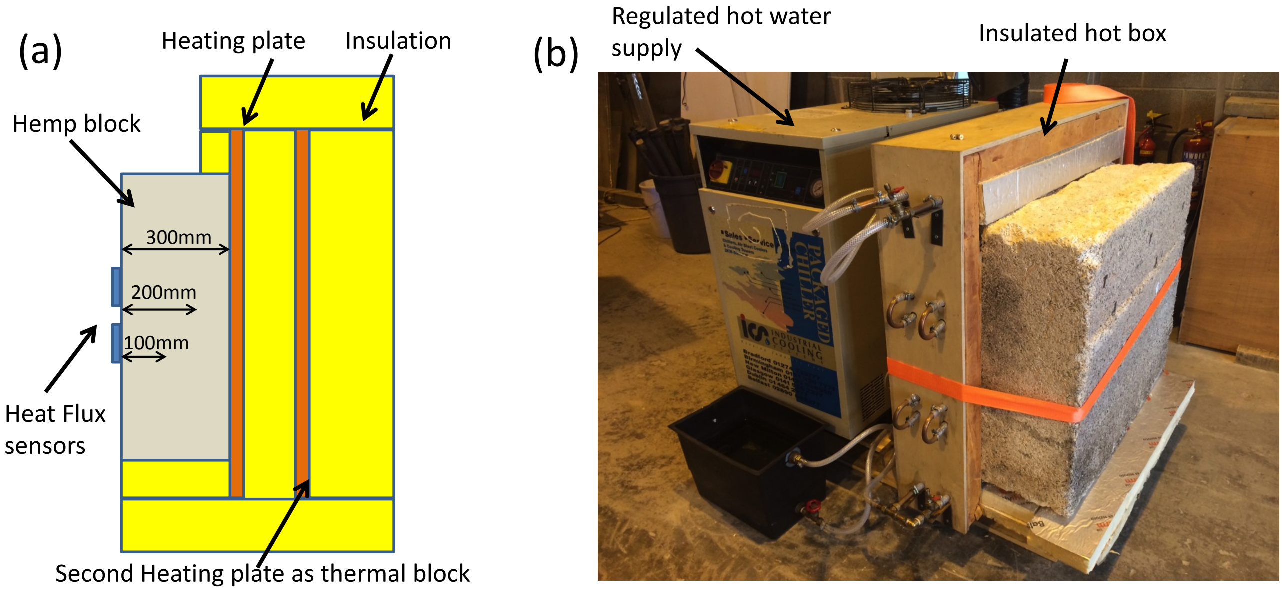

Figure 1: Hemp-lime panel in novel hot box set-up, (a) shows a schematic of the hot box set-up (b) shows the hemp-lime wall installed in the hot box rig.

Heat flux was measured using a Hukseflux TRSYS01 measurement system and Loggernet software for in situ measurement. The thermal conductivity was calculated from the thermal transmittance (U-value) of the walls complying with ISO 9869 and ASTM C1155. Surface and internal wall temperatures were measured using embedded type K thermocouples placed at x = 0, 100, 200 and 300mm either on surface or embedded within the wall. The wall was tested with a hot plate surface temperatures of 60, 50, 45 and 40°C. Exterior air temperatures averaged 20.2°C during summer testing conditions. It varied within 2 degrees of this through the testing period especially during daytime hours.

## 4. Results

### 4.1.1 Thermal response

Figure 2 shows a three-day thermal response of heat flux, in-wall and surface temperatures, to a heat input at the hot plate contact with the hemp-lime wall (at x=0). The temperature distribution is monitored at x=300mm (cold side), x=200mm, x=200mm and x=0mm (hot side) widths through the wall. Heat flux is monitored on the outer surface of the wall at x=0mm (cold side).

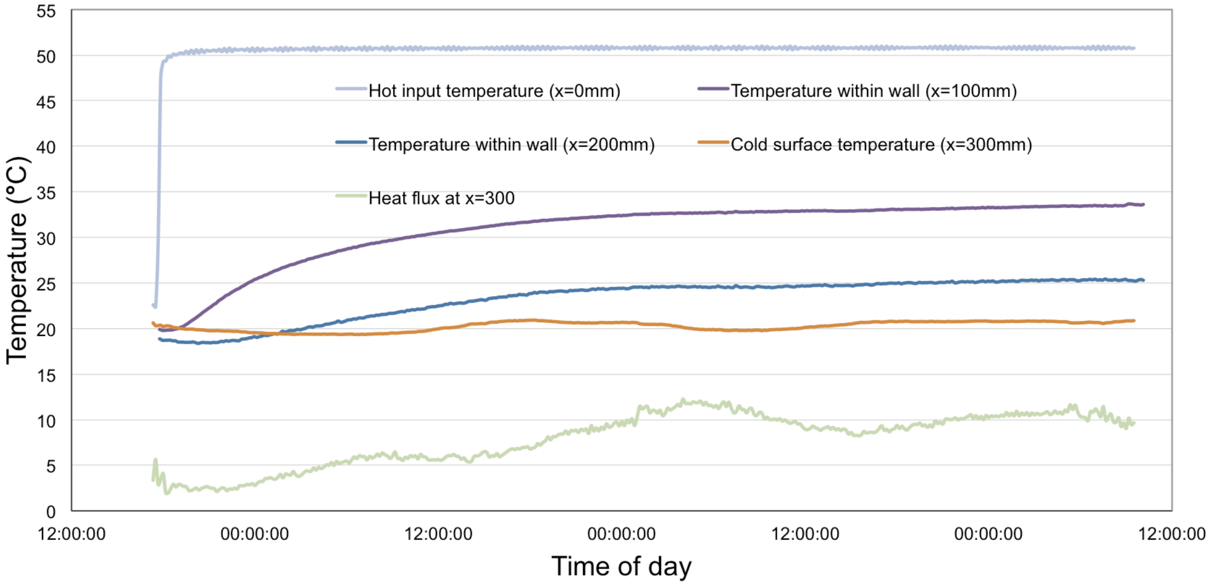

Figure 2: Thermal response of hemp-lime wall to heat input at x=0.

The hemp-lime wall takes almost 40 hours to reach steady state. Conditions vary with varying environmental conditions in the laboratory (*e.g.* solar gain impact and ambient air changes due to diurnal effects). Hence variability is evident in ambient and heat flux readings. The thermal conductivity calculated across a number of test input temperatures averaged 0.105 W/m.K, reduced from 0.129 W/m.K previously calculated [2]. Thermal properties of hemp-lime are calculated using equations listed in Table 1. A specific heat capacity of 1350 J/kg K was measured for the GGBS+WR binder based concrete [2]. Thermal diffusivity ($\alpha$) calculated at steady state as the ratio of conductivity ($\lambda$) to volumetric heat capacity ($\rho c$) is 0.15 $mm^2/s$.

| **Parameter** | **Thermal conductivity** (W/m.K) | **Thermal transmittance** (W/$m^2$K) | **Volumetric Heat Capacity** (J/K.$m^3$) | **Thermal effusivity** (J/$m^2$K$\sqrt{s}$) | **Thermal diffusivity** ($mm^2$/s) |
|---|---|---|---|---|---|
| **Values** | 0.105 | 0.35 | $6.9 \times 10^{-5}$ | 269 | 0.15 |

Table 2: Thermal properties of analysed 300mm hemp-lime walls.

### 4.1.2 Transient response

Figure 3 shows the evolution of heat flux during initial lag and transient phases in response to a heat input step with temperature of 45°C in lab winter conditions ($T_{avg}$=18°C).

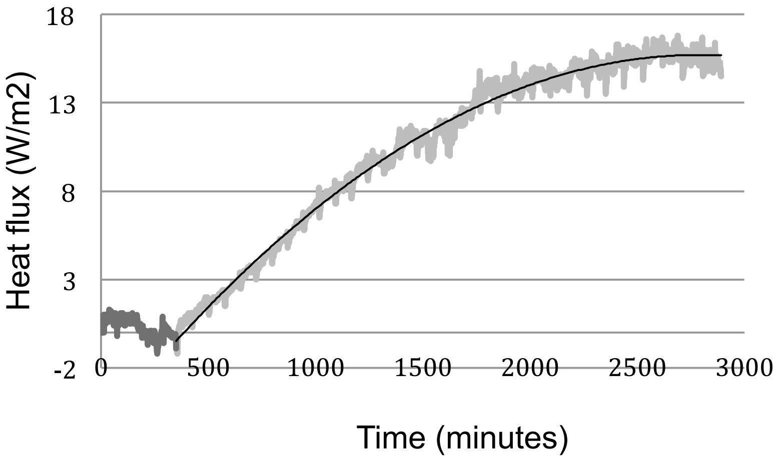

Figure 3: Heat flux response of hemp-lime wall to heat input (temperature x=0) on hot side showing lag and transient heat up phases.

The hemp-lime wall is characterised by a slow thermal response. The time to steady-state ($t_{s\text{-}s}$) observed is approximately 45 hours. Following the temperature input step, a time lag of approximately 4.5-6 hours is observed, across experimental tests. The responsiveness to the heat step input is characterised by the slope over the approximated linear portion of the response curve, taken as up to 33% of the maximum heat flux. At 50°C the slope of the curve is 0.0062. When subject to a step temperature of 60°C the slope of the linear portion of the response curve increases to 0.014.

Figure 3 shows the wall temperature distribution, through the depth of the wall at different times during the test. This distribution is shown for a sudden hot side heat step with temperature of 60°C (Figure 4 (left)), and during natural cool down after removal of the wall sample (Figure 4 (right)). The temperature distribution profile tends to linear with time, but remains nonlinear even after 72 hours of heat input, in contrast to characteristics reported by other authors, who show a quasi-linear characteristic at 48 hours, in simulated studies [12]. In the presented test the internal wall temperature is shown to drop below the ambient, due to the wall interior temperature being lower than ambient at the start of test.

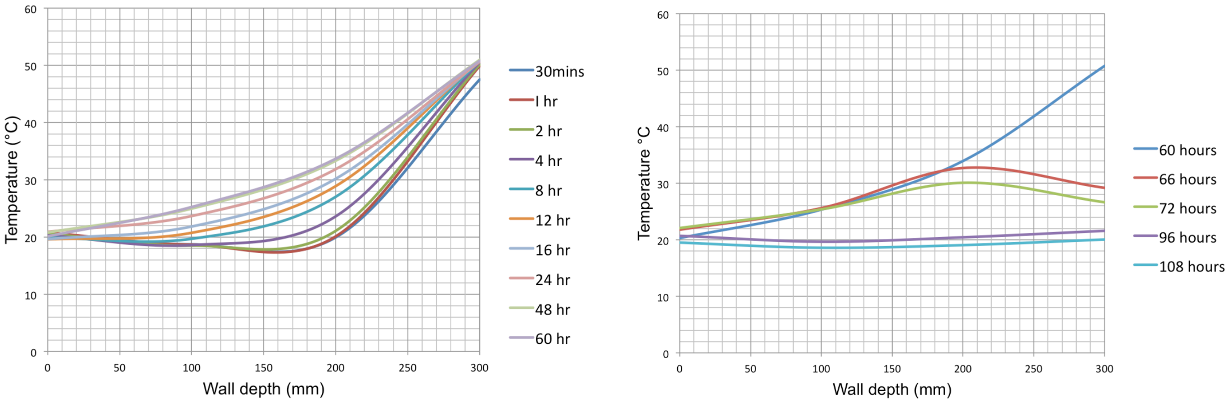

Figure 4: Temperature distribution across width of hemp-lime wall when 50°C heat input (left) applied (at x=300mm), and (right) when removed and allowed naturally cool down after 60 hours of continuous heat input step.

## 5. Discussion

This experimental study focused on the investigation of the thermal response of 300mm hemp-lime walls to heat step inputs. Steady-state parameters and transient responses were identified. Dynamic building envelope properties, such as thermal diffusivity and effusivity, were characterized using steady-state calculated parameters including thermal conductivity.

The value of thermal diffusivity calculated in this study (0.15 $mm^2/s$) is similarly low to those reported by Evrard et al. (0.14 $mm^2/s$) but significantly lower than values of 0.274 to 0.3 $mm^2/s$ reported by other authors who document values for hemp-lime composite with low conductivity (0.094-0.105 W/m.K) and high specific heat capacity (3000-4690 J/kg.K) [4]. Referencing Collet (2004) and El Hadj (2010), Maalouf [18] documents similarly high values of thermal diffusivity (0.266 $mm^2/s$), for hemp with relatively low specific heat capacity, high density (570 $kg/m^3$) and conductivity (0.15 W/m.K).

Although hemp-lime is often claimed to exhibit excellent thermal mass and dynamic thermal performance, in Southern European climates the risk of superheating due to hemp concrete's low effusivity is a concern [10], particularly as temperature are due to rise in climate change conditions. They present an effusivity value of 0.231 J/m2K√s which is low compared to other masonry, high capacitance, building materials. Brick exhibits an effusivity of 1201 J/kg.K and concrete 1966 J/kg.K [18].

The low thermal diffusivity of hemp-lime results in the slow tendency toward linearity. Material with a higher conductivity to volumetric heat capacity ratio would obtain a linear profile much quicker. Conductivity of insulation material varies with temperature [23] and hence diffusivity varies with temperature as shown by the partial differential heat equation which describes thermal diffusivity as the ratio of the time derivative of temperature to its curvature quantifying the rate at which temperature concavity is smoothed out. It is commonly tested in concrete using a dynamic monitoring test [24] and in high conductivity materials using the flash method [25]. Pavlovic et al. (2014) choose not to use a dynamic method for direct measurement of thermal diffusivity when characterizing the transient thermal response of hemp textile fabrics due to the high porosity inherent in them [15]. Dynamic methods of analysis prove to be inadequate for porous media because of thermal convection caused by temperature gradient within the porous specimen during the transient period.

## 6. Conclusion

Dry hemp-lime exhibits characteristics that allow it present appropriate characteristics for good thermal inertia. Although thermal conductivity is low (0.105 W/m.K) relative to other high capacitance materials, the thermal transmittance of a 300mm wall (0.35 $W/m^2K$) is higher than walls with ample widths of classic insulation materials to meet building regulation levels in Ireland (0.21 $W/m^2K$ (domestic), 0.27 $W/m^2K$ (non domestic) [26]. The thermal inertia characteristics of hemp-lime compensate and enable comfortable thermal indoor conditions and low energy operation [9].

High thermal capacity materials (particularly brick or concrete) can generally significantly increase the embodied energy associated with buildings. Hemp lime provides a lightweight material with the characteristics of a heavier material which both insulates, stores heat and mediates fluctuations in external temperature. Future work will investigate dynamic thermal diffusivity evaluation to enable greater confidence in claims of hemp-lime as a material with optimum thermal inertia and mass characteristics.

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