HYGROTHERMAL PERFORMANCE OF HEMPCRETE

Data · December 2016

Journal of Cleaner Production 142 (2017) 3655–3664

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Hygrothermal performance of hempcrete for Ontario (Canada) buildings

Ujwal Dhakal*, Umberto Berardi, Mark Gorgolewski, Russell Richman

Dept. of Architectural Science, Ryerson University, 350 Victoria St, Toronto, ON, M5B 2K3, Canada

ARTICLE INFO

Article history:
Received 29 June 2016
Received in revised form
20 October 2016
Accepted 20 October 2016
Available online 22 October 2016

Keywords:
Hemp
Lime binder
Hygrothermal performance
Water content
Rainscreen wall
Building code

ABSTRACT

Hempcrete is a bio-aggregate based composite material used for building envelopes which typically consists of hemp shiv (hurd), lime binder and water. Hempcrete has several distinct advantages including low thermal conductivity, effective moisture buffering, and high sound absorption, while having a high carbon sequestration “index”. This work investigates the impact of mix proportions on hempcrete properties and the hygrothermal performance of two proposed hempcrete wall assemblies for Ontario, Canada. The experimental results highlight the significant influence of the binder on the density and thermal conductivity of the final material. Thermal conductivity measurements ranged from 0.074 to 0.103 W/mK. Finally, hygrothermal analysis demonstrated that when using hempcrete in the Canadian climate a rain screen wall system is more suitable than a mass wall.

1. Introduction

Buildings are now accepted as a major contributor to resource consumption and depletion across the planet (Berardi, 2016). In response, attention has been growing significantly over the last few years towards using sustainable building materials from biological sources. Various research and pilot projects have looked at the possibility of using natural materials in buildings. However, lack of consistency in the experimental results often due to variations in the characteristics of natural materials and the ad-hoc processes used in their manufacture, have meant that it is sometimes difficult to prove that natural materials are code compliant. In particular, the importance of using natural raw fibers has been extensively discussed in recent papers that have focused on their thermal and acoustical properties (Woolley, 2012; Berardi and Iannace, 2015; Schiavoni et al., 2016).

Hempcrete is one such bio-aggregate- based, natural building material which has potential for use as a thermal and acoustic insulation system (Arnaud and Amziane, 2013). Although it may seem to be a new material, in reality hempcrete is just a modern version of a very old, natural composite construction material (Stanwix and Sparrow, 2014) composed of hemp shiv (hurd), lime binder and water. At the end of its life the hempcrete can be easily broken down and re-used in a new build, or alternatively, being a natural product, it will break down and contribute lime and organic matter to the land (Hemp Edification, 2015).

Hempcrete is a lightweight, cementitious, insulating material that has many useful characteristics: it does not slump, demonstrates more flexibility than concrete, cures within a few hours, weighs only one-seventh the weight of concrete (by volume), and helps to strengthen a stud wall (Kenter, 2015). Hempcrete has a low effusivity and a high thermal inertia, so it does not take as long to warm and once heated, it slowly releases the heat when the surrounding temperature drops (Evrard, 2008). For this reason, hempcrete has been proposed for use as a thermal insulator, although not an exceptional one (Arnaud and Amziane, 2013). Significant characteristics of hempcrete that affect its thermal performance include: particle size, moisture content of the shiv, proportions of hemp to binder, mixing methods, and placing and compaction (Woolley, 2012).

This paper reports on a project which aims to provide more reliable and consistent information on hempcrete in the Canadian context through laboratory tests, literature review and one-dimensional hygrothermal simulations. Given the variance of hempcrete properties listed in the literature, this research aimed to obtain measured values for several mixes of hempcrete (hemp to

---

* Corresponding author.
E-mail address: ujwal.dhakal@ryerson.ca (U. Dhakal).

http://dx.doi.org/10.1016/j.jclepro.2016.10.102
0959-6526/

binder ratio of 1:1, 1:1.5 and 1:2) using locally grown Canadian hemp. Further objectives included defining the required thicknesses of an above grade hempcrete wall to meet the thermal performance requirements of the Ontario Building Code, 2012 and to quantify the hygrothermal behavior of hempcrete walls in the context of Canada.

2. Literature

2.1. Background

Hempcrete construction is relatively simple and can be installed in three ways: spraying (shot concrete or shotcrete), moulding (monolithic) and precasting (Collet and Pretot, 2014). Casting in-situ (moulding) by hand-placing is most common due to its simplicity and the ability of hempcrete to support a monolithic insulation layer with increasing air-tightness (Bevan and Woolley, 2008; Stanwix and Sparrow, 2014). Hempcrete is usually used as the insulation in a composite (timber frame) structure with single or double studs (Woolley, 2012; Stanwix and Sparrow, 2014). Since the thermal conductivity, thermal capacity, effusivity, diffusivity, swelling and shrinkage and dampening of hempcrete and timber (radial) are similar, this provides a quasi-homogenous system, reducing thermal bridging issues (Evrard and HerdeDe, 2005; Bevan and Woolley, 2008; Evrard, 2008; Alembic Studio, 2013). Once fully hardened, hempcrete provides 10 times more racking strength compared to traditional diagonal timber bracing due to its superior tensile strength; adding capability to resist lateral loads (Stanwix and Sparrow, 2014). Hempcrete creates a monolithic material which is inherently airtight (Stanwix and Sparrow, 2014) and if used with timber frame (composite) forms a solid mass that is almost impossible to catch fire (Bevan and Woolley, 2008). Arnaud and Amziane (2013) estimate that hempcrete based walls store more carbon (262 kg CO_2e/m^3) than is emitted (127 kg CO_2e/m^3) due to their construction, representing a lifetime net balance of 135 kg CO_2e/m^3. According to Bevan and Woolley (2008) and Eberlin and Jankovic (2015), carbon sequestration of hempcrete is between 108 and 133 $kgCO_2/m^3$. Further, there is hardly any risk of “off-gassing” or toxicity during the in-use phase of a building, or at end-of-life demolition (Bevan and Woolley, 2008; Ahlberg et al., 2014; Stanwix and Sparrow, 2014).

There are essentially no industry standards for hempcrete at this time; however, some manufacturers have established basic rules for their own use. This results in a lack of clear cross-industry references (Stanwix and Sparrow, 2014). As a rule of thumb a hempcrete based assembly should be protected from the exterior to prevent strong water penetration, while the interior surface of the wall can stay exposed. In addition, with hempcrete being highly alkaline ($pH > 7$) any metals encased in it should be highly corrosion resistant (galvanized); leading to its typical use with timber (Stanwix and Sparrow, 2014).

Consisting of flexible hemp and a more rigid binder, hempcrete is a non-fragile elasto-plastic material which differs from other construction materials due to its high deformability under stress, lack of fracturing, and high ductility (Arnaud and Amziane, 2013). Lawrence et al. (2012) stated that the compression strength of hempcrete (0.05–0.35 MPa) is too low to make it suitable for consideration as a structural material. Walker et al. (2014) concluded that increasing binder hydraulicity enhanced early strength development but did not significantly affect the ultimate strength. In the study by Pinkos et al. (2011), the low values of the Young's Modulus showed that hempcrete can withstand significant geometric changes under residual stress. Colinart et al. (2012), stated that a balance should be struck between the good static and dynamic structural properties of hempcrete and its thermal performance within an enclosure.

Evrard and HerdeDe, (2005) state that hempcrete normally stays in the hygroscopic adsorption region; however, other similarly used materials are normally in the range of 40–70% RH. The small amount of moisture in the hempcrete plays an important role in its thermal performance. By adding a phase change between liquid and vapour, hempcrete slows down the quick flow of heat when temperature changes abruptly maintaining much more thermally stable conditions (Bevan and Woolley, 2008). In fact, the low thermal diffusivity (1.48×10^{-7} m^2/s) and effusivity (286 $J/m^2Ks^{-1/2}$) of hempcrete result in longer times to change temperature (time lag or decrement delay) and create a warm sensation to the touch. Low thermal diffusivity directly relates to increased thermal comfort within the building (Evrard and HerdeDe, 2005; Bevan and Woolley, 2008). The relatively high thermal mass also maintains indoor environment quality (Stanwix and Sparrow, 2014). The high vapour permeance of hempcrete allows moisture to diffuse through the envelope and this helps to maintain indoor environment quality (Bevan and Woolley, 2008). The moisture buffering capabilities (passive regulation of humidity) of hempcrete help to control indoor relative humidity and reduce the risk of mould growth caused by dampness and condensation (Bevan and Woolley, 2008).

The major moisture loading mechanisms in hempcrete as in other walls are rain penetration, condensation, rising damp and initial moisture (Kunzel, 1995; Tolkovsky, 2010). The moisture is stored and transported through diffusion, capillary water and surface diffusion (Evrard, 2008). The average Moisture Buffer Value (MBV) of hempcrete was reported to be 2.14 $g/(m^2\%RH)$, slightly higher in desorption than absorption for an average density 430 kg/m^3 (Collet et al., 2013). Based on the classification of the NORDTEST Project, hempcrete is an excellent hygric regulator (i.e. MBV >2 $g/m^2\%RH$), showing the ability to regulate ambient relative humidity (Collet et al., 2013).

Despite its benefits, the use of hempcrete has not gained momentum in Canada although the country is one of the main producers of this product (Canadian Hemp Trade Alliance, 2015). Conversely, in Europe, hempcrete technologies have been increasingly used since the early 1990's (Rhydwen, 2006). This delayed adoption in Canada may be due to difficulties in getting licenses to grow hemp in North America due to its association with cannabis. This has recently changed. Today, residential hemp construction projects are permissible under Section 9 of the Ontario Building Code, 2012 as alternative solutions (Kenter, 2015).

2.2. Physical characteristics

Several previous studies have published dry density (density of materials at fully dried state) values (ρ_0) ranging between 220 kg/m^3 to 627 kg/m^3 for hempcrete with varied mix proportions, as shown in Table 1.

The density of hempcrete primarily depends on the proportion of binder, level of moisture content and extent of compaction (loose filled or compressed one). When any of these increase, the density and consequently the thermal conductivity (k) values increase. Further, where insulation is more important than strength (such as in the roof) typically hempcrete with small amounts of binder, loose filled/very lightly compacted, and in a fully dried state is used, leading to low density and low thermal conductivity. In contrast, where both insulation and structural integrity are equally significant (wall), higher density hempcrete is required (compromising “k” value) and in this situation more binder and more compaction are to be necessary (Stanwix and Sparrow, 2014; Woolley, 2012).

Regarding the wide variation in measured density (220–627 kg/m^3), the lowest density of 220 kg/m^3 was measured in a fully dried

Table 1
Dry density of hempcrete of different compositions as reported by various authors.

Reference(s)	Dry density (kg/m^3)	Mix proportions (Hemp to Binder)	Application
Cerezo (as cited in Lawrence et al., 2012)	220	(1:1)	Roof
	275	(1:1.5)	Wall
	330	(1:2)	Wall
	440	(1:2) Compressed	Wall
	500	(1:3)	Floor
	600	(1:4)	Floor
Evrard (2008)	440 ± 20	(1:2) Compressed	Wall
Evrard (2006)	361–466	(1:2) Compressed	Wall
Evrard and HerdeDe, (2005)	480	(1:2) Compressed	Wall
Tran Le et al. (2010)	413	(1:2) Compressed	Wall
Collet et al. (2013)	430	(1:2) Compressed	Wall
Collet and Pretot (2014)	381	(1:2)	Wall
Walker and Pavía (2014)	531-627 (approximate)	(1:2) Compressed	Wall
Abbot (2014)	275	Not mentioned	Wall
Mawditt (2008)	330 ± 10	Not mentioned	Wall
Woolley (2012)	300–400	Not mentioned	Wall

state with 1:1 hemp:binder composition and loose filled to get higher insulation performance (low “k” value) suitable for roof applications (Lawrence et al., 2012). However, the high density of 627 kg/m^3 was obtained in a hemp:binder mix of 1:2, tamped by hand at every 300 mm, suitable for a wall application. In the latter case, the sample (wall- 1000 mm wide x 900 mm high x 300 mm thick) was cured outside for 1 year with protective covering followed by 6 weeks curing in laboratory conditions. The authors state that this result may lead to a slightly higher value than the final dry density (Walker and Pavía, 2014).

Hempcrete has both micro (within hemp hurd) and macro (within hempcrete) pore scales. Porosity (Φ) or void volume (m^3/m^3) is defined as the difference of water in the maximum saturated and dry states over volume (ASTM C67, 2000). At the macro scale, the porosity due to the arrangement between the hemp shiv and the binder adhesion can reach milli-metric widths (Collet et al., 2013). Generally, in hempcrete, the pores are interconnected, with large pores open onto smaller ones (pores in hemp particles ~10 μm) through the porosity of the lime binder (~1 μm) (Evrard, 2008). The slope of porosity vs conductivity is quasi-linear (Bouguerra et al., 1998). Studies reported the porosity of the hempcrete in the range from 71.1% to 84.3% by volume (Table 2).

Dry thermal (specific heat) capacity (c_0) of materials denotes its ability to store heat (Evrard, 2008). Studies report the average specific heat capacity of the hempcrete ranged from 1000 J/kg K to 1700 J/kg K (Table 3).

Dry thermal conductivity (rate of the passage of heat flow through the material) (“k_0”) depends primarily on the density of the material and increases in a quasi linear manner in relation to it (Elfordy et al., 2008). Studies reported the dry thermal conductivity of the hempcrete ranged from 0.05 W/mK to 0.138 W/mK (Table 4). The study of thermal conductivity versus water content and density by Collet and Pretot (2014) shows that water content has a lower effect than density on thermal conductivity; the thermal conductivity of high density hempcrete is more than twice the value for low density with the same formulation. Moreover, Cerezo (as cited in Walker and Pavía, 2014) established a relation of density to thermal conductivity through the equation $k = 0.0002 \times \rho + 0.0194$.

Table 3
Specific heat capacity of hempcrete as reported by various authors.

Reference(s)	Specific heat capacity (J/kgK)	Density (kg/m^3)
Evrard (2008)	1560 ± 30	440 ± 20
Walker and Pavía (2014)	1240–1350	531–627
Walker and Pavía (2014)	1300	627
Collet et al. (2013)	1000	430
Evrard and HerdeDe (2005)	1550	480
Mawditt (2008)	1550	330 ± 10
Tran Le et al. (2010)	1000	413
Abbot (2014)	1500–1700	275

Clear wall R-value (containing only insulation and structural framing materials, excluding fenestration etc.) is used to define the thermal performance of enclosures in ASHRAE Standard 90.1. However, nominal center of cavity (ignoring the effects of framing) R value is sometimes used in codes, etc. (Straube, 2007). It is typical that clear wall R-values of walls are lower than nominal values due to thermal bridging from studs. Clear wall R-values of hempcrete walls 300 mm–350 mm thick have generally a thermal resistance value of RSi 3.5 m^2 K/W (R-20) to RSi 5.3 m^2 K/W (R-30) which is equivalent to R 1.7 to R 2.5/inch, depending on the mix (Kenter, 2015). However, Magwood (2014), Stanwix and Sparrow (2014) and Alembic Studio, LLC (2013) claim a value of 0.58 to 0.072 W/mK (R2.0- R2.5/inch) in hempcrete, while Maher (2014) claims hempcrete gives R value between 0.048 and 0.058 W/mK (R2.5 to 3.0/inch).

Hempcrete has a high vapour permeability, ranging from 1.7×10^{-11} to 1.7×10^{-10} kg/msPa for a density of 430 kg/m^3 (Collet et al., 2013). Hempcrete water vapour diffusion resistance factor (resistance to moisture movement of the material over resistance to moisture movement of the air) μ_0 has also been reported in the range from 3.59 to 7.68 (Table 5).

Table 2
Porosity and maximum water content of hempcrete reported by various authors.

Reference(s)	Porosity (% volume)	Maximum water content (kg/m^3)	Density (kg/m^3)
Evrard (2008)	73%	730	440 ± 20
Evrard and HerdeDe (2005)	71.1%	711	480
Mawditt (2008)	71.1%	711	330
Collet et al. (2013)	79%	790	430
Collet and Pretot (2014)	84.3%	843	381

Table 4
Dry thermal conductivity of hempcrete as reported by various authors.

Reference(s)	Dry thermal conductivity (W/mK)	Density (kg/m^3)
Evrard (2008)	0.115 ± 0.006	440 ± 20
Arnaud and Amziane (2013)	0.064–0.09	220–450
Collet and Pretot (2014)	0.13	377
Walker and Pavía (2014)	0.117–0.138	531–627
Arnaud and Gourlay (2012)	0.06–0.12	250–660
Woolley (2012)	0.05–0.12	300–400
Rhydwen (2006)	0.076–0.11	–
Stanwix and Sparrow (2014)	0.06–0.12	–
Abbot (2014)	0.06	275
Mawditt (2008)	0.0697 ± 5%	330 ± 10
Evrard and HerdeDe (2005)	0.11	480
Bedliva and Isaacs (2014)	0.065	275
Tran Le et al. (2010)	0.10	413
Cerezo (as cited in Lawrence et al., 2012)	0.06–0.115	220–440

Table 5
Water vapour diffusion resistance factor of hempcrete as reported by various authors.

Reference(s)	Water vapour diffusion resistance factor (–)	Density (kg/m^3)
Evrard (2008)	4.85 ± 0.24	440 ± 20
Evrard (2006)	3.59–7.68	361–466
Abbot (2014)	4.84	275
Walker and Pavía (2014)	5.47–5.71	531–627
Mawditt (2008)	4.85 ± 0.24	330 ± 10

Maximum water content (W_{max}) is the water content at fully saturation or the state where the porous structure is considered to be completely filled with water. Reference values for W_{max} defined through porosity range from 711 kg/m^3 to 843 kg/m^3 (Table 2).

Free water saturation (W_f) is the amount of water a material absorbs at 100% RH or the water content at free saturation and $MC_{RH80\%Equivalent}$ is the amount of water a material absorbs at about 80% RH. Similarly, saturation the coefficient is a measure of the quantity of open pore space available under average wetting conditions. The lower the coefficient of saturation, the more space is available to accommodate expansion of liquid water as it freezes (Mensinga, 2009). The saturation coefficient is defined as the ratio of free water saturation (W_f) to maximum water content (W_{max}) (ASTM C62, 2013). Table 6 reports the measured free water saturation, $MC_{RH80\%Equivalent,}$ and saturation coefficient of the hempcrete which ranges from 546 kg/m^3 - 596 kg/m^3, 33kg/m^3-36 kg/m^3 and 0.75–0.84.

Thermal conductivity supplement (b) quantifies the increase of thermal conductivity [in (%) referring to dry value] when the water content rises 1% referring to dry mass (Evrard, 2008). To determine “b”, a test was conducted by Evrard (2008) to find “k” in moist state in RH 80% (WC = 33 kg/m^3) and RH 65% (WC = 28 kg/m^3) respectively for 2 samples. The mean temperature for the test was respectively ≈18 °C, 26 °C and 34 °C. The reference mean “k” value in a moist state (0.127 ± 0.002) and “b” value (3.34 ± 0.24%/%mass) were found for a density of 440 kg/m^3. In this regard, Evrard (2008) claims that thermal conductivity in moist state for hempcrete can be based on the numeric relationship $k_w = [1+ (b\ w/\rho_0)]\ k_0$ or $b = \rho_0\ (k\text{-}k_0)/k_0$. However, in another study by Evrard (2006), “b” was found as 2.73%/%$_{mass}$ (for density 361–466 kg/m^3), assuming a linear relationship between thermal conductivity and water content.

The water uptake coefficient (A-value) is a measure of the water sorption as a function of the surface area of the specimen and time (Walker and Pavía, 2014). The liquid transfer coefficient (A) is the slope of the mass uptake curve and is proportional to the square root of time ($\sqrt{h}$, or $\sqrt{s}$) during 24 h (Evrard, 2008). According to Mensinga (2009), the A-value is equal to (σ/SA) ×1000; where, the A-value is the water uptake coefficient (kg/m^2 s$^{-1/2}$), σ is the Initial slope (kg/s$^{1/2}$) and SA is the surface area (m^2).

Walker and Pavía (2014) placed hempcrete samples on a wire grill in a container of water so that the water covered the lower 10 mm of the samples and weighted at intervals over time for the duration of the test 10,000 min (EN 1925:199). According to the test, the water uptake coefficient (A value) varied between 2.65 and 3.37 kg/m^2 h$^{-1/2}$ (0.044–0.056 kg/m^2 s$^{-1/2}$) over the first 24 h for densities 531–627 kg/m^3. Evrard (2008) placed samples in 5 mm of water (lateral side protected with paraffin). Mass uptake was linear for the first 24 h. The water uptake coefficient of hempcrete was 4.42 ± 0.27 kg/m^2 h$^{-1/2}$ = 0.074 ± 0.005 kg/m^2 s$^{-1/2}$ for a density of 440 kg/m^3 (Evrard, 2008). However, De Bruijn et al. (2009) found a water uptake coefficient of 9 kg/m^2 h$^{-1/2}$ (0.15 kg/m^2 s$^{-1/2}$) for high density (587–733 kg/m^3) hempcrete. As can be seen from the capillary behavior of hempcrete, water absorption is initially high, decreasing as time progress (De Bruijn et al., 2009). Table 7 summarizes the measured reference values by various authors for the hempcrete properties.

Table 6
Free water saturation, $MC_{RH80\%Equivalent}$ and saturation coefficient of hempcrete as reported by various authors.

Reference(s)	Free water saturation (kg/m^3)	$MC_{RH\ 80\%\ Equivalent}$ (kg/m^3)	Saturation coefficient (–)	Density (kg/m^3)
Evrard (2008)	546 ± 16	33	0.75	440 ± 20
Evrard and HerdeDe (2005)	596	36	0.84	480

Table 7
Summary of hempcrete properties.

Properties	Unit	Min- Max	General range
Dry Density (ρ_0)	kg/m^3	220 (Cerezo as cited in Lawrence et al., 2012) – 627 (Walker and Pavía, 2014)	300–500
Porosity (Φ)	m^3/m^3	0.71 (Mawditt, 2008; Evrard and HerdeDe, 2005) - 0.84 (Collet and Pretot, 2014)	0.71–0.73
Dry Thermal Capacity (c_0)	J/kgK	1000 (Collet et al., 2013; Tran Le et al., 2010) - 1700 (Abbot, 2014)	1500–1600
Dry Thermal Conductivity (k_0)	W/mK	0.05 (Woolley, 2012) –0.138 (Walker and Pavía, 2014)	0.06–0.12
Dry Vapour Diffusion Resistance Factor (μ_0)	(–)	3.59–7.68 (Evrard, 2006)	4.84–4.85
Moisture Buffer Value (MBV)	g/(m^2%RH)	2.11 (Evrard, 2008) - 2.14 (Collet et al., 2013)	2.11–2.14
Thermal Diffusivity (α)	m^2/s	1.48×10^{-7} (Evrard and HerdeDe, 2005) -1.68×10^{-7}(Evrard, 2008)	1.48×10^{-7}-1.68×10^{-7}
Thermal Effusivity (Eff)	J/m^{2}Ks$^{-1/2}$	286 (Evrard and HerdeDe, 2005) - 297(Evrard, 2008)	286–297
Dampening	%	98.5 (Evrard and HerdeDe, 2005)	98.5
	Time Shift	15 (Evrard and HerdeDe, 2005)	15
Air Tightness	m^3/hm^2@ 50 Pa	1.2 (Stanwix and Sparrow, 2014) - 2.0 (Bevan and Woolley, 2008),	1.2–2.0
Fire Safety	hr	1.22 (Stanwix and Sparrow, 2014) - 1.67 (Bevan and Woolley, 2008)	1.22–1.67
Free Water Saturation (W_f)	kg/m^3	546 (Evrard, 2008) – 596 (Evrard and HerdeDe, 2005)	546-596 (124%mass)
WC at 80% RH ($MC_{80\%\ Equiv}$)	kg/m^3	33 (Evrard, 2008) - 36 (Evrard and HerdeDe, 2005)	33- 36 (7.5%mass)
Maximum WC (W_{max})	kg/m^3	711 (Evrard and HerdeDe, 2005; Mawditt, 2008) - 843 (Collet and Pretot, 2014)	711-843 (166%mass)
Thermal Conductivity Supplement (b)	%/%mass	2.73 (Evrard, 2006) - 3.34 ± 0.24 (Evrard, 2008)	3.34
Liquid Absorption Coefficient (A value)	kg/m^2 s$^{-1/2}$	0.044 (Walker and Pavía, 2014) –0.15 (De Bruijn et al., 2009)	0.074
Saturation Coefficient	(–)	0.75 (Evrard, 2008) - 0.84 (Evrard and HerdeDe, 2005)	0.75–0.84
Carbon Sequestration	kgCO$_2$e/m^3	(–)108 (Bevan and Woolley, 2008) –(-)135 (Arnaud and Amziane, 2013)	(–)108 - (–)135
Compressive Strength	MPa	0.05 (Cerezo, 2005; as cited in Lawrence et al., 2012) –3.5 (Lanos and Collet, 2011)	0.05–0.35
R value	Imperial	1.7 (Kenter, 2015) - 3.0 per inch (Maher, 2014)	2.0–2.5 per inch

3. Methodology

3.1. Materials

A commercially available pre-formulated hemp binder product was used in this research (BATICHANVRE - a natural hydraulic lime mix pre-formulated by St. Astier for use with hemp construction). It comprises of mainly hydrated lime with small amounts of pozzolanic ingredients and 20–30% portland cement which assists the setting process due to a mixture of both carbonation (exposure to air) and hydraulic setting (exposure to water) (Stanwix and Sparrow, 2014). The density of the lime binder on its own was measured to be 712 kg/m^3.

Hemp hurd (without fiber or dust) was sourced from plain hemp grown and processed in Manitoba, Canada. Particle sizes ranged from 5 mm to 25 mm (length), 3 mm–6 mm (width), 1.5 mm–2.5 mm (thickness) and had a density of 125.5 kg/m^3.

3.2. Composition

Three mixes (M1, M2 and M3) with a hemp to binder ratio of: 1:1, 1:1.5 and 1:2 respectively, were studied, as shown in Table 8.

3.3. Mixing and casting

For mixing, the moulding method was followed. A mechanical bell (drum) mixer was used in accordance with the manufacturer written specifications (BATICHANVRE, 2006). To confirm consistency of the mix, as suggested by Stanwix and Sparrow (2014), ball and finger tests were conducted for all mixes before placing in moulds to ensure consistency. In order to achieve precise results, variation was made in volume of the test samples. Four different sized samples were cast in plywood moulds. The numbers and sizes of samples cast are highlighted in Table 9. Moulds were manually filled, lightly pressed by hand (light compaction) avoiding “arching” or an empty zone. Mixing was done at room temperature 20–21 °C and RH ≈ 50%.

Table 8
Mix proportions by mass.

Components	Mix 1		Mix 2		Mix 3	
	Mass	%Mass	Mass	%Mass	Mass	%Mass
Hemp	1	28%	1	22%	1	17%
Binder	1	28%	1.5	33%	2	35%
Water	1.6	44%	2.1	46%	2.75	48%
Total	3.6	100%	4.6	100%	5.75	100%

3.4. Drying

Once filled, the samples were placed in an interior environment (approximately 50% RH, 21 °C) for drying and their mass was measured every 24 h, for 26 days. Evolution of mean density with time is illustrated in Fig. 1. The bulk volume V (m^3) was measured for all samples after they were oven dried. Samples were removed from the mould in day 6 and wrapped with aluminum foil from three sides (one side opened, allowing drying and carbonation simultaneously). The density/mass was stabilized during at around day 26 (below 1% variation of preceding day density). Initial (day 0) and natural drying (day 26) densities are highlighted in Table 10.

3.5. Dry density (ρ_0)

In order to understand the influence of binder on the properties of hempcrete and to increase the material input accuracy of the one-dimensional hygrothermal simulation, several tests were conducted for different parameters. All tests were carried out after 26 days of natural drying which is when density was stabilized.

The original block samples were cut into 36 cubes (12 for each mix) with edges 7.6 × 7.6 × 7.6 cm. According to visual analysis regarding representative volume element (RVE) of hempcrete, the specimens larger than 100 cm^3 (sides >4.7 cm) can take into account the specific pore and particle distribution of the material (Collet et al., 2013). However, 9 original samples (3 for each mix) of size 30.5 × 30.5 × 7.6 cm were not cut down.

Table 9
Sample sizes.

Type	Size (cm)	Number	Total
1	30.5 × 30.5 × 7.6	9	18
2	15.2 × 15.2 × 15.2	3	
3	15.2 × 15.2 × 12.7	3	
4	15.2 × 15.2 × 10.2	3	

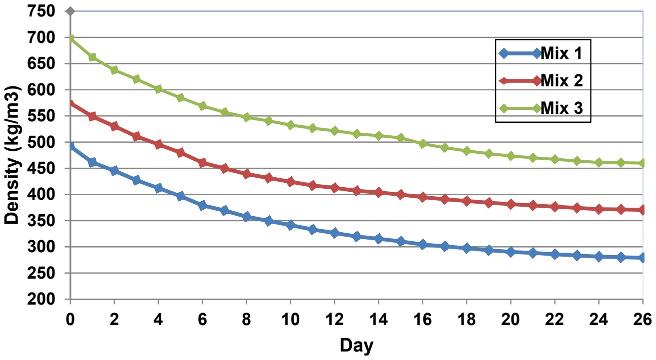


Fig. 1. Evolution of density during natural drying.

The samples (45 numbers –15 for each mix) were dried in an oven for 24 h at 110 °C until two successive weighing at intervals of 2 h show an increment of loss not greater than 0.2% of the last previously determined mass of the specimen. Dry densities (kg/m^3) were measured according to ASTM C 67, 2000 (drying was followed by cooling for a period of approximately 12 h until the surface temperature of the samples was within ±2.8 °C of room temperature).

3.6. *Dry thermal conductivity (k_0)*

Dry thermal conductivity (W/mK) was measured in accordance with ASTM C 518, 2003. The equipment used for the test was NETZSCH-HFM 436/3/E with two heat flux transducers in series with one specimen. Nine dried samples (3 for each mix) of size ≈ 30.5 cm × 30.5cm × 7.6 cm were tested maintaining a temperature difference of 10 °C between hot (25 °C) and cold (15 °C) plates.

3.7. *Free water saturation (W_f)*

Free water saturation (kg/m^3) was measured according to ASTM C67, 2000. Immediately after measuring the dry densities, the samples (15 random cut samples - 5 for each mix) were submerged into cold clean water at 15.5°–30 °C temperature for 48 h (until mass equilibrium of 1% variance was achieved) and were weighed periodically (with a measuring scale sensitive to 1 g). Weighting was completed within 5 min after removing the specimen from the bath and wiping off the surface water with a damp cloth.

3.8. *Maximum water content (W_{max})*

To quantify W_{max} (kg/m^3), two methods listed in ASTM C67, 2000 were used: (i) boiling immediately following 5 h submersion and (ii) boiling from the dry state. For comparative purposes, both methods were executed. W_{max} was the same using both approaches.

3.9. *Water content at 80% RH ($W_{80\%\ equivalent}$), porosity (Φ) and saturation coefficient*

Water Content at 80% RH (kg/m^3) was measured using the value of 7.5% of mass in accordance with references. Porosity (m^3/m^3) and Saturation Coefficient were measured by following W_{Max}/ρ_{Water} (ASTM C67, 2000) and W_f/W_{Max} (ASTM C62, 2013), respectively.

4. Material property results

4.1. *Dry density*

The dry density (the density of the materials at fully dried state) was measured as 233.0 kg/m^3 for Mix 1, 316.8 kg/m^3 for Mix 2 and 387.8 kg/m^3 for Mix 3 (Table 10). It should be noted that dry density was linearly related to the proportion of binder; when binder was increased by 50% and 100%, density increased by ≈ 36% and 67% respectively.

As shown in Table 10, the average density reduction during drying was about 40% (Mix 1 decreased by 43%, the highest of all because more was added water during mixing). Oven drying (which was carried out after natural drying) reduced the density a further approximately 10%. Overall, the decrease in density from initial to oven dried was: Mix1 ≈53%, Mix2≈45% and Mix 3 ≈ 45%. These densities were within the satisfactory range of other references (Table 7).

4.2. *Dry thermal conductivity*

Measurements of mean dry thermal conductivity were Mix 1 = 0.074 W/mK, Mix 2 = 0.088 W/mK and Mix 3 = 0.103 W/mK (Table 11). The value measured for Mix 1 was slightly above published reference values; while, Mix 2 and Mix 3 were in good agreement with published work (Cerezo, 2005; Evrard, 2008; Arnaud and Gourlay, 2012; Collet and Pretot, 2014).

Moreover, dry thermal conductivity of hempcrete maintains a near linear relationship with density (Table 11). For dry density 233 kg/m^3 (Mix 1), mean thermal conductivity is 0.074 W/mK, when densities increased by ≈ 36% (317 kg/m^3) (Mix 2) and 67% (388 kg/m^3) (Mix 3), dry thermal conductivities increase by 18.32% and 38.12% respectively.

4.3. *Free water saturation (W_f), maximum water content (W_{max}), water content at 80% RH, porosity (Φ) and saturation coefficient*

Table 12 lists the measured water content, porosity and saturation coefficient for the three mixes. Free water saturations (W_f) was measured as - Mix 1 = 376.29 kg/m^3 (161.48%mass), Mix 2 = 374.96 kg/m^3 (118.36%mass) and Mix 3 = 423.55 kg/m^3 (109.24%mass). Maximum water content at saturation (W_{Max}) was measured as - Mix 1 = 532.66 kg/m^3 (228.58%mass), Mix 2 = 525.66 kg/m^3 (165.93%mass) and Mix 3 = 655.31 kg/m^3 (169.01%mass). Porosity (Φ) was calculated as 0.53 m^3/m^3 (53% volume) for Mix 1 and Mix 2 and 0.66 m^3/m^3 (66% volume) for Mix 3. Lastly, the saturation coefficient was calculated as 0.71(for Mix 1 and Mix 2) and 0.65 (Mix 3). From these findings, it is evident that Mix 3 has a lower coefficient of saturation; hence it has more space available to accommodate expansion of liquid water as it freezes in comparison to Mix 1 and Mix 2. Fig. 2 shows the visual image of samples in dry condition.

In comparison to reference values, our measured W_f, W_{max}, $WC_{80\%\ Equiv}$, porosity and saturation coefficient (Φ) were slightly less; however, the mass differences in percentage were essentially the same to references.

5. Discussion

Hygrothermal simulations were conducted using WUFI Pro 5.3 software. For input values the measured material properties for dry density, dry thermal conductivity, porosity, maximum water content, free water saturation, water content at 80% RH and initial water content were used. These were supplemented with reference values where necessary. A sensitivity analysis of the reference

Table 10
Variation in densities.

Mix	Density (kg/m^3)			Initial to natural drying	Initial to oven dry	Natural drying to oven dry	Increment in dry density (in reference to Mix1)
	Initial (Day 0)	Natural drying (Day 26)	Oven dry (Dry density) (ρ_0)				
1	491.89	279.12	233.03	−43.26%	−52.63%	−9.37%	–
2	574.37	370.50	316.79	−35.50%	−44.85%	−9.35%	35.94%
3	697.76	459.89	387.74	−34.09%	−44.43%	−10.34%	66.39%
[a]σ=	103.61	90.39	77.44				

[a] σ = Standard Deviation.

Table 11
Measured dry thermal conductivity (k_0) values.

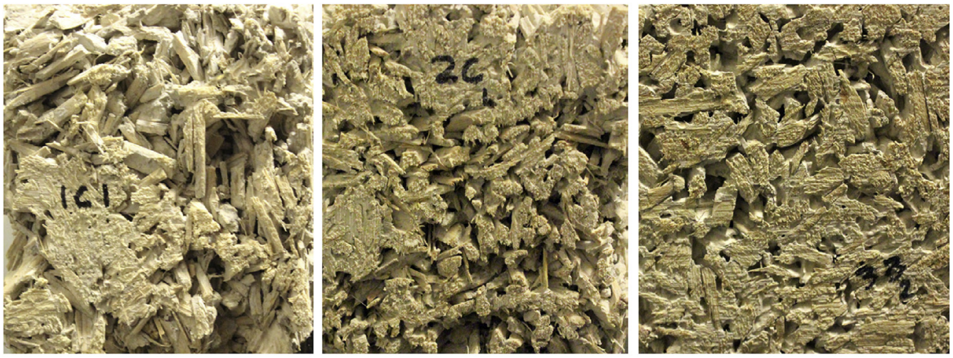
Mix and density	Samples	K (W/mK)	Mean k (W/mK)	Increment (In reference to mix 1)
1	1	0.075	0.074	-
($233 kg/m^3$)	2	0.073		
(Hemp to Binder 1:1)	3	0.075		
2	1	0.088	0.088	18.39%
($317 kg/m^3$)	2	0.088		
(Hemp to Binder 1:1.5)	3	0.088		
3	1	0.104	0.103	38.12%
($388 kg/m^3$)	2	0.106		
(Hemp to Binder 1:2)	3	0.098		

σ (Standard Deviation) = 0.015.

Table 12
Different features of water content.

Mix	W_f (kg/m^3)	W_{max} (kg/m^3)	$WC_{80\%\ Equiv}$ (kg/m^3)	Absorption		Porosity (Φ) (m^3/m^3)	Saturation coefficient
				Cold water (% Mass)	5 Hour boil (% Mass)		
1	376.29	532.66	17.47	161.48%	228.58%	0.53	0.71
2	374.96	525.66	23.77	118.36%	165.93%	0.53	0.71
3	423.55	655.31	29.08	109.24%	169.01%	0.66	0.65
[a]σ=	27.68	72.92	5.81	27.90%	35.32%	0.075	0.035

[a] σ = Standard Deviation.



Mix 1 Mix 2 Mix 3

Fig. 2. Visual image of hempcrete samples in dry state.

values used (i.e. water sorption and range of “k” values) was also carried out to evaluate the impact of using published (reference) values. Hempcrete was inserted into the WUFI material database as a user-defined material with the inputs listed in Table 13.

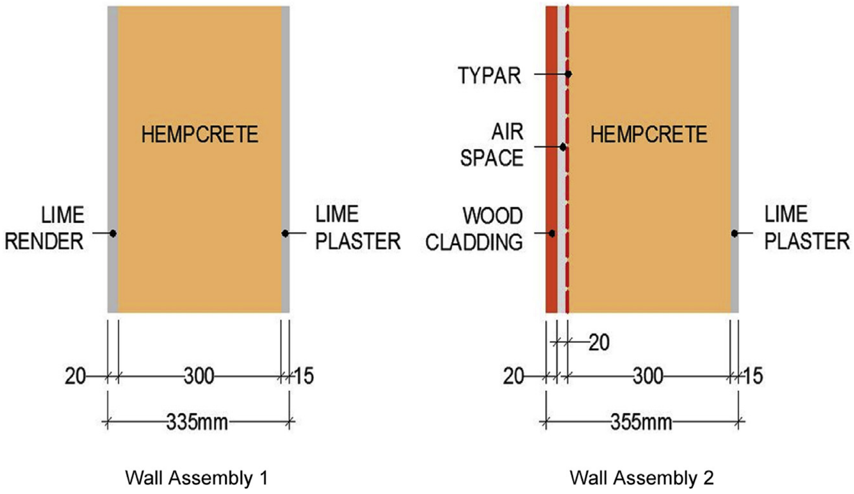
A default climate file for Toronto was used. A user defined sine curve was used to define the inside temperature and RH referring to a typical interior environment in residential buildings. The simulation was then performed for three years. Two types of wall assemblies as described below and shown in Fig. 3 were simulated, with and without exposure of rain, wind and sun:

- Assembly 1: Lime render (20 mm) + Hempcrete (300 mm) + Lime plaster (15 mm); Total thickness: 335 mm (mass wall system)
- Assembly 2: Wood cladding (spruce) (20 mm) + Air layer (20 mm) with continuous air changes of 8 per hour + Typar + Hempcrete (300 mm) + Lime plaster (15 mm); Total thickness: 355 mm (rain screen system)

Fig. 4 shows a regular pattern of seasonal fluctuations in total water content over time based on watering incidents. No long-term

Table 13
Material inputs in WUFI.

States	Hygrothermal parameters	Values	Source(s)
Dry	Dry Density (ρ_0)	388 kg/m^3	Test
	Porosity (Φ)	0.66 m^3/m^3	Test
	Dry Thermal Capacity (c_0)	1560 J/kgK	Reference
	Dry Thermal Conductivity (k_0)	0.1 W/mK	Test
	Dry Vapour Diffusion Resistance Factor (μ_0)	4.85	Reference
Moist	Thermal Conductivity Supplement (b)	3.34%/%mass	Reference
	Maximum WC (W_{max})	655 kg/m^3	Test
	Free Water Saturation (W_f)	424 kg/m^3	Test
	WC at 80% RH ($MC_{80\%\ Equiv}$)	29 kg/m^3 (7.5% mass)	Test/reference
	Liquid Absorption Coefficient (A Value)	0.074 kg/m^2/s$^{1/2}$	Reference
	Typical Built-In (Initial) MC	286 kg/m^3	Test



Wall Assembly 1

Wall Assembly 2

Fig. 3. Simulated wall assemblies.

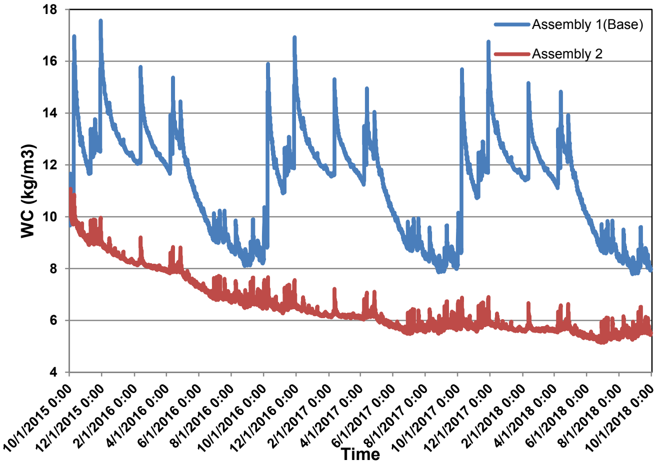


Fig. 4. Total water content - Assembly 1 (mass wall) and Assembly 2 (rain screen).

accumulation of water occurs in either assembly. Assembly 2 (with water content of 0.18%–0.39% of mass) is clearly absorbing less water than assembly 1(with water content of 0.22%–0.49% of mass) highlighting the benefit of a vented cavity in Toronto (Table 14).

Fig. 5 and Table 14 further highlight the benefits of a vented cavity in the Toronto climate as water content in the hempcrete significantly dries out when vented (with water content 3.60%–7.47% of mass) compared to a face-sealed mass wall system (with water content 5.97%–11.36% of mass).

WUFI analysis shows both the wall assemblies (exposed face-sealed mass wall and vented rain screen system) are performing well without any hygrothermal risks such as condensation, frost and salt damage and mould growth. However, when comparing the two assemblies it is clear that vented rain screen is performing significantly better from a hygrothermal perspective. It is drying out faster (expected to reach in dynamic steady state much earlier than the mass wall) and the water content range (Table 14) is also lower. Therefore, the vented rain screen system (wall assembly 2)

Table 14
Water content of hempcrete and total water content range.

Descriptions	Water	Assemblies (Base)		Sensitivity analysis (Assembly 1)			
	Content	Assembly 1	Assembly 2	Sensitivity 1	Sensitivity 2	Sensitivity 3	Sensitivity 4
Hempcrete	kg/m^3	23.18–44.07	13.98–29.00	25.54–46.93	22.90–43.95	23.38–44.15	24.16–44.41
	%Mass	5.97–11.36	3.60–7.47	6.58–12.09	5.90–11.33	6.02–11.38	6.23–11.45
Total	kg/m^3	7.78–17.57	5.13–11.08	8.47–18.47	7.70–17.53	7.84–17.59	8.08–17.67
	%Mass	0.22–0.49	0.18–0.39	0.24–0.51	0.21–0.49	0.22–0.49	0.23–0.49

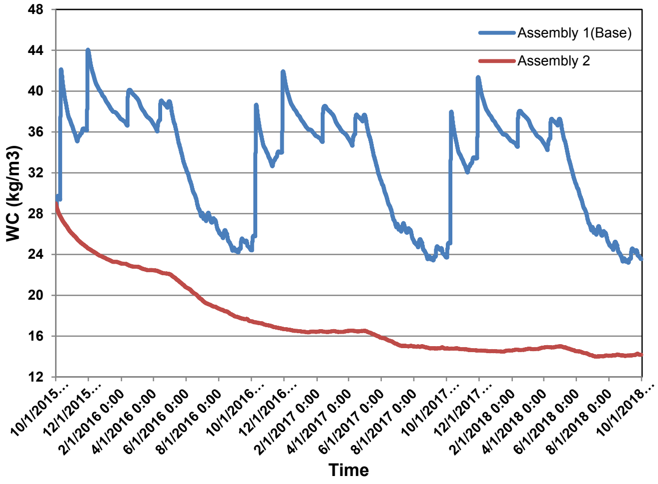


Fig. 5. Water content in hempcrete - Assembly 1 (mass wall) and Assembly 2 (rain screen).

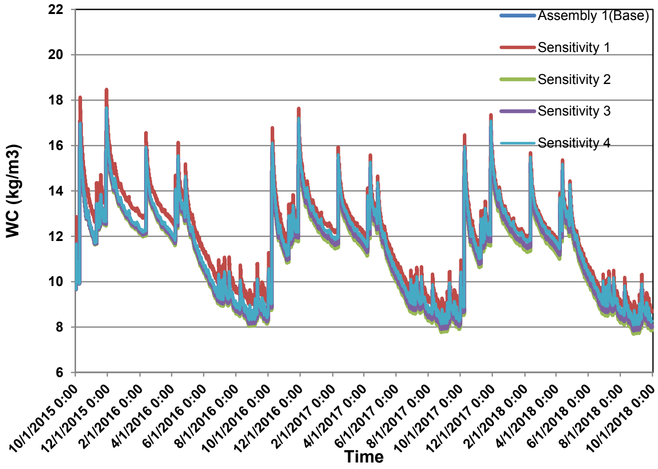


Fig. 6. Total water content - Assembly 1 (mass wall) and Sensitivity analysis.

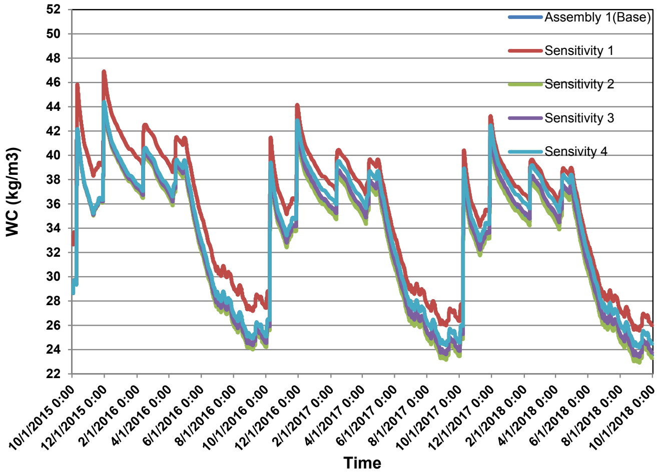


Fig. 7. Water content in hempcrete - Assembly 1 (mass wall) and Sensitivity analysis.

would be the better option for hempcrete in the southern Ontario climate.

Further, to detect the most influential factor on the hygrothermal properties of hempcrete, a, series of (four) sensitivity analyses were conducted by using referenced material properties for wall assembly 1 (mass wall).

1. Sensitivity Analysis 1: Using reference moisture sorption values: Porosity $= 0.73\ m^3/m^3$, $W_{80\%EQUIV} = 33\ kg/m^3$, $W_{max} = 730\ kg/m^3$ and $W_f = 546\ kg/m^3$; to understand the impact of water content in the performance of hempcrete wall.
2. Sensitivity Analysis 2: Using a reference dry “k” value = 0.115 W/mK (high) and moist “k” value = 0.768 W/mK to understand the impact of high “k” value.
3. Sensitivity Analysis 3: Using a mid-level reference dry “k” value = 0.09 W/mK to understand the influence of intermediary thermal insulation.
4. Sensitivity Analysis 4: Using a low-level reference dry “k” value = 0.06 W/mK to understand the hygrothermal behavior of wall in high thermal insulation scenario.

The results of the sensitivity analysis (Table 14, Fig. 6 and Fig. 7) are similar to the base case results (Figs. 4 and 5). The total, and individual layer, water content shows a regular pattern of seasonal fluctuation. Overall, water content is well below 15% in each layer throughout the simulation period. The wall is drying out fast and is approaching dynamic equilibrium in all cases. No long term accumulation of water in one point of any layer was observed. As such, no significant changes in hygrothermal characteristics of hempcrete wall due to some variations in moisture sorption and thermal conductivity have been detected through the sensitivity analysis.

6. Conclusions

This paper concludes that the thermal conductivity of three studied hempcrete mixes (with hemp to binder ratios of 1:1, 1:1.5 and 1:2, respectively) is highly influenced by their density. The higher the binder content, the higher the density, leading to a higher thermal conductivity. This relationship follows a near linear pattern.

Measurements of dry density and thermal conductivity ranged from 233 kg/m^3 to 388 kg/m^3 and 0.074 W/mK, to 0.103 W/mK, respectively. It was also noted that the drying period of hempcrete (in controlled room temperature and RH) was approximately 26 days, where minimum density was stabilized.

One-dimensional hygrothermal analysis showed that both a face-sealed mass wall, and a vented rain screen wall system, can perform well in all the hygrothermal parameters without any deleterious issues in an Ontario (Canada) climate. However, in comparison to the face-sealed system, the vented rain screen system performed significantly better in terms of moisture management. Therefore, the vented rain screen system could be considered as a better option for a hempcrete wall assembly in southern Ontario. Finally, no significant impacts on hygrothermal characteristic of hempcrete wall were noticed during the sensitivity analysis due to some variations in moisture sorption and thermal conductivity, based on published reference values.

References

Abbot, T., 2014. Hempcrete Factsheet. http://limecrete.co.uk/hempcrete-factsheet/.

Ahlberg, J., Georges, E., Norlén, M., 2014. The Potential of Hemp Buildings in Different Climates and the Hempcrete Building System. Uppsala University, Sweden.

Alembic Studio, LLC, 2013. Building with Hempcrete: Specifications and Test Data. http://hempsteads.info/wp-content/uploads/2013/11/ATL-Hemp-Report.pdf.

Arnaud, L., Amziane, S., 2013. Bio-aggregate-based Building Materials: Applications to Hemp Concretes. ISTE Ltd and John Wiley and Sons, Inc.

Arnaud, L., Gourlay, E., 2012. Experimental study of parameters influencing mechanical properties of hemp concretes. Constr. Build. Mater. 28 (1), 50–56.

ASTM C 518-10, 2003. Standard Test Method for Steady-state Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus, pp. 1–15.

ASTM C62-13a, 2013. Standard Specification for Building Brick - Solid Masonry Units Made from Clay or Shale, pp. 1–7.

ASTM C67-14, 2000. Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile 1, 04.

BATICHANVRE® for Eco Build Hemp Construction. St Astier Limes and Mortars, 2006. http://www.womersleys.co.uk/techguides/batichanvre.pdf. http://www.limes.us/applications/hemp-construction/.

Bedlivá, H., Isaacs, N., 2014. Hempcrete – an environmentally friendly material? Adv. Mater. Res. 1041, 83–86.

Berardi, U., 2016. A cross country comparison of building energy consumption and their trends. Resour. Conserv. Recycling. http://dx.doi.org/10.1016/j.resconrec.2016.03.014 (in press).

Berardi, U., Iannace, G., 2015. Acoustic characterization of natural fibers for sound absorption applications. Build. Environ. 94, 840–852.

Bevan, R., Woolley, T., 2008. Hemp Lime Construction: a Guide to Building with Hemp Lime Composites. IHS BRE Press.

Bouguerra, A., Ledhem, A., de Barquin, F., Dheilly, R.M., Quéneudec, M., 1998. Effect of microstructure on the mechanical and thermal properties of lightweight concrete prepared from clay, cement, and wood aggregates. Cem. Concr. Res. 28 (8), 1179–1190.

De Bruijn, P.B., Jeppsson, K.H., Sandin, K., Nilsson, C., 2009. Mechanical properties of lime-hemp concrete containing shives and fibres. Biosyst. Eng. 103 (4), 474–479.

Canadian Hemp Trade Alliance, 2015. http://www.hemptrade.ca/.

Cerezo, V., 2005. Mechanical, Thermal and Acoustic Material Based on Plant Particles: Experimental Approach and Theoretical Modeling. PhD Thesis. ENTPE, Lyon.

Colinart, T., Glouannec, P., Chauvelon, P., 2012. Influence of the setting process and the formulation on the drying of hemp concrete. Constr. Build. Mater. 30, 372–380.

Collet, F., Pretot, S., 2014. Thermal conductivity of hemp concretes: variation with formulation, density and water content. Constr. Build. Mater. 65, 612–619.

Collet, F., Chamoin, J., Pretot, S., Lanos, C., 2013. Comparison of the hygric behaviour of three hemp concretes. Energy Build. 62, 294–303.

Eberlin, C., Jankovic, L., 2015. Exploring the Energy Performance of Hemcrete in Affordable Housing and Future Implications for Carbon Reduction in the Housing Sector. NNFCC.

Elfordy, S., Lucas, F., Tancret, F., Scudeller, Y., Goudet, L., 2008. Mechanical and thermal properties of lime and hemp concrete ("hempcrete") manufactured by a projection process. Constr. Build. Mater. 22 (10), 2116–2123.

Evrard, A., 2006. Sorption behaviour of Lime-Hemp Concrete and its relation to indoor comfort and energy demand. In: 23rd International Conference on Passive and Low Energy Architecture, pp. I553–I557.

Evrard, A., 2008. Transient Hygrothermal Behaviour of Lime-hemp Materials. PHD Thesis. Universite Catholique De Louvain, Belgium.

Evrard, A., De Herde, A., 2005. Bioclimatic envelopes made of lime and hemp concrete. In: Proceeding of CISBAT, pp. 1–6. http://dial.academielouvain.be/vital/access/services/Download/boreal:73818/PDF_01.

Hemp Edification, 2015. http://hempedification.blogspot.ca/2015/07/hempcrete.html.

Kenter, P., 2015. Championing Hemp: Ontario Builder Promoting Use of Hempcrete. http://dailycommercialnews.com/Projects/News/2015/3/Championing-hemp-Ontario-builder-promoting-use-of-hempcrete-1006745W/.

Künzel, H.M., 1995. Simultaneous heat and moisture transport in building components one- and two-dimensional calculation using simple parameters. Fraunhofer Irb Verlag Suttgart, ISBN 3-8167-4103-7. https://www.ibp.fraunhofer.de/content/dam/ibp/de/documents/Publikationen/Dissertationen/hk_dissertation_etcm45-30731.pdf.

Lanos, C., Collet, F., 2011. Mechanical properties of hempcrete. In: Biomaterials and Binders for Construction – Hemp, Lime, Wood European Workshop in Darmstadt, France, pp. 21–22.

Lawrence, M., Fodde, E., Paine, K., Walker, P., 2012. Hygrothermal performance of an experimental hemp-lime building. Key Eng. Mater. 517, 413–421.

Tran Le, A.D., Maalouf, C., Mai, T.H., Wurtz, E., Collet, F., 2010. Transient hygrothermal behaviour of a hemp concrete building envelope. Energy Build. 42 (10), 1797–1806.

Magwood, C., 2014. Building with Hempcrete or Hemp-lime. Endeavour Centre. http://endeavourcentre.org/2014/11/building-with-hempcrete-or-hemp-lime/.

Maher, J.B., 2014. Hempcrete – Sustainability and Superior Performance. 2014 NW EcoBuilding Guild Retreat. Impact HUB, Seattle, WA. http://www.ecobuilding.org/conference/previous-years/presentation-files/2014-presentations/EB2014Hempcrete.pdf.

Mawditt, I., 2008. Unique Thermal Performance of Tradical Hempcrete. Retrieved from. http://www.limetech.info/upload/documents/Hemcrete/Ian Mawditt Presentation.pdf.

Mensinga, P., 2009. Determining the Critical Degree of Saturation of Brick Using Frost. MASc Thesis. University of Waterloo, ON.

Ontario Building Code, 2012. Supplementary Standard SB-12: Energy Efficiency for Housing.

Pinkos, J., Dick, K., Whitmore, E., 2011. Load and Moisture Behaviour of Manitoba Hemp for Use in Hempcrete Wall Systems in a Northern Prairie Climate. The Canadian Society for Bioengineering. Paper No. CSBE11–401.

Rhydwen, R., 2006. Building with Hemp and Lime. http://gse.cat.org.uk/public_downloads/research/hemp/building_with_hemp_and_lime.pdf.

Schiavoni, S., Bianchi, F., Asdrubali, F., 2016. Insulation materials for the building sector: a review and comparative analysis. Renew. Sustain. Energy Rev. 62, 988–1011.

Stanwix, W., Sparrow, A., 2014. The Hempcrete Book: Designing and Building with Hemp-lime. Green Books, UK.

Straube, J., 2007. Thermal Metrics for High Performance Enclosure Walls: the Limitations of R-value. Building Science Corporation. Research Report–0901.

Tolkovsky, A., 2010. Sorption Behaviour of Hemp and Lime Concrete Floors: a Method for Measuring Moisture Content in Hemp and Lime Using a Wood Block Probe for Long Term Moisture Monitoring. MSC Thesis. Graduate School of the Environment, Centre for Alternative Technology and School of Computing and Technology, University of East London, UK.

Walker, R., Pavía, S., 2014. Moisture transfer and thermal properties of hemp-lime concretes. Constr. Build. Mater. 64, 270–276.

Walker, R., Pavia, S., Mitchell, R., 2014. Mechanical properties and durability of hemp-lime concretes. Constr. Build. Mater. 61, 340–348.

Woolley, T., 2012. Low Impact Building. Willey and Blackwell (London).