In: Civil Engineering Research in Ireland, CERAI. Belfast, 2014.

Impact of hydration on the properties of hemp-lime concrete

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ABSTRACT: Hemp-lime concrete is a low-embodied energy, carbon-negative, sustainable building material made with a lime-based binder and hemp aggregate. The material properties depend on several factors including: binder and hemp type and their ratio, water content, density, manufacturing method and curing conditions. This paper investigates hydration of a commercial binder which includes significant hydraulic additions. During curing, hydraulic binders compete for water with the (high suction) hemp particles. This competition can trigger a shortage of water for binder hydration which can undermine the performance of the concrete.

The paper investigates the effect of saturating the concrete in water following an initial curing period. It concludes that hydration restarts following the reintroduction of water: the Scanning Electron Microscope evidenced a significant increase in the amount of hydrates filling pores in the concrete following re-immersion. The results also evidenced that the increase in the amount of hydrates results in a compressive strength enhancement and a reduction in permeability and capillary absorption of the concrete. This paper highlights the importance of considering mixing water content and drying conditions (including time of demoulding, curing humidity and temperature and sample size) to ensure full hydration of hydraulic binder in hemp concrete and obtaining optimum performance of the material.

KEY WORDS: Hemp-lime concrete; Hydration; Microstructure; Strength; Permeability; Capillary absorption

1 INTRODUCTION

Hemp-lime concrete is an alternative to conventional construction materials. It is a low-embodied energy, carbon-negative, sustainable building material made of a lime-based binder and hemp aggregate. It was developed in France in the 1990s and has since been used in hundreds of houses in Europe. Although an innovative material, organic matter has been added to building materials since antiquity.

Hemp-lime concrete is light-weight (average wall density 275-400kg/m^3) and non-structural, typically used in combination with load-bearing frames. The material properties depend on several factors including: binder type, binder:hemp ratio, mixing water content, density, hemp shiv properties, manufacturing method, curing conditions and age.

It typically exhibits low strength and a ductile compressive failure between 0.2-1.2 MPa [1-7] and an open pore structure (70.6% porosity [8]). Hemp-lime concrete has excellent thermal performance: a high thermal capacity (1000 J/kgK [9], 1240-1350 J/kgK [10], 1560±30 J/kgK [11]) coupled with a medium density and a low thermal conductivity (0.05-0.12 W/mK [12]) provide the material with good insulation capabilities.

The hemp-lime concrete comprises of hemp shiv (approximately 5-30mm in length) coated by a binder that forms a matrix that holds the concrete together. Evrard and de Herde (2010) identified three types of pores; 1-10mm air voids that are interconnected and separated from the shiv by a binder coating, micro pores in the hemp shiv c.10um and smaller pores in the lime matrix c.1um [13]. Hydrates in the binder further reduces the pore size.

The binder is typically lime based with hydraulic additions to facilitate setting and early strength development. Commercial binders specially formulated for use with hemp are also available in the market. Their formulation are not accurately known but may contain hydraulic additions including Portland cement, hydraulic lime and pozzolans.

The hydraulicity of the binder should be low to avoid competition for water with hemp particles. Furthermore, strongly hydraulic binders can lead to trapping residual moisture in hemp particles [1].

Following an investigation of hemp concrete durability (freeze:thaw and salt exposure) which involved saturating the concrete in water after 9 months curing, it was evident that exposing hemp concrete made with a commercial binder to water following curing increased binder hydration [7]. Such an increase in hydration was not evident for less hydraulic binders. This research investigates the effect of this additional binder hydration on compressive strength, permeability and capillary action of hemp concrete made with commercial binder.

Additional hydration of hemp-lime concrete, following initial curing has not yet been investigated although De Bruijn et al. (2009) observed an increase in compressive strength of samples with cement binder following freeze/thaw cycling and attributed this to the immersion in water for 24 hours prior to testing [14]. However, Evrard (2003) does not contemplate re-hydration, stating that an initial lack of water for hydration causes the concrete to powder and this is irreversible [1]. In cement mortars, hydration restarts following reintroduction of water however, the material may not achieve its full compressive strength due to cracking and to the formation of different hydrates which may not contribute as much to strength [15].

In relation to mortar properties, increasing hydraulicity enhances pore size distribution and this is partly attributed to hydrates filling pores [16]. Increasing hydraulicity in lime mortars, increases strength, reduces water vapour permeability [17] and reduces capillarity [16]. However, these effects may not be directly comparable to hemp-lime concrete due to the macroporosity of its interparticular spaces [18].

As aforementioned, this research investigates strength development, permeability and capillary action. The concrete develops early strength due to the hydrates in the binder forming a continuous network [19] and it then gains strength more slowly due to carbonation [2]. The effect of the binder's hydraulic strength on hemp concrete has yielded varying opinions. Hirst et al. (2010) found that the strength of the concrete is not directly related to the strength of the binder [5]. Nguyen (2010) however claims that stronger binders can increase the strength of the concrete, provided that their hydraulicity is not compromised by a shortage of water [20]. De Bruijn et al. (2009) and Murphy et al. (2010) also showed that compressive strength of hemp concrete increased with increasing binder hydraulicity [4, 14]. Walker and Pavía (2014) investigated the strength of hemp concrete with a range of binders including calcium-lime/pozzolan; calcium-lime/hydraulic-lime/cement and commercial binder. The authors found that strength development was a function of binder hydraulicity up to 6 months but, at 1 year, all hemp concretes displayed a similar compressive strength (0.32-0.41MPa) [7]. It is evident that the commercial binder did not fully hydrate as discussed in this paper.

Hemp-lime concrete is commonly described as having good water vapour permeability. The common industry figure of water vapour diffusion resistance factor (µ) is 4.85 ± 0.24 [11, 21] in accordance with EN 12572 for samples with a binder:hemp:water ratio of 2:1:3 and density of c.400kg/m^3. Collet et al. (2009) measured water vapour permeability for moulded hemp samples with a binder:hemp ratio of 2:1 and density of c.420kg/m^3 and obtained a value 1.7x10^{-11} kg.m^{-1}.s^{-1}.Pa^{-1}[22]. Le Tran (2011 referring to Grelat 2005) observed that the binder strongly influences hemp concrete permeability with less hydraulic binders having a lower water vapour diffusion resistance factor however, like-with-like was not compared as the density varied between samples [23 referring to 24].

Walker and Pavia (2014) observed a vapour diffusion resistance factor between 5.42 and 5.71 for a range of binders including calcium-lime/pozzolan; calcium-lime/hydraulic-lime/cement and commercial binder for a density of c.360kg/m^3[10]. A trend of decreasing vapour permeability with increasing binder hydraulicity was established although not statistically significant. The lack of significance was attributed to the relatively small variation in binder hydraulicity amongst the concretes (as the commercial binder initially did not fully hydrate as discussed in this paper).

Hemp-lime concretes have high capillarity on account of their open pore structure and ability to hold water in their capillaries. Evrard (2008) measured a water absorption coefficient of 4.42 ± 0.27 kg/m^{2}h$^{1/2}$ for a concrete made with proprietary binder and density c. 487kg/m^3 in accordance with DIN 52617 [11]. Evrard (2003) states that concretes with higher hydraulicity have a lower capillary absorption [1]. Conversely, De Bruijn et al. (2009) observed no significant difference between the capillarity of concretes of varying hydraulic content and calculated the water sorption coefficient at 0.15kg/m^{2}s$^{1/2}$ for concrete with density ranging from 587 to 733 kg/m^3 [14]. In contrast, Walker and Pavía (2014) evidenced a relationship between decreasing permeability and increasing binder hydraulicity measuring water sorption coefficients between 2.65 and 3.37kg/m^{2}h$^{1/2}$ over the first 24 hours for a range of binders including calcium-lime/pozzolan; calcium-lime/hydraulic-lime/cement and commercial binder with density c.360kg/m^3 [10].

2 MATERIALS AND METHODS

2.1 Materials

The concrete was made using a commercial binder whose composition is not accurately known but has been formulated specially for use with hemp and contains hydraulic additions. Industrial hemp shiv was supplied by La Chanvrière De L'aube in central France. The water content was determined by the expertise of a skilled building practitioner, Henry Thompson to produce a suitable workability and was lower than that recommended by the manufacturer. The hemp:binder:water content (by weight) was 2:1:2.9.

2.2 Mixing, Curing and Compaction

Mixing was carried out on site in a large pan mixer at 2 batches per mix. The binder and ¾ of the water were mixed for 2.5 minutes to form a slurry. The hemp was then gradually added as well as the remaining water. The total mixing time was 7 minutes. After mixing, the concrete was put into cling-film lined, 100mm cubic moulds in a single layer. The mould was removed and the samples transferred to a curing room at temperature of 16°C±3°C and 55±10% RH.

2.3 Immersion after curing

For the compressive strength testing; 9 month cured 100mm cubes were immersed in water for 2 days and wrapped in plastic for 2 weeks. They were then allowed to dry for 2 months and then tested at 1 year. The results were compared against control samples that remained in the curing room until testing, also at 1 year. The initial dry density of the concrete was 360kg/m^3 and following saturation c.385kg/m^3.

The permeability and capillary action samples were similarly treated however, they were immersed at 1 year and tested at 1 year and 2.5 months. Their initial dry density was c.400kg/m^3 and c.428kg/m^3 following saturation. Four 100mm hemp-lime concretes cubes were tested for each property.

2.4 Microstructure

The microstructure of the binder and the surface of the hemp were investigated using a Tescan MIRA Field Emission Scanning Electron Microscope. The samples were freshly fractured and covered with a gold coating in an 'Emscope SC500' plasma coating unit. Individual hemp particles were extracted from fractured surfaces and mounted on pin stubs prior to coating.

2.5 Strength

Compressive strength was measured on 100mm cubes using a Zwick Testing apparatus. No standards currently apply to hemp-lime concrete thus the testing procedures of EN459-2 [25] and EN196-1 [26] were used to guide the testing. The samples did not break but continuously deformed in a plastic manner. Failure strength was considered as the point at which the stress/strain curve departs from linear behaviour. The compressive strength (at 1 year) of concretes that were exposed to salt water spray in a SC1000 Open Lid Salt Fog Chamber [7] for 1 month followed by two months of drying is also discussed.

2.6 Permeability

The water vapour permeability was guided by EN 12086:1997 [27]. The specimens were placed on a dish with a small lip with one side exposed to the humid environment of the curing room (20±1°C and 50±5% RH) and the underside exposed to the dish containing 75g of calcium chloride, a desiccant that maintains the RH at 0%. The sides of the specimen are sealed by means of a rubber sleeve and sealant to ensure that water vapour transfer only occurs through the exposed surface of the specimen. The test was continued for 9 weeks and samples weighted at weekly intervals. The samples stabilised during three weeks and the readings from the subsequent six weeks provided the results to determine water vapour permeability.

2.7 Capillary Action

The water absorption coefficient by capillarity was guided by EN 1925:1999 [28]. The standard was altered in order to adapt it to the hemp-lime concrete. On account of the highly porous nature of the concrete, the duration of the test was 10,000 minutes. The samples were placed on a wire grill, in a container of water so that the water covered the lower 5mm of the samples, and weighted at intervals over time. The coefficient is a measure of the water sorption as a function of the surface area of the specimen and time.

3 RESULTS

3.1 Morphology

SEM evidenced abundant hydrates at the hemp-lime interface as shown in Figure 1. However, a large increase in the quantity of hydrates in the commercial binder as a result of water saturation is observed (Figure 2). Abundant needle-shaped hydrates are evident growing into the pores suggesting a reduction in pore size.

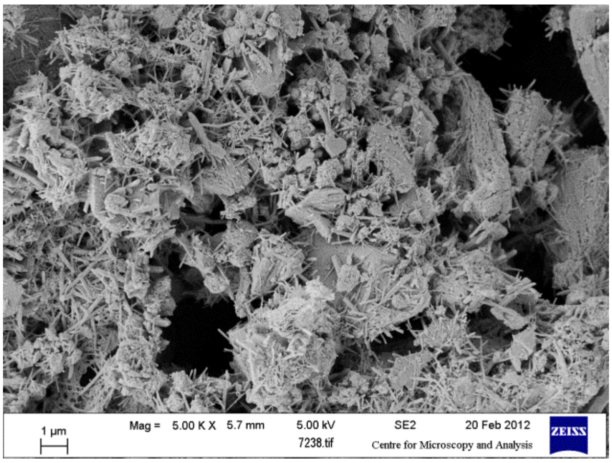

Figure 1. Hydrates in hemp-lime concrete made with commercial binder.

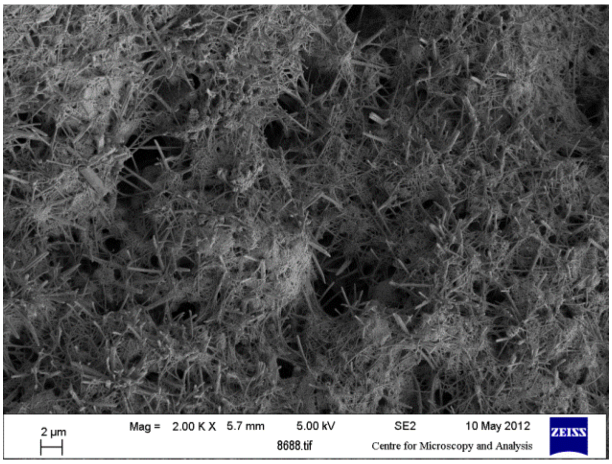

Figure 2. Increased quantity of hydrates in the binder of hemp concrete saturated with water for 2 weeks.

A weight gain of approximately 7% in the concretes immersed after curing further supports the evidence of an increased hydration: water was likely incorporated in additional hydrates resulting in weight gain of the hemp-lime concrete.

3.2 Strength

As aforementioned, the strength of 1 year concrete (immersed after curing) and 1 year (control) concrete was compared to the strength of 1 year concrete exposed to a salt spray solution at regular intervals for 1 month.

Compressive strength increased by 77% and 127% following saturation in water for 2 weeks and salt water spraying for 4 weeks respectively, as shown in Figure 3. This further suggests that the re-introduction of water into the concrete bearing hydraulic binder allows further hydration to occur. The high hydraulic component of the commercial binder clearly did not fully hydrate during initial curing. Re-introducing water allows additional hydration and clearly increases concrete strength (compared to the initial partially-hydrated concrete). The formation of new hydrates leading to strength increase is likely facilitated by a combination of the high water storage and outstanding water transfer properties

of the hemp concrete which allow water to penetrate; and the concrete's ductility which reduces the likelihood of cracking.
It was also observed that, when the concrete is exposed to water for longer (1 month spray test as opposed to 2 weeks water saturation), it exhibits an even higher compressive strength.

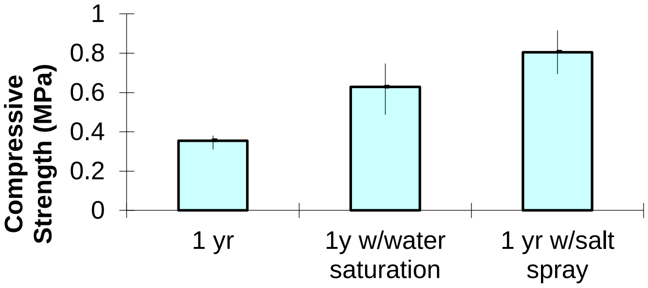

Figure 3. Compressive strength of concrete at 1 year.

3.3 *Water Vapour Permeability*

The water vapour permeability is initially very low, with a water vapour diffusion factor at 1 week of 11.5 and 16 for the control and saturated concretes respectively as shown in Figure 4. The permeability rate stabilised from about 3 weeks and it is observed that it takes longer for the water saturated concrete to achieve a constant permeability rate. There is a significant difference in the average water vapour diffusion factor of 6.1 for the concrete (curing room) and 7.6 for the concrete (water saturated) achieved between weeks 3 and 9. The results show a strong relationship between increasing binder hydraulicity and decreasing permeability. The results agree with Le Tran (2011 referring to Grelat 2005) who observed that the binder strongly influences the permeability of the concrete with less hydraulic binders having a lower water vapour diffusion resistance factor [23 referring to 24].

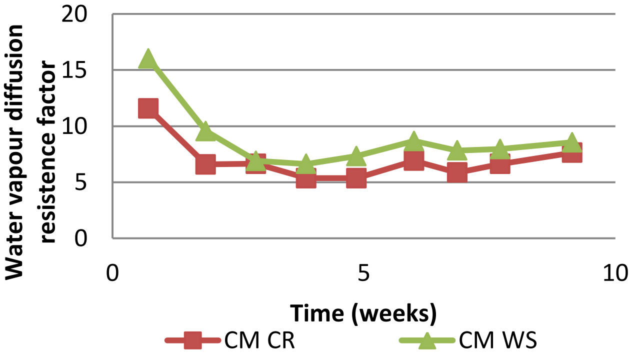

Figure 4. Water vapour permeability of concretes. CM CR – control concrete (curing room); CM WS concrete saturated in water for 2 weeks. Concrete tested at 14.5 months.

3.4 *Capillary Action*

The control and saturated concretes reached water sorption coefficient (slope of the line) of 2.14 and 3.88 respectively. The results further suggest that additional hydration due to reintroduction of water after initial curing reduces the sizes of the capillary pores and pore connectivity thereby reducing the water absorption due to capillary uptake at early ages (Figure 5). (Walker and Pavia 2014) also observed a relationship between decreasing capillary action and increasing binder hydraulicity in hemp-lime concrete with different binders [10].

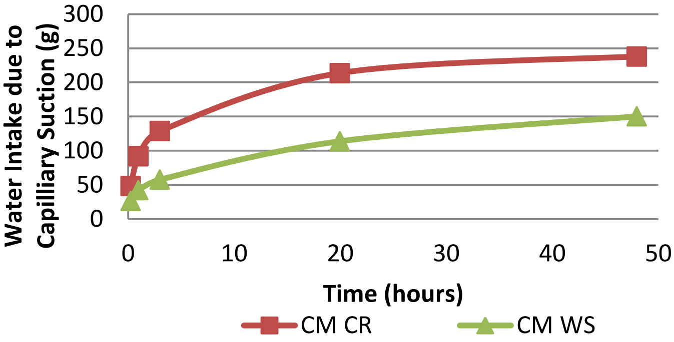

Figure 5. Water absorption due to capillary uptake over time. CM CR – control concrete (curing room); CM WS concrete saturated in water for 2 weeks. Concrete tested at 14.5 months.

4 DISCUSSION

The commercial binder is marketed as a lime based binder and therefore the high level of hydration recorded in this research was not expected. Evidently, there is a competition for water between the binder and hemp and the binder did not have enough water to fully hydrate. It appears that re-introducing water restarts the hydration process for unreacted binder. This disagrees with the assertion by Evrard (2003) that the lack of water for hydration causes the concrete to powder and this is irreversible [1].
In this research, there was insufficient water available for the full hydration of the concrete made with the commercial binder. This is due to either or both: low mixing water content or fast drying which will reduce the quantity of water available for binder hydration. However, the concrete was mixed and cured in a similar manner to other authors using commercial binders suggesting that it achieved similar hydration. The compressive strength reached by the concrete is similar to that reported by other authors which suggests similar hydration.
The water content slightly varied from the recommended quantity however it provided a suitable workability as determined by a skilled practitioner. The quantity of mixing water was 49% (by weight) which is within the range of other authors 42.4%-50.9% [19], 43%-48% [5] and similar to 50% [29]–all using commercial binders.
The curing conditions were also similar to those by other authors: 16°C±3°C and relative humidity 55%±10% which would result in similar drying conditions to 20±1°C and 60±5% RH [5] and 20°C and 65% used by [29]. Furthermore, Arnaud and Gourlay (2012) found that the ideal curing conditions for hydraulic lime and a commercial binder to achieve optimum compressive strength at 28 days is 20°C and 50% RH and that high relative humidity (98% and 75%) reduces the 28 day strength of a commercial and hydraulic lime binder [19].
The small specimen size (100mm cube) compared to the cylinders used by [5 and 19] likely hastened drying. Drying may also have been further hastened on account of directly demoulding the samples, which differed from demoulding at 6

days [5] and 5 days [29]. However, the duration of drying of the samples (c. 40 days) is longer than c. 30 days observed by [29]

In relation to mixing, prewetting the hemp may prove beneficial for hydraulic commercial binder. Cerezo (2005) and Nguyen (2010) prewet the hemp to avoid competition for water between binder and hemp shiv, this could enhance hydration of an eminently hydraulic binder [2, 20].

However, as aforementioned, irrespective of mixing and drying conditions, the compressive strength achieved by the concrete in this research suggests a similar level of hydration to other authors. The average compressive strength of the concrete at 28 days is 0.21MPa which is similar to 0.18MPa ([5] density 375kg/m^3) and 0.15-0.3MPa [19]. Furthermore, the compressive strength achieved following salt water spray for 1 month is 0.81MPa at 1 year for an initial concrete density of c.360kg/m^3. This is at the upper end of the compressive strength range achieved for hemp-lime concretes by other authors, and suggests that this quantity of hydrates is rarely achieved in the concrete.

It is evident that the binder did not fully hydrate, and this illustrates the importance of considering the binder's hydraulicity when selecting optimum mixing water content and curing conditions to ensure full hydration.

5 CONCLUSION

- Water saturation can restart hydration in partly hydrated hydraulic binders of hemp concretes. Weight gain is attributed to incorporating water in the formation of new hydrates.
- Additional hydration reduces pore sizes in the binder.
- Additional hydration increases compressive strength and reduces permeability and capillary action.
- Mixing water content and drying conditions (including time of demoulding, curing humidity and temperature and sample size) must be carefully controlled to ensure full hydration of the concrete binder.

ACKNOWLEDGMENTS

The authors wish to thank the Environmental Protection Agency for funding this research. The authors also thank the Traditional Lime Company, Clogrennane Lime and Ecocem for the provision of materials and also Dr Heath Bagshaw (Centre for Microscopy and Analysis) for his help with the SEM.

REFERENCES

[1] Evrard, A. (2003), *'Hemp Concrete- A synthesis of physical properties',* Construire en Chanvre, France.

[2] Cerezo, V. (2005), *'Propriétés mécaniques, thermiques et acoustiques d'un matériau à base de particules végétales: approche expérimentale et modélisation théorique',* PhD thesis, L'Institut National des Sciences Appliquées de Lyon, France.

[3] De Bruijn, P. (2008), *'Hemp Concretes - Mechanical Properties using both Shives and Fibres',* Licentiate Thesis, Swedish University of Agricultural Sciences, Sweden.

[4] Murphy, F., Pavia, S., Walker, R. (2010), 'An assessment of some physical properties of limehemp concrete', *Proceedings of the Bridge and Concrete Research Ireland (BCRI),* University of Cork, Cork, 431 – 438.

[5] Hirst, E., Walker, P., Paine, K., and Yates, T. (2010), 'Characterisation of Low Density Hemp-Lime Concrete Building Materials under Compression Loading', *Proceedings of the 2nd International Conference on Sustainable Construction Materials and Technologies,* Italy.

[6] Gourlay, E., and Arnaud, L. (2010), 'Comportement hygrothermique des murs de béton de chanvre', *Proceeding of Société Française de Thermique,* Le Touquet, France.

[7] Walker, R., and Pavia, S. (2014), 'Mechanical properties and durability of hemp-lime concretes', *Construction and Building Materials, in press.*

[8] Collet, F., Bart, M., Serres, L., and Miriel, J. (2008), 'Porous structure and water vapour sorption of hemp-based materials', *Construction and Building Materials,* 22(6), 1271-1280.

[9] Tran Le, A. D., Maalouf, C., Mai, T. H., Wurtz, E., and Collet, F. (2010), 'Transient hygrothermal behaviour of a hemp concrete building envelope', *Energy and Buildings,* 42(10), 1797-1806.

[10] Walker, R., and Pavia, S. (2014a), 'Moisture transfer and thermal properties of hemp-lime concretes', *Construction and Building Materials, in press.*

[11] Evrard, A. (2008), *'Transient hygothermal behaviour of hemp-lime material',* PhD thesis, Universite catholique de Louvain, Belgium.

[12] Daly, P., Ronchetti, P. and Woolley, T. (2012), *'Hemp Lime Bio-concrete as a Construction Material',* Enivoronmental Protection Agency, Ireland.

[13] Evrard, A., and de Herde, A. (2010). "Hygrothermal Performance of Lime-Hemp Wall Assemblies." *Journal of Building Physics,* 34, 5-25.

[14] De Bruijn, P. B., Jeppssona, K.-H., Sandin, K., and Nilssona, C. (2009), 'Mechanical properties of lime–hemp concrete containing shives and fibres', *Biosystems Engineering,* 103(4), 474-479.

[15] Takeshi, I., and Taketo, U. (2003), 'Effect of curing condition at early age on microstructure of hardened cement', *Japan Society of Civil Engineers,* 17-26.

[16] Arandigoyen, M., and Alvarez, J. I. (2006), 'Blended pastes of cement and lime: Pore structure and capillary porosity', *Applied Surface Science,* 252(23), 8077-8085.

[17] Svennberg, K. (2006), *'Moisture Buffering in the Indoor Environment',* PhD thesis, Lund University, Sweden.

[18] Wilkinson, S. (2009), *'A study of the moisture buffering potential of hemp in combination with lime and clay based binders',* MSc thesis, Centre for Alternative Technology, UK.

[19] Arnaud, L., and Gourlay, E. (2012), 'Experimental study of parameters influencing mechanical properties of hemp concretes', *Construction and Building Materials,* 28(1), 50-56.

[20] Nguyen, T. (2010), *'Contribution à l'étude de la formulation et du procédé de fabrication d'éléments de construction en béton de chanvre',* PhD thesis, Université de Bretagne-Sud, France.

[21] Evrard, A., and de Herde, A., (2005), 'Bioclimatic Envelopes made of lime and hemp concrete', *Proceedings of CISBAT,* Ecole Polytechnique Federale de Lausanne, Switzerland.

[22] Collet, F. (2009), 'Hydric characterization of sprayed hempcrete', *Proceedings of the 4th International Building Physics Conference,* Istanbul, Turkey.

[23] Tran Le, A. (2011), *'Etude des transferts hygrothermique dans le beton de chanvre et leur application au batiments',* PhD thesis, University of Reims Champagne-Ardenne, France.

[24] Grelat, A. (2005), *'Utilisation des matériaux renouvelables en parois de maisons individuelles à ossature bois',* Rapport final de l'Annexe 3-Expérimentations en laboratoire, Instrumentation in situ. Fédération Française Du Bâtiment, France.

[25] EN 459-1:2010 Building lime. Definitions, specifications and conformity criteria.

[26] EN 196-1-2005 Methods of testing cement. Determination of strength.

[27] EN 12086:1997 Thermal insulating products for building applications — Determination of water vapour transmission properties.

[28] EN 1925:1999 Natural stone test methods - Determination of water absorption coefficient by capillarity

[29] Evrard, A. (2006), "Sorption behaviour of Hemp-lime Concrete and its relation to indoor comfort and energy demand', *Proceeding of PLEA2006 - The 23rd Conference on Passive and Low Energy Architecture,* Geneva, Switzerland.