Chapter 6
Hygric and Thermal Properties of Bio-aggregate Based Building Materials

Florence Collet

Abstract This chapter gives the state of the art of previous studies on hygric and thermal properties of bio-aggregate based building materials. Firstly, hygric characteristics such as sorption isotherms, water vapor permeability and moisture diffusivity are given. The ability of bio-aggregate based building materials to moderate ambient relative humidity may be valued using moisture buffer value. Then thermal properties (thermal conductivity, thermal diffusivity conductivity and specific heat capacity) are reported. Finally, concluding remarks on hygrothermal behavior with simultaneous heat and mass transfer are provided, they underline that considering only thermal conductivity and specific heat capacity is not sufficient to evaluate the energy performance of bio-aggregate based building materials. The results found in bibliography mainly concern wood-based and hemp-based materials.

Keywords Thermal conductivity · Thermal diffusivity · Specific heat capacity · Sorption isotherm · Water vapour permeabilty · Moisture buffer value

6.1 Introduction

Bio-aggregate based building materials (BBM) are made from various binders and bio-aggregates. The more efficient formulation parameter is the aggregate to binder ratio. These materials are highly porous. Their porosity includes a wide range of pore sizes: macropores due to the imperfect arrangement of bio-aggregates, mesopores within aggregate and binder, and micropores in the binder. This porosity is open and interconnected and is thus the place of heat and mass transfer and moisture storage.

F. Collet (✉)
Laboratoire de Génie Civil et Génie Mécanique de Rennes, équipe
Matériaux-Thermo-Rhéologie, Université de Rennes 1, Rennes, France
e-mail: florence.collet@univ-rennes1.fr

F. Collet
IUT Génie Civil Construction Durable, 3, Rue Du Clos Courtel, BP 90422,
35704 Rennes Cedex, France

S. Amziane and F. Collet (eds.), *Bio-aggregates Based Building Materials*,
RILEM State-of-the-Art Reports 23, DOI 10.1007/978-94-024-1031-0_6

This chapter gives the state of the art of previous studies on hygrothermal behavior of bio-aggregate based building materials. Firstly, hygric characteristics such as sorption isotherms, water vapour permeability and moisture diffusivity are given. Their ability to moderate ambient relative humidity is also quantified by moisture buffer value. Then thermal properties (conductivity and specific heat capacity) are investigated. Finally, concluding remarks on hygrothermal behavior with simultaneous heat and mass transfer are provided.

6.2 Hygric Properties

6.2.1 Moisture Storage: Sorption Isotherm

Sorption isotherm relates the equilibrium moisture content of the material to the ambient relative humidity for a given temperature. From dry state to humid state, the water uptake occurs following three stages. Firstly molecules of water are adsorbed on the internal pore wall surfaces forming a monolayer: this is the monomolecular adsorption. Then water molecules adhere to the monolayer: this is the polymolecular adsorption. Finally, molecules of water lead to a liquid bridge and fill the pore with the formation of liquid menisci: this is the capillary condensation. Depending on the porous structure of the material, these phenomena may occur successively or simultaneously (the first and the following layers are thus adsorbed simultaneously). Besides, a hysteresis may appear between adsorption and desorption branches. This hysteresis is often explained qualitatively by capillary condensation, by existence of ink-bottle shaped pores or, more generally, interconnected pores spaces (Naono and Hakuman 1993). The IUPAC gives a classification of physisorption isotherms in six types with reference to pore size and of hysteresis loops in four types related with pore structures (IUPAC 1986). Sorption isotherms can be measured according to continuous methods (under quasi-equilibrium) or discontinuous methods (at successive stages). Several models have been developed to describe sorption curve. The GAB model is often met as, despite it is valid when there is no capillary condensation; it is convenient to fit experimental adsorption data all over the relative humidity range (Guggenheim 1966; Anderson 1946; Anderson and Hall 1948; de Boer 1953).

Bio-aggregate based building materials are strongly hygroscopic. Their water uptake is much higher than in other building materials, as illustrated Fig. 6.1 by comparing hemp concrete with Aerated Autoclaved Concrete and with Vertical Perforated Bricks (Amziane and Arnaud 2013). As well for wood concrete as for hemp concretes, the water content at equilibrium at very high relative humidity (resp. 99.9 and 95%RH) is much lower than the water content at saturation (Bouguerra et al. 1999; de Bruijn and Johansson 2013). This is linked to the macroporosity due to the bio-based aggregate. Moreover, their sorption curves show hysteresis which extends all over the range of relative humidity, as well for

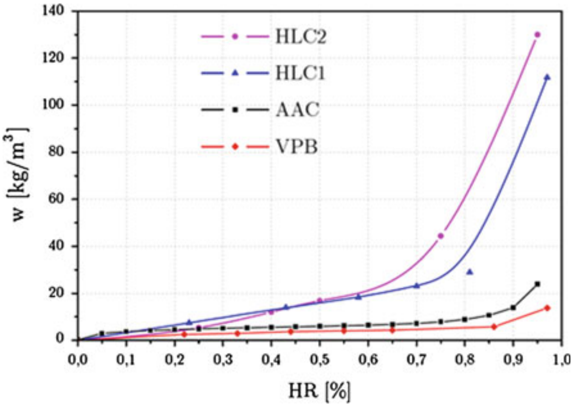


Fig. 6.1 Adsorption isotherms of materials. *HLC* Hemp-Lime Concrete, *AAC* Aerat-ed Autoclaved Concrete, *VPB* Vertical Perforated Bricks (Amziane and Arnaud 2013)

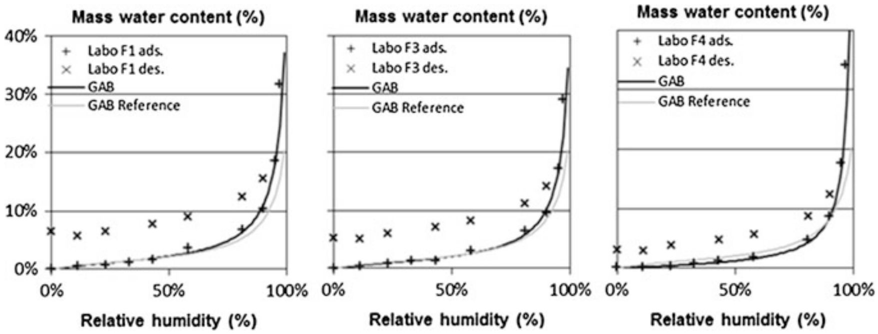


Fig. 6.2 Sorption isotherms of hemp concretes with increasing substitution of lime-based binder for calcium sulphate-based binder. *F1* 1/3 sulphate-based binder + 2/3 lime-based binder; *F3* 1/2 + 1/2; *F4* 2/3 + 1/3 (Chamoin 2013)

wood concrete as for hemp concretes (Figs. 6.2 and 6.3) (Bouguerra et al. 1999; Cerezo 2005; Chamoin 2013; Collet 2004; Collet et al. 2008, 2013).

Comparing sorption curve of hemp concrete with sorption curve of hemp shiv (Zaknoune 2011; Collet et al. 2013) underline that hemp concrete shows lower sorption curve than hemp shiv but exhibits larger hysteresis. So, the porosity of the binder widely influences the hygroscopic behavior of the mix. Actually, the binder develops specific surface area and is the place of capillary condensation in the inter-particle pores. The kind of binder slightly impacts the sorption curve. In Chamoin (2013), substituting lime-based binder for calcium sulphate-based binder leads to similar values of water content as the reference material, excepted at highest relative humidity (>80%RH), where capillary condensation takes place. The hysteresis is also slightly impacted, but the effect depends on the calcium

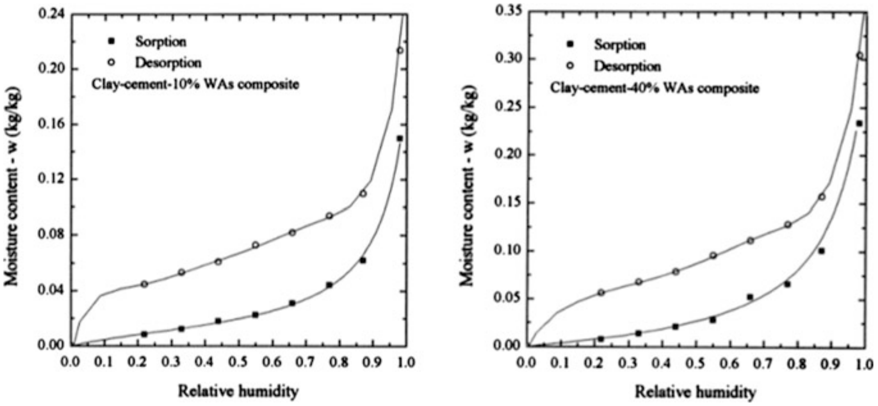


Fig. 6.3 Sorption-desorption isotherms of various mixtures obtained by substituting clay with wood aggregates (Bouguerra et al. 1999)

sulphate-based binder ratio. When the calcium sulphate-ratio increases, the hysteresis firstly increases and then decreases.

It is shown in Collet et al. (2013) and in Chamoin (2013) that the fact that hemp shiv is defibered or not (i.e. fibered) does not impact significantly the sorption curves of respectively hemp concrete for the two considered kinds of binders. As for the binder, slight differences appear for highest values of relative humidity (>80%RH).

Finally, as well for wood concrete as for hemp concrete, an increase in bio-aggregate to binder ratio induces higher values of water content, particularly for highest relative humidity. This is correlated, on the one hand, to higher polymolecular adsorption and, on the other hand, to capillary condensation. Actually, Bouguerra et al. remind that raising the aggregate to binder ratio increases macroporosity and the specific surface area is thus the highest for highest aggregate to binder ratio (Bouguerra et al. 1999). Collet et al. point out that, in the range of relative humidity 81–97%RH, the capillary condensation occurs in pores of width from 0.005 to 0.040 µm. This size of pore is met in the skin of the cell wall of hemp shiv (Collet et al. 2013). Increasing the hemp to binder ratio increases these phenomena.

6.2.2 *Moisture Transfer: Water Vapor Permeability, Capillarity, Moisture Diffusivity*

Moisture transfer takes place under vapor or/and liquid transport. The driving force for vapor diffusion is the vapor pressure gradient. The liquid transport occurs by surface diffusion or capillary flow, in both cases the driving force is the capillary pressure.

Water vapor permeability characterizes the ability of a material to transfer moisture under a vapor pressure gradient once the steady state is reached. The commonly called "vapor permeability" includes (i) vapor transfer by diffusion (transport by collision of water molecules with each other), (ii) vapor transfer by effusion (transport by collision of water molecules with walls of pores) and (iii) liquid transfer (connected with capillary condensation). For hygroscopic materials, the water vapor permeability increases with the water content of the material. The measurement of water vapor permeability is often performed following the well-known cup method.

The mainly open high porosity of bio-aggregate based building material gives them high moisture vapor permeability (i.e. low water vapor diffusion resistance). The water vapor diffusion resistance, at dry point, is 15 for wood shaving concrete (Amziane and Arnaud 2013), it ranges from 5 to 12 for hemp concrete (Collet 2004; Evrard 2008; Walker and Pavia 2014) while it is equal to 130 for solid concrete, 50 for light weight aggregate (natural pumice stone) concrete, and 10 for aerated autoclaved concrete (ThU 2005). Besides, for hygroscopic materials, such as bio-aggregate based building materials, the water vapor permeability is a strong function of the local relative humidity. Figure 6.4 gives the variation of water vapor permeability with relative humidity for two hemp concretes (Collet et al. 2013) and for clay brick and concrete brick (Kumaran et al. 2002). This figure highlights the high water vapor permeability of hemp concrete and its increase with relative humidity.

As well as in Chamoin (2013) as in Walker and Pavia (2014), the type of binder does not have a significant effect on the water vapor permeability of hemp concrete. In Chamoin (2013) hemp concretes with fibered hemp shiv show similar values as hemp concrete with defibered hemp shiv in the hygroscopic domain. For highest values of relative humidity, fibered hemp shiv leads to lower values than defibered hemp shiv. The macropores between hemp particles have a greater influence on the water vapor permeability than the micropores in binder. However, the use of water retainer in Walker and Pavia (2014) reduces the water vapor permeability of hemp concrete.

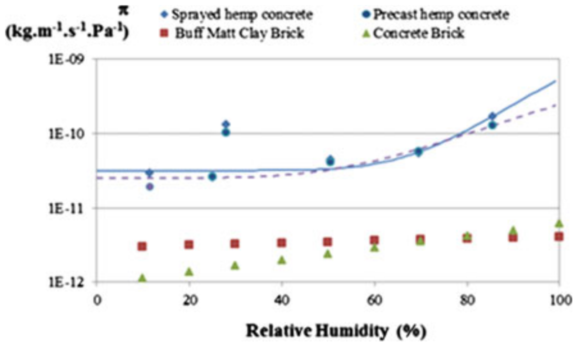


Fig. 6.4 Variation of moisture permeability versus ambient relative humidity for several building material: sprayed and precast hemp concrete (Collet et al. 2013), clay brick and concrete brick (Kumaran et al. 2002)

The capillary action characterizes the spontaneous flow of a liquid into a porous structure. The water absorption coefficient gives the amount of water absorbed par unit area as function of the square root of time.

The water absorption coefficient by capillarity (free water uptake) ranges from 2.40 to 4.42 kg/(m^2 $h^{1/2}$) for hemp concretes (Walker and Pavia 2014; Evrard 2008; Evrard and de Herde 2010). A higher value of water absorption coefficient [9 kg/(m^2 $h^{1/2}$)] is found in de Bruijn et al. (2009) for higher density of hemp concrete. These values are in the range of values found in Nielsen (1976) where the water absorption coefficient are 2.52 kg/(m^2 $h^{1/2}$) for sand-lime brick, 4.92 kg/(m^2 $h^{1/2}$) for cellular concrete, 10.5 and 13.98 kg/(m^2 $h^{1/2}$) for brick with respective density of 1775 and 2025 kg/m^3. Bouguerra et al. observe by Magnetic Resonance Imaging the nonsorption effect of wood aggregates on the capillary absorption of the wood composite. The macrostructure of wood aggregate, embedded in a clay-cement matrix which shows essentially micropores, tend to slow down the capillary invasion in the material. Finally, the presence of wood aggregates leads to a significant reduction in the sorptivity (Bouguerra et al. 1999).

The moisture diffusivity of a material characterizes the rate of change of its moisture content under transient moisture evolutions. De Vries has shown that the variation of moisture diffusivity versus water content evolves according to three phenomena (de Vries, 1958) (Fig. 6.5): (i) for low water content ($u < u_k$), moisture transfer is essentially due to vapor transport (diffusion and effusion), the condensed phase exists in the form of an adsorbed film or in small islands of water; (ii) when water content increases, small islands of water increase in number and in size, the area for vapor flux decreases and moisture transfer occurs by mechanisms of condensation and evaporation at vapor–liquid interfaces, as soon as the continuity of the liquid phase is reached ($u = u_k$) the liquid transfer increases; (iii) then, for high water content, liquid transfer is predominant.

The isothermal moisture diffusivity calculated from the derivative of the sorption curve and from the vapor permeability ranges from 10^{-10} to 10^{-7} m^2 s^{-1} (Collet 2004; Amziane and Arnaud, 2013; Collet et al. 2013). For comparison, the value given by Peuhkuri (2003) for aerated autoclaved concrete is 8.10^{-9} m^2 s^{-1} for relative humidity ranging between 40 and 60%. However, as underline in Rode

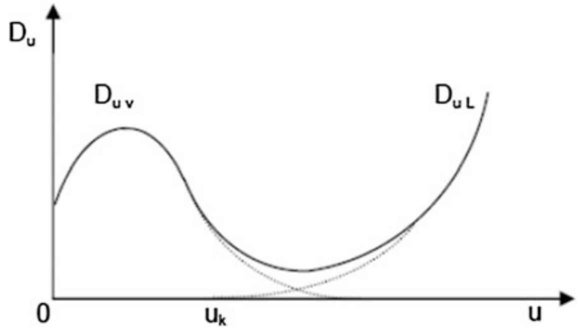


Fig. 6.5 Variation of isothermal moisture diffusion coefficient (vapor phase and liquid phase) with moisture content (de Vries 1958)

(2005), there may be some discrepancy between the basic material properties depending on whether they have been determined under steady state or dynamic conditions. It is shown in Collet and Pretot (2012a) that the moisture effusivity is slightly higher when it is calculated from steady-state data than when it is from dynamic measurements. It is suggested that it is due to a non-fickian behavior of sprayed hemp concrete. New method to determine the mass diffusivity in materials, was developed by Perré et al. (2015). This method allows non-Fickian behavior to be detected, and can still be used in such case with dual-scale model in the identification procedure. No data are found with such method on bio-aggregate based building materials.

The moisture diffusivity calculated from capillary test ranges from 10^{-10} to 10^{-8} m^2 s^{-1} for wood concrete (Bouguerra et al. 1999) and from 10^{-10} to 10^{-8} m^2 s^{-1} for cellular concrete (Kumaran et al. 2002) (Fig. 6.6).

In line with previous comments, the formulation of binder does not have a significant effect on moisture diffusivity. It is shown in Chamoin (2013) that by increasing the substitution rate of lime-based binder for calcium sulphate-based binder, the moisture diffusivity is slightly but not significantly amplified (Fig. 6.7).

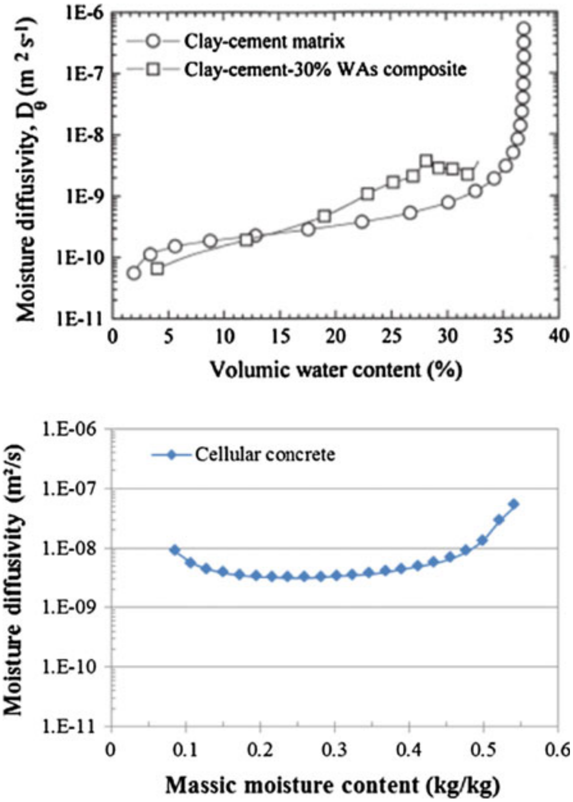


Fig. 6.6 Moisture diffusivity of materials from capillary test—*top* clay-cement matrix and clay-cement-30% of wood aggregates composite (Bouguerra et al. 1999); *bottom* cellular con-crete (Kumaran et al. 2002)

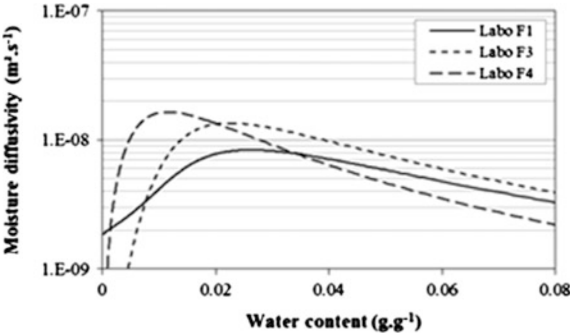


Fig. 6.7 Moisture diffusivity of hemp concrete with increasing substitution of lime-based binder for sulphate-based binder. *F1*: 1/3 sulphate-based binder + 2/3 lime-based binder; *F2* 1/2 + 1/2; *F3* 2/3 + 1/3 (Chamoin 2013)

Moreover, Bouguerra et al. (1999) underline that the wood aggregates do not seem to participate to the liquid phase transfer because of their macroporous structure. Thus, the liquid transfer occurs mainly in the microporous matrix.

6.2.3 *Moisture Buffering: Moisture Buffer Value*

The moisture buffer value MBV quantifies the moisture buffering ability of a material. It is measured according to the method defined in the NORDTEST project. This project defines the practical moisture buffer value of materials, measured under dynamic conditions (Rode 2005). This value relates the amount of moisture uptake (and release), per open surface area, under daily cyclic variation of relative humidity. This value is mainly but not only a property of the material as the mass transfer coefficient at the boundary plays a role. Though, for many materials, the internal resistance to moisture transport is significantly larger than the convective surface resistance.

The moisture buffering quality of hemp concretes was studied by several authors (Evrard 2006; Tran Le 2010, Collet and Pretot 2012a, b, c; Collet et al. 2013; Dubois et al. 2012, 2013; Latif et al. 2015). The experimental investigations are generally performed following the Nordtest protocol. It is shown that hemp concrete is an excellent hygric regulator with moisture buffer values globally higher than 2 g/(m^2 %RH). Figure 6.8 summarizes results found in literature for usual building materials and for hemp concretes. According to the NORDTEST project classification, the moisture buffering capacity of concrete is limited [<0.5 g/(m^2 %RH)] while it is moderate [<1 g/(m^2 %RH)] for gypsum, good for cellular concrete and wood fibreboard [<2 g/(m^2 %RH)] and finally excellent [>2 g/(m^2 %RH)] for cellulose insulation and hemp concretes. Latif et al. (2015) found higher values of MBV for hemp concrete [4.3 g/(m^2 %RH)]. This higher value is due to higher air velocity which increases mass transfer at the surface of the material.

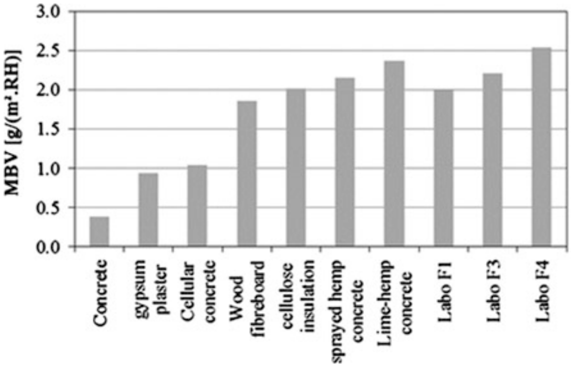


Fig. 6.8 Review of moisture buffer value of building materials: concrete and cellular concrete from (Rode 2005), gypsum plaster, wood fibreboard and cellulose insulation from (Janssen and Roels 2008), sprayed hemp concrete from (Collet and Pretot 2012), lime-hemp concrete from (Dubois et al. 2012), hemp lime concretes with increasing substitution of lime-based binder for sulphate-based binder. *F1* 1/3 sulphate-based binder + 2/3 lime-based binder; *F3* 1/2 + 1/2; *F4* 2/3 + 1/3 (Collet and Pretot 2012b)

The composition and the manufacturing method impact the moisture buffering ability of hemp concretes (Collet et al. 2013). It is shown in Collet and Pretot (2012b) that the composition of binder slightly affects the MBV. Actually, the MBV of hemp concrete made of mix binder increases with increasing substitution of lime-based binder for calcium sulphate-based binder. This phenomenon is correlated with an increase in moisture effusivity.

Finally, it should be underlined that this ability is impacted when hemp concrete is coated. Collet and Pretot (2012c) show that the MBV is more or less reduced depending on the kind of coating added on its surface. For closed coating (sand-lime plaster), the MBV is nearly half the value of neck hemp concrete [respectively 1.08 and 2.14 g/(m^2 %RH)]. For open coating (hemp-lime plaster), the value is much less reduced [from 2.14 to 1.82 g/(m^2 %RH). Similar results are found in Latif et al. (2015). The wall assemblies with breather membrane show the lower moisture buffer potential.

Dubois and Lebeau (2013) performed inverse modelling from MBV test in order to estimate hygric parameters such as vapor permeability and hygric capacity. Boundary and initial conditions are also optimized: vapor diffusion resistance factor at exchange surface and initial equilibrium relative humidity in the specimen. It is shown that the vapor resistance factor of the material (or its vapor permeability) and its moisture capacity are strongly correlated. Actually, these two parameters can be combined in one: the moisture diffusivity.

6.3 Thermal Properties

6.3.1 Thermal Conductivity

Thermal conductivity characterizes the ability of a material to conduct heat. It quantifies the quantity of heat transferred, under steady state, through a unit thickness in a direction normal to a surface of unit area, due to a unit temperature gradient. In porous media, heat transfer can take place by three modes such as conduction, convection and radiation. Furthermore, hygroscopic phenomena are also associated with energy transfer.

Several methods are used to measure thermal properties of building materials. Steady-state methods like guarded hot plate, heat flow meter and guarded hot boxes and transient methods like hot wire and line source give thermal conductivity value. Other transient methods such as flash method, transient plane source or hot disk allow simultaneous measurement of conductivity and diffusivity and/or heat capacity. Small discrepancies may appear between the results from these different methods.

Several authors use the self-consistent homogenization to compute thermal conductivity of bio-aggregate based building materials. This homogenization is performed at dry state versus the formulation and the density of the material or at humid state, taking into account the water content of the material (Arnaud 2000; Collet 2004; Cerezo 2005; Bederina et al. 2007).

6.3.1.1 Thermal Conductivity of Bio-aggregate Based Building Materials

Figure 6.9 gives examples of thermal conductivity versus density found in literature for several bio-aggregate based building materials BBM (made of wood aggregate or hemp shiv) (Agoua et al. 2013; Aigbomian and Fan 2013; Al Rim et al. 1999; Bederina et al. 2007; Pretot et al. 2009; Sassoni et al. 2014; Taoukil et al. 2013; Walker and Pavia 2014; Magniont et al. 2012). The thermal conductivity of BBM ranges from very low (about 0.04 W m^{-1} K^{-1}), allowing their use as insulating material, to medium (1–2 W m^{-1} K^{-1}). In a general way, BBM are lightweight materials and therefore good, not exceptional, thermal insulator; with thermal conductivity about 0.1–0.3 W m^{-1} K^{-1}. Their thermal conductivity is equivalent to that of other building materials with similar density. Actually, cellular concrete shows a thermal conductivity of 0.115 W m^{-1} K^{-1} for a density of 400 kg m^{-3} (resp. 0.162 W m^{-1} K^{-1} for 600 kg m^{-3}) (Gawin et al. 2004).

Thermal conductivity of bio-aggregate based building materials is thus related with density. It also depends on several parameters such as formulation (binder, aggregate, aggregate to binder ratio…), production method and water content. The density is induced by the formulation and the production method. The effect of the formulation data will be detailed further.

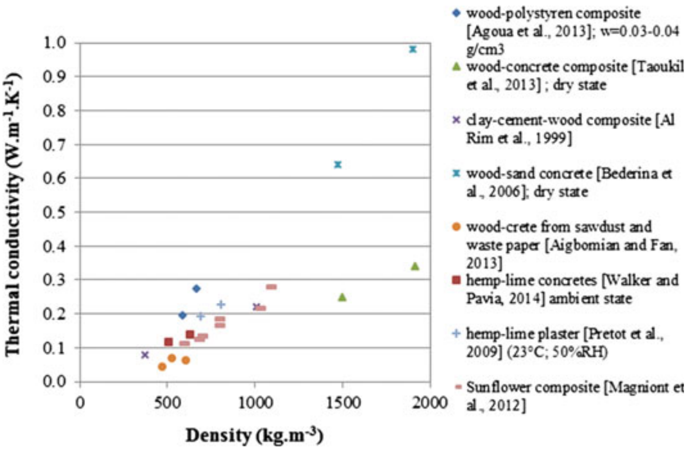
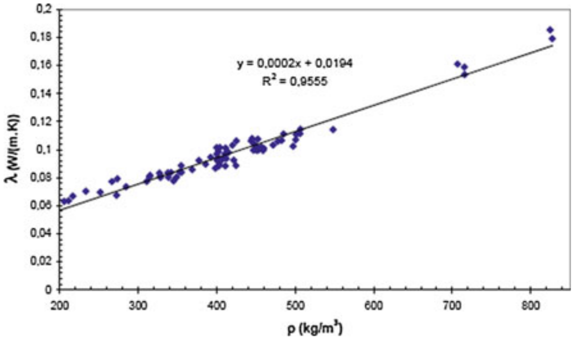


Fig. 6.9 Thermal conductivity of bio-aggregate based building composites (made of wood or hemp shiv)

Fig. 6.10 Evolution of thermal conductivity of hemp concrete depending on density (Cerezo 2005)



Cerezo gives a linear relationship between thermal conductivity and density of hemp concrete (Cerezo 2005) (Fig. 6.10). This curve fit with high accuracy the experimental data for density ranging from 300 to 520 kg m^{-3}. Actually these points correspond to hemp concrete with similar formulation. For higher and lower densities, the hemp-binder-water ratios differ. For a given formulation Cerezo models the variation of thermal conductivity with density from self-consistent homogenization (Cerezo 2005) (Fig. 6.11). There is a high correlation between experimental data and modeling. Similar results are found by Collet and Pretot on sprayed hemp concrete (Collet and Pretot 2014). The variation of thermal conductivity with density is measured and modeled with self-consistent homogenization as the spraying process induces a variation of density (Elfordy et al. 2008). For a given formulation (the one used to build wall), the variation of thermal conductivity versus density fit a linear regression curve. At dry state, the thermal conductivity rises by 109% while density increases from 250 to 600 kg m^{-3}.

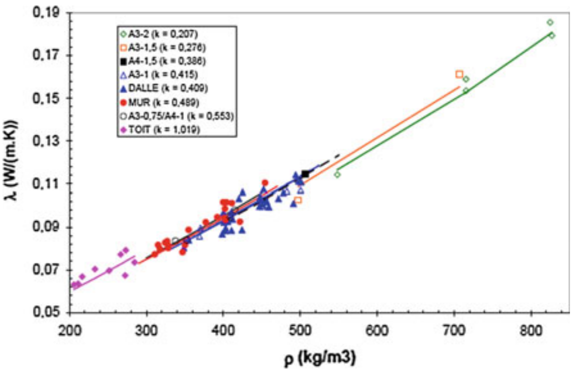


Fig. 6.11 Comparison of experimental data to self-consistent homogenization of thermal conductivity (Cerezo 2005)

6.3.1.2 Effect of Formulation and Manufacturing Method on Thermal Conductivity of Bio-Aggregate Based Building Materials

The formulation embeds several data: the type of binder, the type of aggregate, the aggregate to binder ratio, the water to binder ratio and the use of water retainer. The water to binder ratio is generally adjusted to ensure a good workability of the fresh product in connection with the mixing and manufacturing method. So, the effect of formulation and manufacturing method can not be studied separately.

Binder

Thermal conductivity of bio-aggregate based building materials is significantly dependent on the binder used in the formulation.

Actually, the thermal conductivity of binders themselves is dependent on the type of binder, the proportion of the binders in case of mixture, and the water to binder ratio. Stefanidou et al. (2010) used six different binders (traditional binders such as lime, natural pozzolans, brick dust, and white cement) to produce 15 pastes. The thermal conductivities of studied materials range from 0.16 (mixture of air lime and pozzolan) to 0.39 W m^{-1} K^{-1} (white cement). They show that, with similar proportion by mass, traditional materials such as lime are less conductive than modern materials like cements. They also underline that adding white cement increases the thermal conductivity of mixtures and that adding pozzolanic materials reduces the thermal conductivity in comparison with pure lime. Finally, they also show that an increase in the water to binder ratio in the mixture of binder increases the porosity and thus reduces the thermal conductivity of the binder.

Furthermore, the physico-chemical interaction occurring between the bio-aggregate and the binder affects the microstructure of the composite and thus its thermal conductivity. Gourlay and Arnaud (2010) give the thermal conductivity of hemp concretes made with three kinds of binder. They show that hemp concretes made with cement based binder are less conductive than hemp concretes made of lime based binder (respective thermal conductivities of 0.06 and 0.08 W m^{-1} K^{-1}). They underline that, with the same hemp-binder-water ratio, the density of hemp

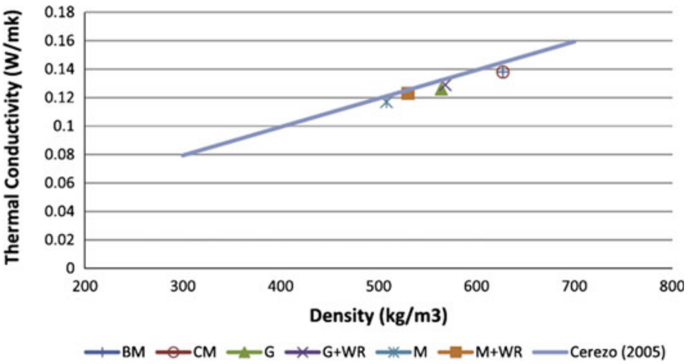


Fig. 6.12 Relationship between density and thermal conductivity of hemp concrete walls and the relationship established by Cerezo (2005). *BM* builder's mix, *CM* commercial mix, *G* lime: Ground Granulated Blastfurnace Slag (GGBS) binder, *G* + *WR* lime: GGBS binder with water retainer, *M* lime: metakaolin binder, *M* + *WR* lime: metakaolin binder with water retainer (Walker and Pavia 2014)

concretes is lower with cement based binder than with lime-based binder (resp. 297/393 kg m^{-3}) even if the density of cement-based binder is higher than the density of lime-based binder (resp. 1166/843 kg m^{-3}). They conclude that the physico-chemical interaction between hemp aggregates and binder affects the microstructure of the material by increasing its porosity and this induces a decrease in thermal conductivity. Walker and Pavia (2014) also show that increasing the binder's hydraulic content in hemp concretes slightly reduces thermal conductivity. The decrease in thermal conductivity occurs simultaneously with a decrease in density (Fig. 6.12).

Bio-aggregate

Thermal conductivity of bio-aggregate based building materials also depends on the characteristics of the bio-aggregate. The lower the thermal conductivity of inclusions, the more the material is insulating. In addition, the increase in porosity decreases the density of the composite and consequently its thermal conductivity. The characteristics of bio-aggregate rely on the kind of material, its origin, its species, and its processing (treatment, separation of woody core from fiber, particle size…).

The morphological characteristics of bio-aggregates depend on their growing conditions (land, weather…). Stevulova et al. compared lightweight composites made with technical hemp (cannabis sativa) from two origins (Stevulova et al. 2013). They show that Hungarian hemp leads to higher values of thermal conductivity of concrete than Netherlands hemp (respective thermal conductivity: 0.111 and 0.069 W m^{-1} K^{-1} for same components ratios), while giving higher strength parameter. They suggest that this fact is probably due to creating a stronger structure during the growing, with smaller pores.

For the same kind of material, the species also impact the characteristics of the bio-aggregate. Agoua et al. (2013) investigate composites made of sawdust of recycled wood and glue from polystyrene of recuperation. Two species of wood, several particle sizes, and two wood-glue ratios are considered. They show that, whatever particle sizes and glue content, one species of wood (Kaya senegalensis) systematically leads to slightly higher conductivity of the composite than the other species (Pterocarpus Erinaceus) (respective mean values: 0.263 ± 0.022/0.242 ± 0.022 W m^{-1} K^{-1}).

Depending on the kind of raw material, the processing may include a separation of fiber from woody core or not. Nguyen (2010) compares compacted hemp concretes made with fibered and defibered hemp shiv. He shows that, for similar formulation (kind of binder and hemp-binder ratio), the fibered hemp shiv leads to lower conductivity of the composite than defibered hemp shiv. According to the author, the fibers induce a higher inter-particular porosity, for the same density of the composite, leading to lower thermal conductivity. It would be interesting to corroborate this result for other processing methods.

The particle size distribution, resulting from the processing, also impacts the thermal conductivity of composites. Agoua et al. show that the more the composites contain thin elements of sawdust of wood, the more they drive heat (Agoua et al. 2013). Similar results are found with hemp-based materials. Stevulova et al. show that decreasing the mean particle length in hemp composites induces a stronger structure with smaller pores and also leads to higher thermal conductivity (Stevulova et al. 2013). Pretot et al. compare two hemp-lime plasters (Pretot et al. 2009). The hemp with the finest particle size distribution leads to slightly higher thermal conductivity (0.227 vs. 0.193 W m^{-1} K^{-1}: +17.6%), simultaneously with higher density (809 vs. 692 kg m^{-3}: +16.9%).

Bio-aggregate to binder ratio

Bio-aggregate to binder ratio impacts the thermal properties of bio-based building materials. Studies performed on wood-aggregate based composites and on hemp-aggregate based composites show that by increasing the bio-aggregate to binder ratio, the thermal conductivity of the composite decreases (Agoua et al. 2013; Al Rim et al. 1999; Bederina et al. 2007; Benfratello et al. 2013; Bouguerra 1999; Collet and Pretot 2014; de Bruijn and Johansson 2013; Ledhem et al. 2000; Taoukil et al. 2013). The increase in bio-aggregate to binder ratio induces a decrease in density of the composite due to a low density of the bio-aggregate. Furthermore the bio-aggregate induces porosity in the matrix which appears to be more porous when the aggregate ratio increases (Al Rim et al. 1999). Bederina et al. underline that the decrease in thermal conductivity is not linearly proportional to the increase of bio-aggregate in wood-based composite (Bederina et al. 2007) (Fig. 6.13]. Similar results are found on hemp concretes (Benfratello et al. 2013; Collet and Pretot 2014).

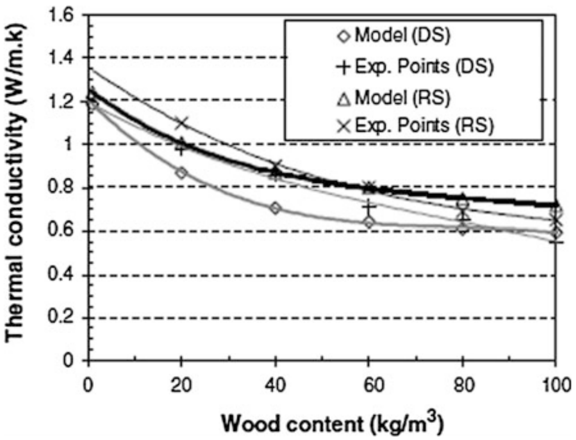


Fig. 6.13 Thermal conductivity according to the content of wood: confrontation of the experimental results to the results obtained by auto-coherent model (Bederina et al. 2007)

Anisotropy

The geometry and the capillary structure of bio-aggregate make them anisotropic. It is shown in Carré and Le Gall (1990) and in Suleiman et al. (1999) that the longitudinal thermal conductivity of wood (parallel to capillaries network) is higher than the transversal one.

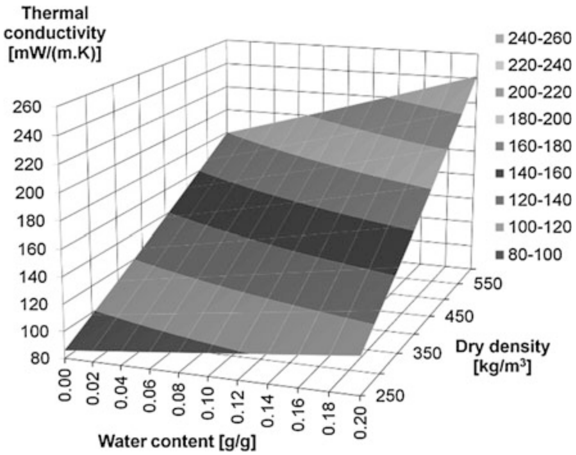
Depending on the production method, bio-aggregate based building materials can also show anisotropy. Nguyen studied the effect of anisotropy on thermal conductivity of compacted hemp concretes (Nguyen 2010). He shows that, depending on the formulation, the thermal conductivity in longitudinal axis was 1.2–1.8 higher than the thermal conductivity in the transversal axis. Such results were also found in Pierre et al. (2013) where the longitudinal thermal conductivity was higher than the transversal conductivity of hemp concrete and in Dinh et al. (2015) where the ratio between thermal conductivity measured according to parallel direction and perpendicular direction of compaction was from 1.13 to 1.19 for dry hempcretes and from 1.15 to 1.17 for humid hempcretes.

6.3.1.3 Effect of Water Content on Thermal Properties of Bio-aggregate Based Building Materials

The hygroscopicity of bio-aggregate based building materials impacts their thermal properties.

Actually, an increase in water content induces an increase in thermal conductivity, as water shows much higher thermal conductivity than air ($\lambda_{water} = 0.6$; $\lambda_{air} = 0.026\ \mathrm{W\ m^{-1}\ K^{-1}}$). This increase is more or less important, depending on the density and on the porosity of the material. For wood concrete, the thermal conductivity increases rapidly with water content. The thermal conductivity at saturation is two to three times higher than the value at dry state (Taoukil et al. 2013). It can reach five times this value in Bouguerra (1999). For hemp-based materials,

Fig. 6.14 Thermal conductivity of sprayed hemp concrete (wall formulation) versus density and water content (Collet and Pretot 2014)



thermal conductivity also increases with water content. In Amziane and Arnaud (2013), the variation of thermal conductivity with water content is modeled by double homogenization for two hemp concretes. For the HLC1 hemp concrete, thermal conductivity is related to water content following:

$$\lambda = 0.105 + 0.035 \times w \tag{6.1}$$

with λ the thermal conductivity (W m^{-1} K^{-1}) *and w* the mass water content (%).

The values from this equation are in line with experimental data obtained by Cerezo (2005) and are also consistent with the results from Collet (2004) who considers a three phase model with air, water and solid phase. Taking into account adsorption/desorption isotherm, the thermal conductivity rises by 30% when the material has been left in humid environment (75%RH) (Amziane and Arnaud 2013). In Collet and Pretot (2014), it is underlined that the ambient humidity impacts more or less the thermal conductivity of hemp concrete, as, depending on their formulation, they are more or less hygroscopic. From dry to humid state (90%RH), the thermal conductivity of hemp concrete rises by 25% for wall formulation with low density; while, in the same range of relative humidity, it increases by 11% for floor formulation (water content at 90%RH about 0.08 g g^{-1}). Finally, for a given formulation, even if the impact of moisture content is lower than the impact of density (Fig. 6.14), it is not negligible.

6.3.2 Heat Capacity and Thermal Diffusivity

Specific heat capacity and volumetric heat capacity characterize the ability of a material to store heat. The specific heat capacity is the amount of heat per unit mass required to raise the temperature by one degree Celsius while the volumetric heat capacity is related to a unit of volume.

Thermal diffusivity describes the rate at which heat flows through a material. Thermal diffusivity is related to thermal conductivity, density and specific heat capacity according:

$$a = \frac{\lambda}{\rho . C_p} \tag{6.2}$$

with a the thermal diffusivity ($\mathrm{m}^2\ \mathrm{s}^{-1}$), λ the thermal conductivity ($\mathrm{W\ m}^{-1}\ \mathrm{K}^{-1}$), ρ the density ($\mathrm{kg\ m}^{-3}$) and C_p the specific heat capacity ($\mathrm{J.kg}^{-1}\ \mathrm{K}^{-1}$).

Thermal diffusivity and/or heat capacity are measured with transient methods as flash method, transient plane source or hot disk. Specific heat capacity can also be measured with calorimeter or DSC.

6.3.2.1 Heat Capacity and Thermal Diffusivity of Bio-aggregate Based Building Materials

The specific heat capacity of bio-aggregate based building materials is in the same range as the specific heat capacity of usual building materials. For wood concrete, Taoukil et al. estimate the thermal diffusivity for several wood shaving ratios (Taoukil et al. 2013). The specific heat capacity calculated from these measures ranges from 640 to 1490 J $\mathrm{kg}^{-1}\ \mathrm{K}^{-1}$, depending on wood shaving ratio. For hemp concrete, the study of Walker and Pavia with six kinds of binder gives specific heat capacities ranging from 1240 to 1350 J $\mathrm{kg}^{-1}\ \mathrm{K}^{-1}$ (Walker and Pavia 2014). The specific heat capacity of sprayed hemp concrete, calculated from the thermal diffusivity at dry point at 20 °C in Pierre et al. (2013), ranges from 650 to 870 J $\mathrm{kg}^{-1}\ \mathrm{K}^{-1}$. There is a high discrepancy between these results that may be linked with the measurement methods. Actually, one should underline that the measurement of thermal diffusivity of such materials appears difficult. Taoukil et al. underline that the value depends on the counting model used to estimate the thermal diffusivity from experimental thermogram (Taoukil et al. 2013). On the other hand, the use of calorimetry may also be distorted by chemical reaction producing heat during the measurement.

6.3.2.2 Effect of Formulation and Manufacturing Method on Heat Capacity and Thermal Diffusivity of Bio-Aggregate Based Building Materials

Like thermal conductivity, heat capacity and thermal diffusivity are impacted by formulation of bio-aggregate based building materials.

The effect of the kind of binder is studied in Walker and Pavia (2014). They show that increasing the binder's hydraulic content in hemp concretes slightly increases heat capacity, while it reduces thermal conductivity. More, in their study the use of water retainers increases both heat capacity and conductivity.

The effect of bio-aggregate to binder ratio is investigated on hemp concrete and on wood concrete. De Bruijn and Johansson (2013) find that the amount of hemp in hemp lime concrete has no significant effect on their thermal diffusivity as the measured values overlap. However, they conclude that a larger amount of hemp in hemp lime concrete leads to better thermal properties, especially for wet conditions, with lower thermal conductivity and lower specific heat capacity. Taoukil et al. estimate the thermal diffusivity of wood-concrete for several wood shaving ratios (Taoukil et al. 2013). It is highlighted that increasing the wood-shaving content in composite decreases its thermal diffusivity, in link with the decrease in thermal conductivity. Globally, increasing the bio-aggregate amount in the composite allows improving its thermal insulating performance.

6.3.2.3 Effect of Water Content on Heat Capacity and Thermal Diffusivity of Bio-Aggregate Based Building Materials

Regarding the variation of thermal diffusivity with water content, the study performed by de Bruijn and Johansson on two hemp-lime concretes conditioned to 15 and 65%RH, does not allow concluding (de Bruijn and Johansson 2013). Taoukil et al. highlight that a maximum value, for given water content, can be observed on wood-concrete (Taoukil et al. 2013). This is explained by the fact that in a first step, the thermal conductivity increases faster than volumetric heat capacity, inducing an increase in thermal diffusivity. Then, the thermal conductivity increases slower than volumetric heat capacity and thermal diffusivity thus decreases.

Evrard (2008) uses the thermal balance to calculate the variation of the specific heat capacity of hemp concrete with water content.

$$C(w) = \frac{(\rho_0 \times C_0 + w \times C_w)}{\rho} \tag{6.3}$$

with: ρ the density (kg m^{-3}); C the specific heat capacity (J kg^{-1} K^{-1}); subscript *0*: at dry state; w the water content (kg kg^{-1}); C_w the specific heat capacity of water stored in the porous structure (J kg^{-1} K^{-1}).

The variation of specific heat capacity with ambient relative humidity is thus calculated from this relationship and from sorption curves. Figure 6.15 illustrates the direct increase from thermal capacity of water stored.

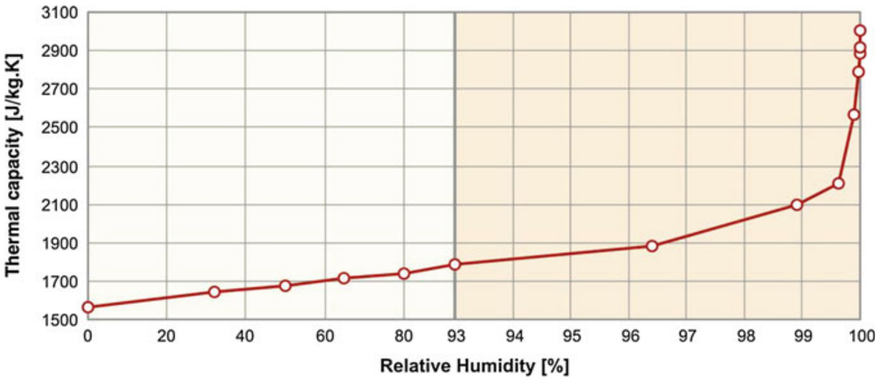


Fig. 6.15 Evolution of thermal capacity of hemp lime material—wall in moist state (Evrard 2008)

6.4 Concluding Remarks on Hygrothermal Behavior of Bio-aggregate Based Building Materials

The hygric and thermal properties of bio-aggregate based building materials give them a particular hygrothermal behavior which allows reducing energy demand of building while maintaining indoor relative humidity (Tran Le et al. 2010; Evrard and de Herde 2010).

It was shown in Evrard and de Herde (2010) and in Lawrence et al. (2013) that hemp concrete wall perform better than traditional wall assemblies on phase shift point of view. For example, in the simulation of Evrard and de Herde (2010) the phase shift was 15 h in the hemp concrete wall while it was 5 h in the mineral wool wall.

These performances are correlated with hygric behavior of hemp concrete. Actually, Lawrence et al. (2013) underline that, after a sudden drop in temperature on one side of the experimental wall, the steady state is reached at approximately 240 h while it is reached within 72 h in simulations ignoring the effects of relative humidity. Thus, relative humidity has a strong effect on the hygrothermal behavior of the wall. Pretot and Collet (2012) studied the response of a hemp concrete test—wall to several hygrothermal solicitations. They show that (i) under isothermal conditions with vapor pressure gradient, homogeneous vapor diffusion occurs; (ii) under constant vapor pressure with a decrease of ambient temperature, huge variations of vapor pressure are observed through the wall, in correlation with adsorption-desorption and/or condensation-evaporation phenomena. The experimental study reported by Arnaud, Samri and Gourlay in Amziane and Arnaud (2013) shows that an internal source (or well) of heat and/or the presence of another flow of heat (notably by convection) exist in hemp concrete and directly impact the heat balance equation.

Numerical studies at building scale show that hemp concrete allows high hygrothermal performances of building. Tran Le et al. compare hemp concrete behaviour to that of cellular concrete (Tran le et al. 2010). They found that hemp concrete induces a reduction ranging from 15 to 45% in energy consumption, depending on ventilation strategy. More, Maalouf et al. compare hemp concrete with other building materials (Maalouf et al. 2014). They show that hemp concrete has the lowest thermal diffusivity and the highest time lag which means that it can better reduce the propagation of outdoor weather conditions through building envelope. However, these authors also show that, in South France, there is a risk of indoor superheating due to low effusivity of hemp concrete.

Finally, to take into account the full range of hygrothermal performance of bio-aggregate based building materials it is necessary to consider hygrothermal dynamic behavior, not only steady-state characteristics like thermal transmittance of wall (U-value). Actually, mass transfer has a significant impact on the heat transfer in bio-aggregate based building materials, in correlation with latent heat of phase-change or sorption heat. It is thus necessary to accurately model mass transfer taking into account the sorption hysteresis of bio-aggregate based building materials. Currently numerical model are developed following this objective (Aït Oumeziane et al. 2014). Besides, it is necessary to develop new experimental benches to highlight the contribution of hygric behavior in the whole energetic performance of these materials. More, investigations are needed to develop measurement methods of thermal diffusivity and/or heat capacity of bio-aggregate based building material as usual methods are not well adapted.

References

Agoua, E., Allognon-Houessou, E., Adjovic, E., Togbedji, B.: Thermal conductivity of composites made of wastes of wood and expanded polystyrene. Constr. Build. Mater. **41**, 557–562 (2013)

Aigbomian, E.P., Fan, M.: Development of wood-crete building materials from sawdust and waste paper. Constr. Build. Mater. **40**, 4361–4366 (2013)

Al Rim, K., Ledhem, A., Douzane, O., Dheilly, R.M., Queneudec, M.: Influence of the proportion of wood on the thermal and mechanical performances of clay-cement-wood composites. Cem. Concr. Compos. **21**, 269–276 (1999)

Amziane, S., Arnaud L. (eds.): Bio-aggregate-based Building Materials. Applications to Hemp Concrete. ISTE Ltd and Wiley, Inc (2013)

Anderson, R.B.: Modifications of the Brunauer, Emmett and Teller. J. Am. Chem. Soc. **68**(4), 686–691 (1946)

Anderson, R.B., Hall, W.K.: Modifications of the Brunauer Emmett and Teller, equation II. J. Am. Chem. Soc. **70**(5), 1727–1734 (1948)

Arnaud, L.: Mechanical and thermal properties of hemp mortars and wools: experimental and theoretical approaches. In: 3rd International Symposium Of Bioresource Hemp (2000)

Bederina, M., Marmoret, L., Mezreb, K., Khenfer, M.M., Bali, A., Quéneudec, M.: Effect of the addition of wood shavings on thermal conductivity of sand concretes: experimental study and modelling. Constr. Build. Mater. **21**, 662–668 (2007)

Benfratello, S., Capitano, C., Peri, G., Rizzo, G., Scaccianoce, G., Sorrentino, G.: Thermal and structural properties of a hemp-lime biocomposite. Constr. Build. Mater. **48**, 745–754 (2013)

Bouguerra, A.: Prediction of effective thermal conductivity of moist wood concrete. J. Phys. D: Appl. Phys. **32**(12), 1407–1414 (1999)

Bouguerra, A., Sallée, H., de Barquin, F., Dheilly, R.M., Quéneudec, M.: Isothermal moisture properties of wood-cementitious composites. Cem. Concr. Res. **29**, 339–347 (1999)

Carré, P., Le Gall, R.: Définition et détermination des conductivités thermiques dans les structures multicouches C.V.R. – balsa. Rev. Gén. Therm. **340**, 211–215 (1990)

Cerezo, V.: Propriétés mécanique, thermique et acoustique d'un matériau à base de particules végétales: approche expérimentale et modélisation théorique. Ph.D. thesis, ENTPE, INSA de Lyon (juin 2005)

Chamoin, J.: Optimisation des propriétés (physiques, hydriques et mécaniques) de bétons de chanvre par la maîtrise de la formulation. Ph.D. thesis, INSA de Rennes (juillet 2013)

Collet, F.: Caractérisation hydrique et thermique de matériaux de génie civil à faibles impacts environnementaux. Ph.D. thesis, INSA de Rennes (décembre 2004)

Collet, F., Pretot, S.: Experimental investigation of moisture buffering capacity of sprayed hemp concrete. Constr. Build. Mater. **36**, 58–65 (2012)

Collet, F., Pretot, S.: Variation de la capacité hydrique tampon de bétons de chanvre en fonction de la formulation, Ecobat Sciences et techniques 1ère édition, 7 et 8, communication orale, Paris (mars 2012)

Collet, F., Pretot, S.: Effect of coating on moisture buffering of hemp concrete. In: 2nd International Conference on Building Energy and Environment, Boulder, Colorado, 1–4 August 2012

Collet, F., Pretot, S.: Thermal conductivity of hemp concretes: variation with formulation, density and water content. Constr. Build. Mater. **65**, 612–619. doi:10.1016/j.conbuildmat.2014.05.039 (2014)

Collet, F., Bart, M., Serres, L., Miriel, J.: Porous structure and water vapour sorption of hemp-based materials. Constr. Build. Mater. **22**, 1271–1280 (2008)

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

De Boer, J.H.: The Dynamical Character of Adsorption. Clarendon Press, Oxford (1953)

de Bruijn, P., Jeppssona, K.H., Sandin, K., Nilssona, C.: Mechanical properties of lime–hemp concrete containing shives and fibres. Biosyst. Eng. **103**(4), 474–479 (2009)

de Bruijn, P., Johansson, P.: Moisture fixation and thermal properties of lime-hemp concrete. Constr. Build. Mater. **47**, 1235–1242 (2013)

de Vries, D.A.: Simultaneous transfer of heat and moisture in porous media. Eos, Trans. Am. Geophys. Union **39**, 909–916 (1958)

Dinh, T.M., Magniont, C., Coutand, M., Escadeillas, G.: Hemp concrete using innovative pozzolanic binder. In: ICBBM 2015, Clermont Ferrand, France, 22–24 June 2015

Dubois, S., Lebeau, F.: Hygrothermal behavior of different lime-hemp concrete mixes. In: First International Conference on Concrete Sustainability (ICCS13), Tokyo, Japan (2013)

Dubois, S., Evrard, A., Lebeau, F.: Hygrothermal modelling of lime-hemp concrete used as building material and indoor climate buffering characterization. In: International Conference of Agricultural Engineering, Valence, Espagne, 8–12 July 2012

Dubois S., Evrard A., Lebeau F.: Modeling the hygrothermal behavior of biobased construction materials. J. Build. Phys. (2013)

Elfordy, S., Lucas, F., Tancret, F., Scudeller, Y., Goudet, L.: Mechanical and thermal 415 properties of lime and hemp concrete ("hempcrete") manufactured by a projection process. Constr. Build. Mater. **22**(10), 2116–2123 (2008)

Evrard, A.: Sorption behaviour of Lime-hemp concrete and its relation to indoor comfort and energy demand. In: 23rd Conference on Passive and Low Energy Architecture, Geneva, Switzerland, 6–8 September 2006

Evrard, A.: Transient hygrothermal behavior of Lime–Hemp materials, Ph.D. thesis, Université catholique de Louvain (2008)

Evrard, A., De Herde, A.: Hygrothermal performance of lime-hemp wall assemblies. J. Build. Phys. **34**, 15–25 (2010)

Gawin D., Kosny J., and Wilkes K.: Thermal conductivity of moist cellular concrete—experimental and numerical study. ASHRAE Build. **IX**, 1–10 (2004)

Gourlay, E., Arnaud, L.: Comportement hygrother-mique des murs de béton de Chanvre. Actes du congrès SFT, Le Touquet, France (2010)

Guggenheim, E.A.: Application of Statistical Mechanics. Clarendon Press, Oxford (1966). (Chapter 11)

International Union of Pure and Applied Chemistry: Reporting physisorption data for gas/solid systems with special reference to the determination of surface area and porosity. Pure Appl. Chem. **57**(4), 603–619 (1986)

Janssen, H., Roels, S.: The dependable characterisation of the moisture buffer potential of interior claddings, Proceedings of the Nordic Symposium on Building Physics, Copenhagen, Denmark, June 2008, pp. 16–18 (2008)

Kumaran, K., Lackey, J., Normandin, N., van Reenen, D., Tariku, F.: Summary Report from Task 3 of MEWS Project at the Institute for Research in Construction—Hygrothermal Properties of Several Building Materials, IRC-RR-110 (2002)

Latif, E., Lawrence, M., Shea, A., Walker, P.: Moisture buffer potential of wall assemblies incorporating hemp-lime. In: ICBBM 2015, Clermont Ferrand, France. 22–24 June 2015

Lawrence, M., Shea, A., Walker, P., De Wilde, P.: Hygrothermal performance of bio-based insulation materials. Proc. Inst. Civil Eng. Constr. Mater. **166**(4), 257–263. ISSN: 1747-650X (2013)

Ledhem, A., Dheilly, R.M., Benmalek, M.L., Queneudec, M.: Properties of wood-based composites formulated with aggregate industry waste. Constr. Build. Mater. **14**, 341–350 (2000)

Maaloufa, C., Tran Le, A.D., Umurigirwaa, S.B., Lachia, M., Douzane, O.: Study of hygrothermal behaviour of a hemp concrete building envelope under summer conditions in France. Energy Build. **77**, 48–57 (2014)

Magniont, C., Escadeillas, G., Coutand, M., Oms-Multon, C.: Use of plant aggregates in building ecomaterials. Eur. J. Environ. Civil Eng. **16**(Supplement 1), s17–s33 (2012)

Naono, H., Hakuman, N.: Analysis of porous texture by means of water vapour adsorption isotherm with particular attention to the lower limit of hysteresis loop. J. Colloid. Interf. Sci. **158**, 19–26 (1993)

Nguyen, T.T.: Contribution à l'étude de la formulation et du procédé de fabrication d'éléments de construction en béton de chanvre. Ph.D. thesis, Université de Bretagne Sud (janvier 2010)

Nielsen, A.F.: Free Water Intake of Cellular Concrete and Bricks Measured by Gamma Ray Attenuation. Thermal Insulation Laboratory, Technical University of Denmark, Report no. 41 (January 1976)

Oumeziane, Y.A., Bart, M., Moissette, S., Lanos, C.: Hysteretic behaviour and moisture buffering of hemp concrete. Transp. Porous Med. (2014). doi:10.1007/s11242-014-0314-7

Perré, P., Pierre, F., Casalinho, J., Ayouz, M.: Determination of the mass diffusion coefficient based on the relative humidity measured at the back face of the sample during unsteady regimes. Drying Technol. Int. J. doi:10.1080/07373937.2014.982253 (2015)

Peuhkuri, R.: Moisture dynamics in building envelopes. Doctoral thesis, Department of Civil Engineering, Technical University of Benmark, Denmark (2003)

Pierre, T., Colinart, T., Glouannec, P.: Measurement of thermal properties of biosourced building materials. Int. J. Thermophys. doi:10.1007/s10765-013-1477-0 (2013)

Pretot, S., Collet, F., Glouannec, P., Lang, V.: Variation des propriétés thermiques de bétons de chanvre en fonction de la formulation, Congrès français de thermique-Efficacité énergétique, Vannes 2009, Tome 2, pp. 865–870, Editions Société Française de Thermique, ISBN: 2-905267-67-2

Pretot, S., Collet, F.: Experimental study of hygrothermal behavior of a hemp concrete wall (without and with coating). In: 2nd International Conference on Building Energy and Environment, communication orale, Boulder, Colorado, 1er au 4 août 2012

Réglementation Thermique.: Règles Th-U—Fascicule 2 (2005)

Rode, C.: Moisture Buffering of Building Materials, Report BYG•DTU R-126, ISSN 1601-2917, ISBN 87-7877-195 (2005)

Sassoni, E., Manzi, S., Motori, A., Montecchi, M., Canti, M.: Novel sustainable hemp-based composites for application in building industry: physical, thermal and mechanical characterization. Energy Build. **77**, 219–226 (2014)

Stefanidou, M., Assael, M., Antoniadis, K., Matziaroglou, G.: Thermal conductivity of building materials employed in the preservation of traditional structures. Int. J. Thermophys. **31**, 844–851 (2010)

Stevulovaa, N., Kidalovaa, L., Cigasovaa, J., Junaka, J., Sicakovaa, A., Terpakovaa, E.: Lightweight composites containing hemp hurds. Proced. Eng. **65**, 69–74 (2013)

Suleiman, B.M., Larfeldt, J., Leckner, B., Gustavsson, M.: Thermal conductivity and diffusivity of wood. Wood Sci. Technol. **33**, 465–473 (1999)

Taoukil, D., El bouardi, A., Sick, F., Mimet, A., Ezbakhe, H., Ajzoul, T.: Moisture content influence on the thermal conductivity and diffusivity of wood–concrete composite. Constr. Build. Mater. **48**, 104–115 (2013)

Tran Le, A.D.: Etude des transferts hygrothermiques dans le béton de chanvre et leur application au bâtiment. Ph.D. thesis, Université de Reims Champagne- Ardenne; November (2010) [in French]

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

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

Zaknoune, A.: Etude du comportement thermohydrique de matériaux « chanvre-chaux » lors de la phase de séchage – estimation par technique inverse des propriétés hydriques. Ph.D. thesis, Université de Bretagne Sud (December 2011) [in French]