Chapter 8
Durability of Bio-based Concretes

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Abstract Used for several decades for building insulation, concretes containing plant aggregates have thermal, acoustic and hygrothermal properties that greatly improve the comfort of homes (Amziane and Arnaud 2013). Nevertheless, during their life time, they are submitted to a hydrothermal environment (humidity and temperature variations) that can change these functional properties and/or induce the development of microorganisms on their surface. The objective of this chapter is to present the state of the art on the evolution of the properties of these vegetal concretes after different types of aging in laboratory.

Keywords Durability · Aging · Environment · Temperature · Humidity · Fungal growth · Carbonation

8.1 Introduction

The assessment of the durability of buildings is an activity for sustainable development, which results in requirements of the long term-performance of the structures in the whole life of structure. This is defined by the overall behaviour of the functions required by the product. This performance is studied for the product lifetime, from its commissioning to its failure.

Different terms can be used to characterize the lifetime of the construction materials (Talon 2006):

- The durability is the ability to perform a function until a limit state is reached.
- Aging refers to the functional changes decreasing the ability of a product to perform a function.
- The evolution of the properties refers to positive or negative changes of the characteristics of the material according to its expected performance.

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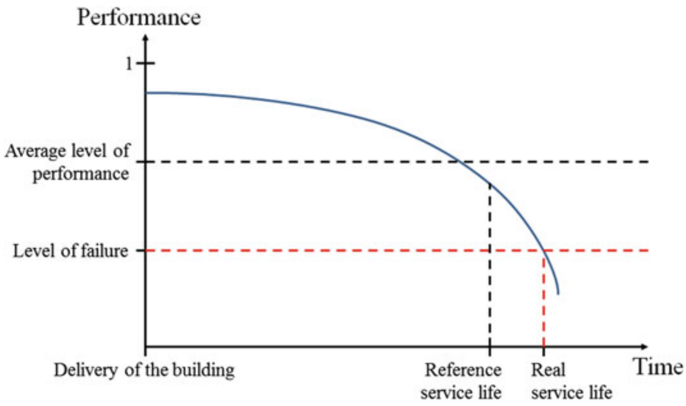

Fig. 8.1 Concepts of performance and service life (Talon 2006)

– The effective life of a material is the time between commissioning and the moment when its performance level becomes lower than a failure threshold (Fig. 8.1).

The evolution of the properties of construction materials in a building is related to several parameters: the initial properties of the material, its environment and its conditions of use. Based on the previously described properties of vegetal concretes, several factors can influence their performances: concerning environmental and use conditions, relative humidity, temperature, or exposure to liquid water can play a role. The alkaline character of the binder and the presence of ions may also be responsible of properties modifications. Finally, because of the nature of the plant aggregates, microorganisms' growth is possible. It also depends on the environment in which the material is used.

These factors play a role in modifying microstructural properties of materials. Their thermal, acoustic and mechanical performance, highly dependent on their microstructure, can also be modified over time.

A common method to study the durability of building materials is to achieve accelerated aging tests in laboratories, according to the specific properties of materials and their environment of use. The comparison of the characteristics of materials after these accelerated aging and in natural conditions is then used to model the evolution of their performance and determine their lifetime. In the case of vegetal concretes, few studies exist and they are based on previous works performed on concrete durability. These studies aim to analyse the impact of humidity, of immersion in water, immersion and drying, wetting and drying or freeze/thaw cycles, accelerated carbonation on material properties. Protocols have also been developed to observe the potential development of microorganisms on the surface of the bio-based building materials.

In this chapter the different accelerated aging protocols used in laboratory to assess the durability of bio-based construction materials is firstly described. The behaviour of plant-based concrete submitted to these tests is then presented. To better understand these performances, the state-of-the art is expanded to several investigations of aging of vegetal fibres and composites containing vegetal fibres embedded in a mineral matrix.

Table 8.1 Different types of aging tests used for vegetal concretes

Reference	Material	Description	Duration
Arizzi et al. (2016)	Hemp concrete	Dynamic: 3 Climatic simulations: variation of temperature, humidity, rainfall, influence of salts	12 days
Walker et al. (2014)	Hemp-lime concretes	Freeze/thaw cycles	10 cycles between −15 and 20 °C
		Exposition to salts (NaCl) during 12 h and drying during 12 h	20 °C during two weeks and 40 °C during the next two weeks
		Biological aging	Inoculation and storage at 30 °C and 80% HR during 7 months
Hellebois 2013, Hellebois et al. (2013)	Hemp concrete	Wetting and drying cycles	30 °C, 40 and 90% RH
		Immersion and drying cycles	20 °C, 2 cycles, 41 days, Drying at 40 °C
		Biological aging	3 months at 30 °C and 98% RH
Abdellaoui (2014), Marceau et al. (2015)	Hemp concrete	Wetting and drying cycles	30 °C, 40 and 98% RH
		Biological aging	3 months at 30 °C and 98% RH
Sonebi et al. (2015), Castel et al. (2016)	Hemp concrete	Full Immersion in water and drying cycles	Immersion at 20 °C, drying at 50 °C during 48 h
Magniont et al. (2012)	Hemp concrete	Storage at 25 °C and RH > 95%	Until 2.5 years
Bessette et al. (2015)	Precast hemp concrete	Storage in inside climate	90 days
		Storage in external climate	One year
Le Bayon et al. (2015)	Different bio-based construction materials	Development of a mould test method	

8.2 Accelerated Aging Protocols for Bio-based Construction Materials

Various types of aging protocols were used to accelerate the evolution of the properties of plant-based concretes in laboratory: environmental aging, based on temperature and/or humidity variations in static or dynamic mode and biological aging. These experiments were performed essentially on hemp concretes. The main parameters of these studies are reported on Table 8.1.

8.2.1 Environmental Aging

The protocols used to study the durability of bio-based concretes subjected to environmental constraints are varied: cyclic variations of humidity at constant temperature (Hellebois et al. 2013; Marceau et al. 2015), simultaneous variations of temperature and humidity (Arrizi et al. 2015; Arrizi et al. 2016), freeze/thaw cycles (Walker et al. 2014), immersion and drying cycles (Hellebois et al. 2013; Sonebi et al. 2015; Castel et al. 2016) or storage in static conditions of temperature and humidity, accelerated carbonation (Chabannes et al. 2015). Moreover, the properties of the plant-based concretes measured before and after these aging protocols are also very different. Therefore, the comparison of the results of the different studies is very difficult.

On the other hand, when the conditions of aging are cyclic, the duration of the test is often short, up to three months. This aging time is probably too short to highlight significant variations in the properties of the materials by keeping aging mechanisms similar to those that occur naturally in a building.

8.2.2 Biological Aging

Plants, either in the form of aggregates or fibres, naturally contain microorganisms. Their proliferation can affect the indoor air quality in buildings where bio-based construction materials are used. Moreover, it may also modify the intrinsic properties of the materials. It is therefore useful to identify the necessary conditions for their growth and their impact on the performances of plant concretes.

8.2.2.1 Description of the Microorganisms

Different kinds of microorganisms are able to grow on the surface of materials: moulds and bacteria (CSHPF 2006; Dehoux and Dehoux 1997). Bacteria may form colonies with agglutinated cells remaining in an aqueous gel (biofilm).

Moulds have to draw into their environment the water and organic and inorganic substances necessary for their development. Their vegetative system consists of filaments or hyphae which constitute a network called mycelium. Fungi are propagated by spores formed from the mycelium. Spores are kinds of microscopic seeds which are dispersed by air currents, runoff water or by sticking on objects. Under favourable conditions of temperature and moisture, spores can germinate and create mycelium again that can, in turn, resporulate and recontaminate.

Fungi need humidity to develop and the presence of different genera depends on the water activity A_w in the materials: for low water activity ($A_w < 0.8$), *Penicillium* and *Aspergillus* will colonize the substrate. *Clostrium* will appear when the humidity increases ($0.8 < A_w < 0.9$) and for wet surfaces ($A_w > 0.9$), *Strachybotrys* can be observed (Gueguen et al. 2015; Pasanen et al. 1992). The nature of the support may also influence the installation of adapted species.

Their presence is not always dangerous for inhabitants. However, they may present risks to human health: allergies, infections…

8.2.2.2 Mechanisms of Biodegradation

Colonization of materials by moulds generally induces their biodegradation and results from two mechanisms:

– A physical action, linked to the development of hyphae in the material, which can lead to its breakage,
– A chemical action, due to the production of various metabolites, which act by assimilation or dissimilation.

During the assimilation process, the constituents of the material are used as nutrients after their reduction by different extracellular enzymes that facilitate penetration of the hyphae in the material. The dissimilation processes are related to the production of organic acids and pigments. Organic acids (such as gluconic, citric, oxalic acids…) are produced in varying amounts during the metabolic activity and can react with the substrate. In addition to the direct action of these acids, their production promotes the growth of acidophilic fungal species that can continue the degradation of the support.

8.2.2.3 Methods for Determination of Fungal Resistance of Construction Products

Several standards of various origins exist to determine the performance of construction products against a fungal contamination. The assessment procedures proposed include three recurring phases:

– Product contamination, by spraying a liquid suspension, or by deposition of microorganisms from a liquid inoculum.

- Incubation of the contaminated material in static conditions: samples are generally incubated between 25 and 32 °C, with relative humidity close to saturation for periods during several weeks.
- Evaluation of microbial growth: the evaluation techniques consist in determining, quantitatively, by measuring the fungal biomass, or semi-quantitatively, the level of development of fungi. Less common techniques rely on mass variation or modification of various physical properties.

8.2.2.4 Proposal of a Fungal Resistance Test Development Tailored to Bio-based Insulation Materials

A laboratory test method has been developed in order to assess the resistance of bio-based insulation materials against moulds (Le Bayon et al. 2015). According to this study, the parameters having the highest impact on fungal growth are humidity, the composition of bio-based material and the additives it contains.

The parameters of the mould test take into account the climatic conditions of insulation materials used in buildings. The test is performed at 85% RH and 26 °C. The samples are inoculated with a fungal solution containing three fungal strains (*Aspergillus Niger, Penicillium Brevicompactum, Cladosporium Sphaerospermum*). The mould growth is visually assessed and quantified by measuring the number of cultivable fungal units.

8.3 Aging of Bio-based Concretes

The evaluation of the lifetime of construction materials requires to characterize the evolution of their properties by subjecting them to accelerated aging protocols in laboratory. The results obtained are then compared to those measured after aging under natural exposure conditions in a building.

In this section, the results published about the impact of natural aging are firstly presented. Then, the results concerning different types of laboratory aging tests are then detailed.

8.3.1 Natural Aging of Bio-based Concretes

There are limited results published regarding the evolution of the properties of bio-based concretes under natural conditions. Three investigations on hemp concretes were reported.

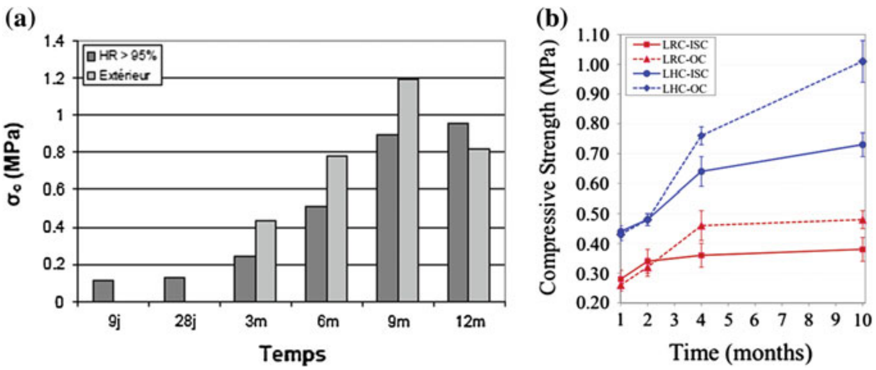

Fig. 8.2 Evolution of the compression strength **a** for hemp concretes stored in controlled atmosphere and outdoor conditions (Magniont 2010) and **b** for hemp concretes (LHC) and rice husk concretes (LRC) stored outdoor (*OC* outdoor conditions) and in indoor standard conditions (ISC) (Chabannes et al. 2015)

In the first study, (Magniont 2010) the compression strength of hemp concretes stored until one year in different environments: controlled atmosphere (20 °C and relative humidity above 95%) and outdoor conditions without protection were measured (Fig. 8.2a).

Figure 8.2 indicates that the compression strength increases up to 12 months for samples stored in controlled conditions. For samples stored in outdoor conditions, it increases until 9 months, and after it drops at 12 months. This reduction of compressive strength could be attributed to the experimental dispersion of the results or to the high water content of the specimens at the time of the test. This result can also result from long-term degradation mechanisms under conditions of outdoor exposure, like leaching phenomena of the mineral binder.

The same type of study has been performed on hemp concretes (LRC) and rice husk concretes (LHC) (Chabannes et al. 2015): samples were stored outdoor (OC: outdoor conditions) and in indoor standard conditions (ISC) 24 h after mixing. The evolution of the compressive strength of the concretes is reported on Fig. 8.2b. It can be observed that the compressive strength of both concretes increased as a function of the time, but this increase is limited after four months for rice husk concretes. These evolutions of compressive strength are in agreement with the previous study (Magniont 2010).

Another result is the difference between the two curing conditions: The strength enhancement was higher for specimens exposed outdoors whether the type of concrete. This was explained by favourable conditions to the carbonation process in the outdoor conditions. Indeed, in this environment, the relative humidity varied from 45 to 75% and these conditions were beneficial for CO_2 diffusion and dissolution.

The third investigation (Bessette et al. 2015) focussed on the development of mould on hemp concrete walls coated with two different renders and exposed to external conditions during one year. The first render used was permeable to vapour water but not to liquid water, whereas the second was permeable to both liquid and vapour water. After one year, the results showed that the presence of a render impermeable to liquid water limited the presence of microorganisms whereas a permeable render couldn't prevent their proliferation. Thus, the choice of the render was essential to protect hemp concrete walls from microorganisms' development.

8.3.2 Influence of Environmental Aging on the Mechanical Properties

Several studies have focussed in laboratory on the influence of different environments on the properties of bio-based concretes.

8.3.2.1 Static Conditions

In order to study the long-term performances of hemp concretes, Magniont (Magniont et al. 2012) stored hemp concretes in a humid room with relative humidity higher than 95% during one year. The evolution of the compressive strength of hemp concrete and of the pure binder paste is presented on Fig. 8.3.

It can be observed that the evolutions of the compressive strength of the pure binder paste and of the concrete are decoupled. The maximum compressive strength is constant after about 50 days for the binder paste, whereas it increases continuously until one year for the hemp concrete. This decoupling may be explained by a setting delay due to the presence of vegetal aggregates (Sedan 2007). However, other studies mentioned delays of about several minutes to several hours and therefore, this statement cannot be used to support the shift of several months observed here.

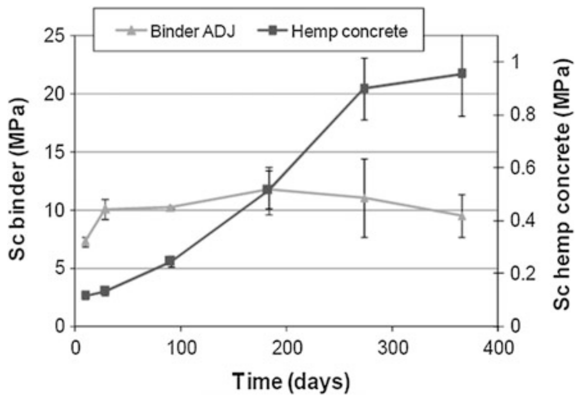

Fig. 8.3 Evolution of compressive strength of the pure binder paste and hemp concrete with time (Magniont et al. 2012)

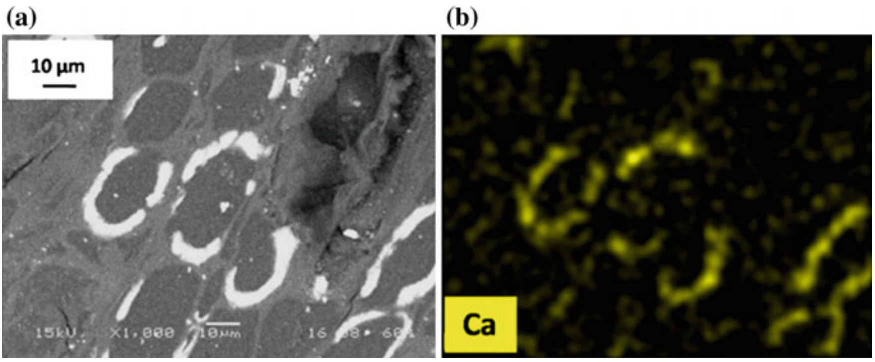

Fig. 8.4 SEM observations and CA EDS mapping of cross sections of hemp shiv extracted from a 2.5 years concrete (Magniont et al. 2012)

Another phenomenon could explain the increase of the strength of the hemp concrete: the mineralization of plant aggregate. This was demonstrated by SEM on hemp shiv extracted from a 2.5 years concrete (Fig. 8.4). Mineral products are visible in the walls of the pores of the hemp shiv. During the storage in a wet chamber, calcic phases of the binder dissolved and calcium species could diffuse into the pores of hemp shiv, where they could re-precipitate as calcite. This mineralization of the vegetal aggregate could explain the enhancement of the compressive strength of concretes and the stiffening of hemp aggregates.

8.3.2.2 Dynamic Conditions

More complex aging protocols have also been set up to simulate actual use conditions of bio-based concretes used in buildings.

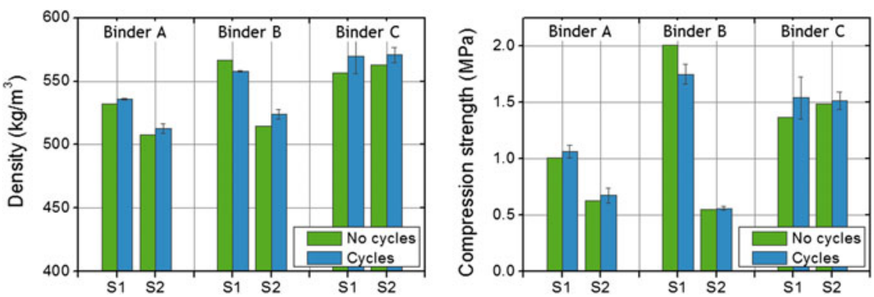

Fig. 8.5 Variation of the density and of the compressive strength of hemp concretes (Hellebois et al. 2013)

Table 8.2 Variation of the thermal conductivity of two hemp concretes before and after 75 days of wetting and drying cycles (Abdellaoui 2014; Marceau et al. 2015)

Thermal conductivity (W/(m.K))	PNC—shiv A	PNC—shiv B
100 days	0.102 ± 0.006	0.105 ± 0.005
After aging	0.103 ± 0.003	0.112 ± 0.008

Wetting and Drying Cycles

In several studies (Abdellaoui 2014; Marceau et al. 2015), the aging of hemp concretes has been simulated in laboratory with humidity cycles. The temperature was fixed at 30 °C for both investigations. It corresponds to the temperature range where fungal growth is possible. The humidity was varied from 40% to 90 and 98%. The duration of the cycles in these investigations varied from one to two weeks.

The variation of density and of compressive strength was small after the wetting and drying cycles (Fig. 8.5). In this study (Hellebois et al. 2013), three different binders and two type of shiv have been used. It can be observed that the density and the compressive strength of the concretes depended on both the type of binder and shiv. The variation of these properties after wetting and drying cycles (duration: 45 days) was also different depending on the composition of the material. The variation of compressive strength was linked to the variation of density of the concretes after the cycles. Without any further experiment, no explanation of these results can be obtained.

In the second study (Abdellaoui 2014; Marceau et al. 2015), a slight increase of the density of the two hemp concretes was observed after 75 days of cycles, corresponding to a weak reduction of the porosity of the material. However, none of these studies have shown significant variations of the insulation properties of the hemp concretes (Table 8.2): no evolution of the thermal conductivity and of the acoustic behaviour has been observed.

Full Immersion in Water and Drying Cycles

Full immersion in water and drying cycles of hemp concrete were reported in 3 investigations (Hellebois 2013; Sonebi et al. 2015; Castel et al. 2016):

– Long cycles (2 cycles of 22 days) have been applied on hemp concretes until a saturation state is obtained for water absorption and desorption (Hellebois 2013). These tests show that hemp concretes can absorb their weight of liquid water and that this absorption is rapid (80% of weight increase in 100 h). As in the case of wetting and drying cycles, the density variations after two immersions depend on the type of binder and aggregate. The compressive strength of the concretes was then linked to their density variations. In the case of prompt natural cement, a hydraulic binder, the increase of density and compression

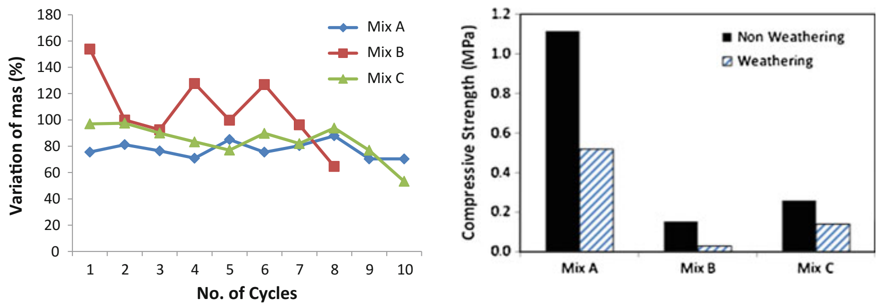

Fig. 8.6 Variation of weight and of compressive strength after 10 cycles of full immersion and drying (Sonebi et al. 2015)

strength may suggest that hydration of the binder continued during the immersions. This result is not observed when the binder contains lime. Leaching of the binder was also observed, especially for the first immersion, wherein the pH of the solution increases up to 12 in a few hours.

– Sonebi et al. (2015) submitted hemp concrete specimens to 10 cycles of full immersion in water and drying in oven. The samples are successively immersed in a water bath at 20 °C during 48 h and then placed in a ventilated oven to dry at 40 °C for 48 h. Figure 8.6 presents the variation of mass after 10 cycles. The masses of hemp concrete are reduced after the cycles. Depending on the mix, the reduction of compressive strength varies from 53 to 81% (Fig. 8.6). The weathering affected significantly the compressive strength after only 10 cycles. This reduction after immersion and drying cycles can be attributed to the softening of the hemp concrete and the weakening of the interface zone between

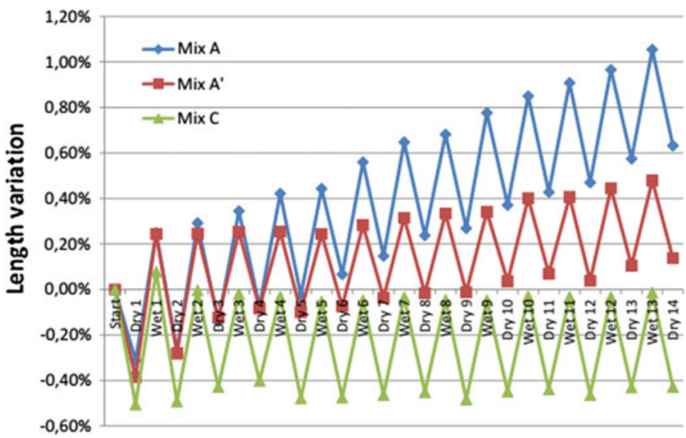

Fig. 8.7 Length variation of the samples during immersion and drying cycles (Castel et al. 2016)

hemp shiv and binder, which can also led to an increase in the porosity. It was also observed after cycles that the water colour changed. This may result from leaching of materials.

Short cycles (13 cycles) was also carried out in another study (Castel et al. 2016) on hemp shiv concretes. During these cycles, the weight and the length (Fig. 8.7) of the samples have been measured after each absorption and desorption. Different behaviours were observed for A and A' concretes, corresponding to render formulations, the length of the specimen increases as a function of cycles, whereas for concrete C (floor formulation), the length of the sample was constant. In these last samples, the porosity was high enough to compensate the swelling of the vegetal aggregates during the water immersion. After these cycles, the compressive strength decreased for all the concretes, whatever their composition.

Climatic Simulations

Real climatic conditions have been simulated to study the long-term durability of hemp concretes (Arizzi et al. 2015, 2016). Three types of climate were selected: Mediterranean, tropical and semi-arid climates (Fig. 8.8).

The mean values of temperature, relative humidity and rainfall for one month are applied during one day in the accelerated aging test. Thus, the total duration of the aging in laboratory is 12 days, corresponding to one year. The effect of airborne salt in coastal areas has also been taken into account, by soaking a part of the samples in a NaCl solution before the aging test.

During the cycles, the weight of the samples remained constant, except for rainfall events that cause a massive increase proportional to the spraying duration and to the amount of sprayed water.

At the end of each weathering simulation, the microbial colonisation of the samples is observed and identified. To do this, adhesive tape samples were collected to analyse the microbial community present on the materials. After inoculation on

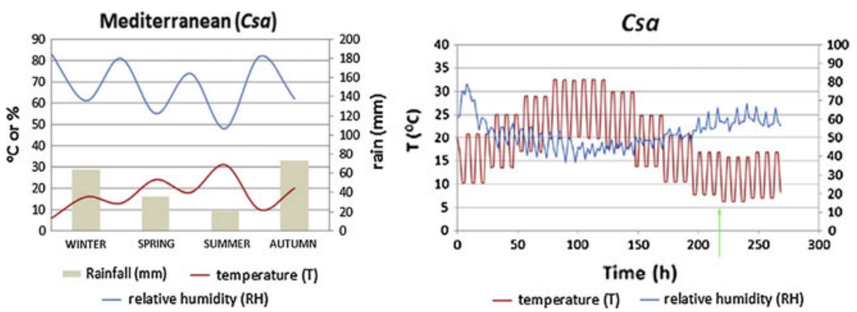

Fig. 8.8 Average conditions of temperature, relative humidity and rainfall recorded in a whole year in the Mediterranean zone and corresponding test conditions of temperature and relative humidity (Arizzi et al. 2016)

Petri plates and incubation at 28 °C during one week, the different colonies were separated and identified. In both control and test samples, different common bacteria have been detected. Some fungi were also isolated.

Due to the higher temperature and relative humidity in the tropical climate, microbial colonisation was more intense in these conditions. The colonisation was less important for the arid climate. However, no predominance of one type of microorganism over another has been observed in this study and most of the detected microorganisms were often present under a large range of environmental conditions.

The presence of a biofilm of bacteria in the surface of specimen was also visible by ESEM. It could have an impact on the properties of the materials by closing the porosity and decreasing the water permeability of the concretes.

The characterisation of the sample mineralogy after the different weathering tests has shown the presence of vaterite at the surface of the samples. This component can be produced by bacilli, that may precipitate carbonates, and by fungi, which have the capacity to transform and precipitate minerals. The presence of vaterite was higher after the Mediterranean and the tropical simulations, where the biological activity was the more important.

Accelerated Carbonation Test

The carbonation reaction is a natural reaction taking place between the CO_2 of the surrounding air and hydrated lime or portlandite $Ca(OH)_2$ (Cizer et al. 2012). It proceeds from the surface to the core of the concretes by diffusion of gaseous CO_2 in the open pores. The overall carbonation reaction is:

$$Ca(OH)_2(s) + CO_2(g) \rightarrow CaCO_3(s) + H_2O(aq) + 74\ \text{kJ/mol}$$

The reaction is very slow, due to the low concentration of CO_2 in the atmosphere. It depends on the nature of the binder phase, to the pore network and to the relative humidity. The formation of $CaCO_3$ induces an increase of the bulk density of the material and a decrease of its porosity and its alkalinity. Thus, these variation of microstructure can have an influence on the functional properties of the materials, such as mechanical, thermal or acoustical behaviour.

During 10 months of aging in outdoor conditions, Chabannes (Chabannes et al. 2015) showed that this environment enhanced the compressive strength of bio-based concretes by increasing the carbonation of the binder (Fig. 8.2b).

In the same study, the influence of accelerated carbonation curing (ACC) during one month is also investigated: after 40 days of drying at 20 °C and 50% RH, the concrete specimens were exposed to CO_2 curing. The conditions in the enclosure are fixed to 20 °C and 65% RH. CO_2 was injected with an initial concentration of 50% v/v and regular injections are performed when the CO_2 is entirely consumed by the carbonation reaction. The compressive strength of the concretes was

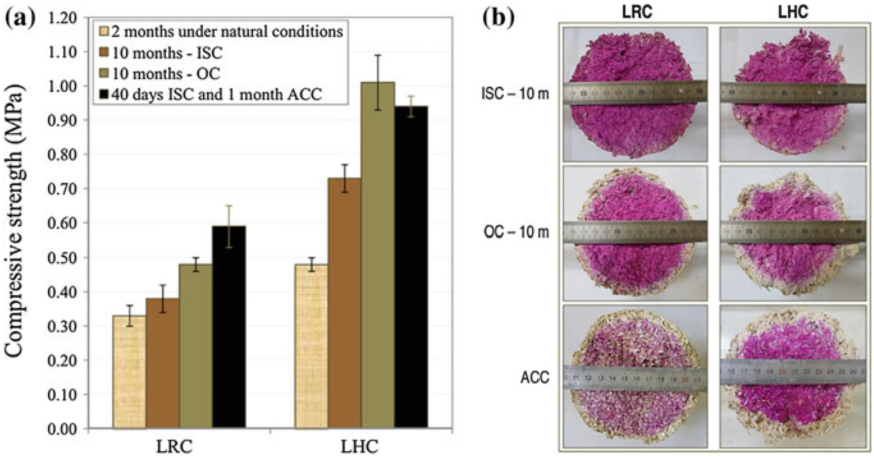

Fig. 8.9 **a** Compressive strength of hemp concretes (LHC) and rice husk concretes (LRC) after accelerated carbonation curing (ACC) compared to natural conditions (*ISC* indoor standard conditions, *OC* outdoor conditions), **b** comparison of the cross sectional views of the samples after spraying with phenol-phthalein (Chabannes et al. 2015)

measured after the initial curing and after one month of accelerated carbonation curing (Fig. 8.9a).

These results showed that the compressive strength after ACC is almost equivalent to that observed after 10 months of outdoor exposure. It was doubled if it is compared to that measured after two months of natural exposure.

The carbonation profiles of theses samples (Fig. 8.9b) show that:

– For sampled stored in indoor standard conditions (ISC), the binder was uncarbonated,
– A carbonation front was visible for samples stored 10 months in outdoor conditions (OC), varying from 0.8 to 1.5 cm depending on the plant aggregate,
– After one month of ACC, the carbonation front was almost the same as that observed after 10 months of outdoor exposure. Moreover, the core of the hemp concretes appeared more carbonated and was coloured in pale pink.

These results are confirmed by the measurements of the $CaCO_3$ contents in the core of the samples. Moreover, this work showed that the slow C_2S hydration is linked to the carbonation of the hydrated lime of the binder. Indeed the water released by the carbonation reaction enables the C_2S hydration.

Other Aging Tests

Other aging tests, based on those performed on civil engineering concretes, have also been applied to hemp concretes, such as freeze/thaw cycles and salt exposure (Walker et al. 2014).

Freeze/thaw cycles didn't create any cracks in the materials, and no visible variations of the microstructure can be observed by SEM. Similarly, sodium chloride exposure during one month does not modify the compressive strength of the samples. This can be explained by the high ductility of the plant aggregates that can accommodate expansive salt crystallisation pressures.

8.3.3 Microbial Aging

The development of microorganisms created a real obstacle to wide spreading of bio-based materials in buildings. Due to the hydrophilicity of the materials and the presence of vegetal aggregates, the microorganisms find conditions very favourable to their proliferation.

In the last section, results regarding the microorganisms' growth after weathering tests were presented. It has reported that their presence has, among other things, an impact on the mineralogical composition of the concretes with the formation of vaterite (Arizzi et al. 2016).

Before the definition of a fungal resistance test developed for bio-based construction materials (Part 8.2.2.3), several studies have been performed in order to analyse specifically this type of aging on hemp concretes. Most of these studies consist in storing hemp shiv or hemp concretes in conditions favourable to the growth of bacteria and fungi (temperature between 22 and 35 °C, high relative

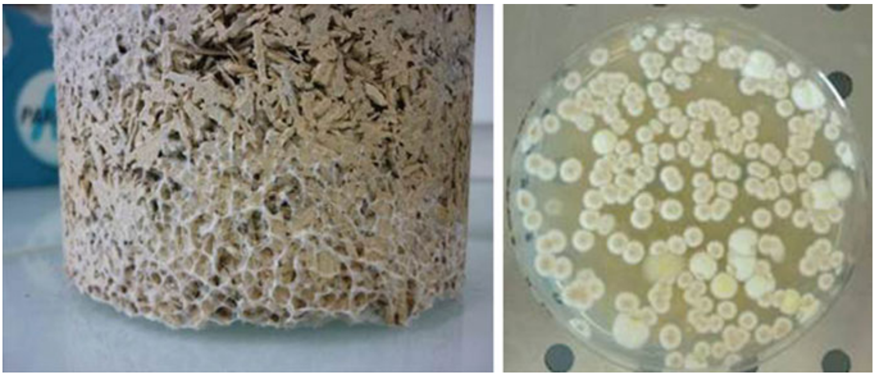

Fig. 8.10 Presence of fungi after conservation of hemp concrete at 30 °C and 98% RH (Hellebois et al. 2013)

Table 8.3 Influence of the material pH on fungal growth (Abdellaoui 2014)

Age of the concrete	14 days		120 days	
Type of shiv	A	B	A	B
Surface pH	10.5	10.4	8.7	9.2
Presence of moulds?	No	No	Yes	Yes

humidity). This can be done with microorganisms naturally present in the material or after inoculation with a stain solution (Marceau et al. 2015).

After 7 months of storage in a humidity chamber at 30 °C and 80% RH, for hemp concretes inoculated with a culture of microorganisms, no microbial development has been observed (Walker et al. 2014).

The natural microbial growth has also been studied on different hemp concretes after 3 months of storage at 30 °C and a relative humidity higher than 95% (Hellebois et al. 2013). Fungal growth is visible on the concretes, whatever their composition (Fig. 8.10).

These fungi were collected, cultivated and used to inoculate new samples of hemp concretes (Abdellaoui 2014; Marceau et al. 2015). At the time of their inoculation, the concretes were aged of 14 and 120 days. They were then incubated in environmental conditions favourable to microorganisms' development (30 °C, 98% RH) and the presence of moulds was observed 100 days after (Table 8.3). The surface pH of the concretes has also been measured at the same time.

In Table 8.3, it can be observed that the presence of moulds is only visible for samples inoculated 120 days after their manufacturing and the surface pH of the material is about 9. For samples inoculated 14 days after their manufacturing, no fungal growth is observed and the pH surface is around 10.5. The pH value is reduced, due to the natural carbonation reaction of the binder. This lower value of pH allowed the microorganisms to grow at the surface of the hemp concretes. The pH value seems to be one of the factors to take into account to assess the risk of mould growth in plan concretes.

8.3.4 *Conclusion*

Because of their recent development, few studies have focused on the assessment of the durability of hemp concretes. The protocols used in laboratory and the measured properties were very different. Therefore, it is still difficult to identify precisely the main degradation mechanisms of these materials. However, many others studies have focused on the durability of composites containing a mineral matrix reinforced with vegetal fibres, used for their mechanical properties. The main results of these investigations, in connection with the bio-based concretes, are presented in the next section.

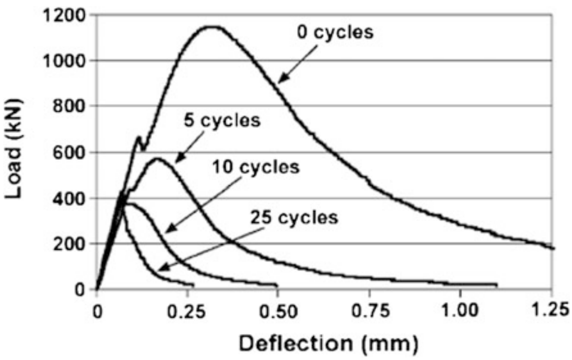

Fig. 8.11 Typical load-deflection curves of kraft pulp fibre-cement composites exposed to wetting and drying cycles (Mohr et al. 2005)

8.4 Aging of Natural Fibres-Cement Composites

Composites containing natural fibres reinforcements in a mineral matrix are promising structural materials for construction. Several studies gave results about the evolution of their mechanical properties when they are exposed to different kinds of environments, especially humidity.

The aging protocols are generally immersion and drying cycles and the mechanical properties of the composites are measured as a function of time (Melo Filho et al. 2013; Mohr et al. 2005, 2006; Ramakrishna and Sundararajan 2005; Sivaraja et al. 2010; MacVicar et al. 1999; Juarez et al. 2007; Ferreira et al. 2015; Toledo Filho et al. 2009). A reduction of mechanical strength of the composites, accompanied by a decrease of their ductility was observed in the early aging cycles (Fig. 8.11). Physicochemical and microstructural analyses were performed to understand these results. Two explanations are proposed to understand these results: the mineralisation of the fibres and their degradation in the alkaline binder.

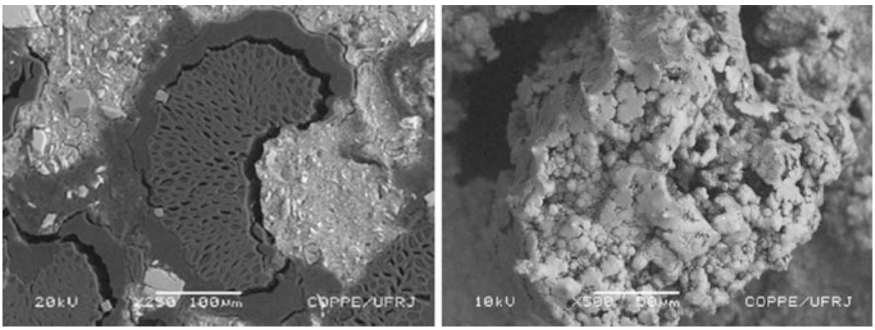

Fig. 8.12 Initial structural fibre geometry and mineralized fibre inside the composite (Toledo Filho et al. 2009)

8.4.1 Mineralisation of the Vegetal Fibres

Hydrated mineral binders contain portlandite $Ca(OH)_2$. This compound is soluble in the interstitial solution located in the pores of the material. By diffusion, calcium and hydroxide ions migrate into the pores of the elementary fibres of the plant. When the water content decreases, portlandite can re-precipitate on the fibres and within the lumen (Fig. 8.12). This resulted in a reduction of the porosity of the plant and of the tensile strength of fibres.

These phenomena of mineralization of natural fibres are consistent with observations of Magniont (Magniont et al. 2012) on hemp shiv in a mineral matrix presented in part 8.3.2.1 of this chapter.

8.4.2 Degradation Mechanisms of Vegetal Fibres

The degradation of natural fibres in an alkaline medium is described by Wei (Wei and Meyer 2014, 2015) in four steps (Fig. 8.13). Lignin plays the role of glue in the cell wall and protects the fibre against microbial and chemical degradation of polysaccharides, whereas hemicelluloses bind the cellulose micro-fibrils. These two components are amorphous and sensitive to the alkaline environment of the cement matrix. Therefore, the first step of the mechanism corresponds to the degradation of lignin and of a part of hemicellulose, leading to the exposure of holocellulose. Then, the degradation of the hemicellulose induces the decreasing of the integrity and of the stability of the vegetal cell walls. The third step is the destruction of the intra-molecular hydrogen bonding, leading to the dispersion of the cellulose

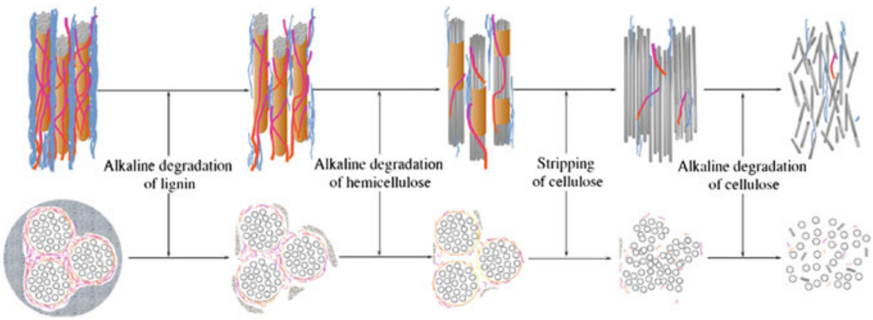

Fig. 8.13 Diagrammatic description of vegetal fibre's alkaline degradation mechanism (Wei and Meyer 2015)

micro-fibrils. Then, the amorphous regions of cellulose are hydrolysed, inducing the complete degradation of cellulose micro-fibrils.

During this degradation process, the hydration products of the binder, such as C-S-H and soluble portlandite, can diffuse in the cell wall, leading to a faster mineralization and embrittlement of natural fibres.

After the first step of the alkaline degradation, Pejic (Pejic et al. 2008) observed that the degradation of lignin and hemicellulose hemp fibre led to a reduction of the water vapour permeability.

8.5 Concluding Remarks

Because of their relatively recent development, few studies have focused on the durability of plant concrete until now. The aging protocols applied in laboratory and the analysed properties are diverse, making the comparison of obtained results very complex. In addition, the aging times used are rather short, and significant variations of the material properties are perhaps not visible for these aging durations. The protocols implemented until now are focused on similar factors that could influence the material properties: temperature, relative humidity and potential microbiological growth. These can lead to physicochemical and microstructural modifications of the materials and therefore impact the performances of materials in a building.

The understanding of aging mechanisms of plant concretes and the prediction of their lifetime requires comprehensive studies, including multidisciplinary and multi-scale analysis, which take into account the variability of the formulations and of the final properties of the materials. Data on the evolution of their performances in real conditions are also needed. Finally, the construction systems in which plant concretes are integrated into a building, such as the bearing structure and the interior and exterior plasters, have also to be taken into account.

Available data on composites containing vegetal fibres in a mineral matrix, used for their structural properties, allow to understanding the chemical interactions between plants components and a cement matrix. They can be transposed to the plant aggregates used in the bio-based insulation.

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