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Predicting the long-term durability of hemp–lime renders in inland and coastal areas using Mediterranean, Tropical and Semi-arid climatic simulations

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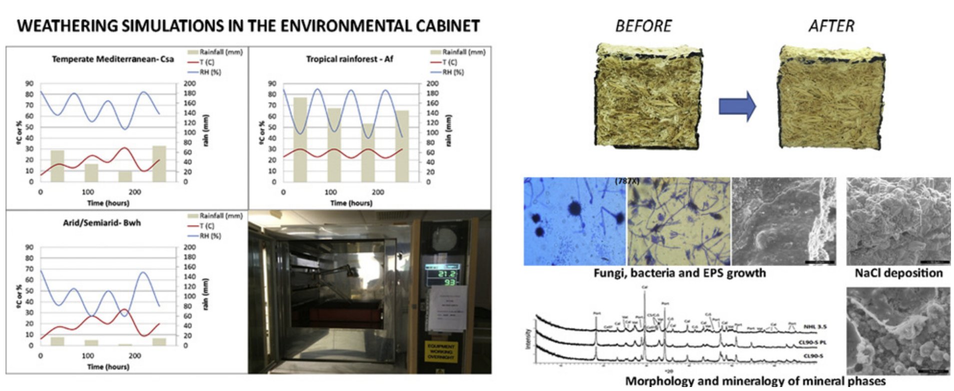
HIGHLIGHTS

- Realistic simulations in the cabinet of one-year exposure to environmental conditions
- Influence of the lime type on the durability of hemp–lime renders
- Improvement of the carbonation of lime under Mediterranean and Tropical conditions
- More intense colonisation of alkaliphiles fungi and bacteria under heavy rainfall
- Superficial deposition and leaching of NaCl, with no damage observed in the samples

GRAPHICAL ABSTRACT



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ABSTRACT

Hemp-based composites are eco-friendly building materials as they improve energy efficiency in buildings and entail low waste production and pollutant emissions during their manufacturing process. Nevertheless, the organic nature of hemp enhances the bio-receptivity of the material, with likely negative consequences for its long-term performance in the building. The main purpose of this study was to study the response at macro- and micro-scale of hemp–lime renders subjected to weathering simulations in an environmental cabinet (one year was condensed in twelve days), so as to predict their long-term durability in coastal and inland areas with Mediterranean, Tropical and Semi-arid climates, also in relation with the lime type used. The simulated climatic conditions caused almost unnoticeable mass, volume and colour changes in hemp–lime renders. No efflorescence or physical breakdown was detected in samples subjected to NaCl, because the salt mainly precipitates on the surface of samples and is washed away by the rain. Although there was no visible microbial colonisation, alkaliphilic fungi (mainly *Penicillium* and *Aspergillus*) and bacteria (mainly *Bacillus* and *Micrococcus*) were isolated in all samples. Microbial growth and diversification were higher under Tropical climate, due to heavier rainfall. The influence of the bacterial activity on the hardening of samples has also been discussed here and related with the formation and stabilisation of vaterite in hemp–lime mixes. This study has

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demonstrated that hemp–lime renders show good durability towards a wide range of environmental conditions and factors. However, it might be useful to take some specific preventive and maintenance measures to reduce the bio-receptivity of this material, thus ensuring a longer durability on site.

1. Introduction

Within the last two decades, growing awareness of the need to reduce the carbon footprint of buildings (i.e. reduction of gas emissions and waste and use of renewable resources) and to increase their energy efficiency has promoted the development of novel building materials that provide a sustainable and technically valid alternative to cement and synthetic polymer-based materials. Most of these novel materials are composed of an inorganic binder (e.g. lime, clay, gypsum) and plant aggregates. Flax, wool, bamboo, kenaf and, in particular, hemp are some examples of the non-food crops lately being revaluated by the construction sector (RILEM PRO99, 2015). The reason for the increasing interest in using hemp in building materials is twofold: first, its growth represents a benefit for the environment (annual crop; carbon-sequestering plant; there is no need for pesticides and fertilisers; cleaning and improvement of the soil) and second, its use in buildings favours healthier in-door spaces (buffering activity against humidity variations) and improved energy efficiency (thermal and acoustic insulation) (Pervaiz and Sain, 2003; Esmail, 2010; Tran Le et al., 2010; Faruk et al., 2012).

However, recent studies on hemp concrete and hemp–lime have shown that prolonged water absorption under moist conditions, scarce ventilation and the wrong choice of the protective coating may lead to intense bio-decay (Arizzi et al., 2015a; Bessette et al., 2015; Lamoulie et al., 2015; Marceau et al., 2015; Simons et al., 2015). The protective action of lime (which normally acts as a disinfectant), indeed, seems to be limited against alkaliphilic bacteria and fungi (Walker et al., 2014; Arizzi et al., 2015a). Although none of the isolated microorganisms induce mycosis in healthy individuals, this finding is still worrying in terms of aesthetic appearance and, more importantly, long-term performance of the hemp–lime composite in the masonry system (unless microbial colonisation is desired, such as in green buildings, Manso et al., 2014). Obviously, the exposure conditions applied in the laboratory are not the same as the climatic conditions on site, and so it would be wrong assuming that the same bio-decay would occur in the hemp–lime mixes once in the building. However, since the growth of microorganisms is strongly influenced by conditions of temperature and relative humidity (Camuffo, 2014), it is necessary to study the behaviour of hemp–lime composites under specific climatic conditions to be able to make realistic predictions on their long-term durability. To the best of our knowledge, there are few studies on the durability of hemp-based building materials in the literature. In particular, most of this research only describes the response of hemp concrete to accelerated ageing tests (common standard laboratory tests), such as wetting-drying, freezing-thawing and salt crystallisation cycles (Walker et al., 2014; Marceau et al., 2015), without studying the durability of hemp concrete under several climatic factors acting simultaneously. Furthermore, when hemp–lime composites are used as external surface protective finish (i.e. render) their susceptibility to weathering is expected to be even higher than that of hemp-based mixes used as infill. Bevan and Woolley (2008), in fact, commented that there is no firm evidence of how well the render or plaster performs when it is made with hemp–lime.

With the purpose of filling this knowledge gap, we have developed and applied new weathering tests specifically conceived to study the durability of hemp–lime renders. To obtain a more realistic response from the material, we have reproduced the environmental conditions of three selected climates typical of the geographic areas where hemp is mostly grown and/or applied in sustainable construction. The updated Köppen–Geiger's climate classification (Kottec et al., 2006) has been used to select and name the three climates listed below:

1) Warm temperate (named *Mediterranean climate*, *Csa*): characterised by warm annual temperatures, with hot and dry summer, typical of Mediterranean countries.
2) Equatorial rainforest, fully humid (named *Tropical climate*, *Af*): characterised by high annual temperature and heavy rainfall, typical of equatorial countries.
3) Arid desert (named *Semi-arid climate*, *Bwh*): characterised by large annual temperature range, dry winter, typical of hot arid countries.

For each climate, specific cycles were designed and then simulated in an environmental cabinet. The conditions in both coastal and inland areas were also simulated for each climate, taking into account the presence and absence of airborne salt (NaCl), respectively. The macroscopic characteristics of the samples (mass, volume and chromatic variations) were monitored before, during and after the weathering tests whilst chemical-mineralogical and microstructural modifications were investigated at the end of each test. Finally, microbiological tests were performed to study how the bio-receptivity of hemp–lime composites is influenced by the climatic conditions (especially RH variations, Jain et al., 2009; Johansson et al., 2014, and rainfall, Caneva et al., 1992) and the presence of sodium chloride (e.g. growth of different number or type of microbe species), taking into account that soluble salts may affect microorganism growth, favouring halophilic (i.e. salt tolerant) species (Altieri and Pinna, 2005). The influence of the type of lime (aerial dry hydrated and putty and natural hydraulic) on the durability of the hemp–lime mixes has also been studied in this work.

2. Materials and methods

2.1. Hemp–lime samples

Three types of hemp–lime mixes were prepared in the same way as in a previous study (Arizzi et al., 2015a), to compare the response of the materials under laboratory and simulated realistic conditions. Hemp shiv (Cannhabitat®, produced by AgroFibre, Euralis, Cazeres, France, and supplied by Cannabric, Guadix, Granada, Spain) were mixed with dry hydrated lime (CL90S, BS-EN 459-1, 2010, produced by ANCASA, Seville, Spain), lime putty (CL90-S PL, BS-EN 459-1, 2010, produced by ComCal, Barcelona, Spain), and natural hydraulic lime (NHL3.5, BS-EN 459-1, 2010, produced by Socli, Italcementi Group, Izaourt, France) in a lime:hemp:water dosage by volume of 3:5:2.5. Mixes were named as C, N and P, according to the type of lime (CL90S, NHL 3.5 and CL90S PL, respectively), and they were cured under T = 17 °C and RH = 75% for three months before the study. For more information on the binder choice and the mix procedure, dosages and conditions refer to Arizzi et al. (2015a).

In total, 36 hemp–lime mix samples were tested, giving four samples per composite type under each climatic simulation (half of them were subjected to salt attack). In the cabinet, samples ($2 \times 4 \times 4$ cm^3) were placed with the largest surface (4×4 cm^2) facing the water hose, so as to reproduce the exposure conditions of a render (with the largest surface facing the external conditions).

2.2. Simulations of the climatic conditions in the environmental cabinet

Climatic simulations were carried out in a Sanyo-FE 300H/MP/R20 environmental cabinet (inner volume: $675 \times 630 \times 650$ mm^3). Four