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From the experimental characterization of the hygrothermal properties of straw-clay mixtures to the numerical assessment of their buffering potential

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ABSTRACT

The development of innovative materials has to respond to both environmental and energy concerns. Bio-based materials are relevant because they are made from renewable raw materials and are carbon neutral. Similarly, unprocessed earth has a very low embodied energy. In this paper, the basic hygrothermal properties of straw-clay samples provided by two French companies were determined. Mixes with densities lower than 450 kg m^{-3} would be suitable for use as self-insulating material in current construction. In addition, the material showed a high sorption capacity and very high water vapour permeability. The measurements were then implemented in a numerical model in order to simulate the hygric response of a small room. The straw-clay mixture was found to have a moisture buffering effect of the same magnitude as walls made of hemp concrete and largely higher than conventional walls. The influence of various indoor finishing materials was investigated through additional simulations.

1. Introduction

Within the context of sustainable development, the reduction of environmental impacts has become a priority in many sectors. In France, the building sector is responsible for 43% of energy consumption and 25% of greenhouse gas emissions. It also uses large quantities of non-renewable raw materials and produces large amounts of waste [1]. These impacts are generated during the production of construction materials and also by the use of the building. In consequence, the development of innovative materials has to respect environmental and social concerns. From the energy point of view, the building's overall energy consumption has to be minimized first, which brings the need for thermally efficient materials to the fore. Second, a low environmental footprint is required and, finally, achieving comfortable, healthy indoor conditions without using energy consuming systems (such as HVACs) is an ongoing topic.

1.1. *On the use of earth mixed with bio-based materials in construction*

Concerning the environmental aspects, bio-based materials are relevant in the field of building construction: they are made from renewable raw materials (mainly local by-products of agricultural activities) and are carbon neutral. Similarly, unprocessed earth is an abundant local resource with very low embodied energy, which is cheap and easy to work. These advantages explain why earth construction is still the most widespread building technique in the world. Today, a third of the world's population still live in earth housing, half of them in developing countries [2]. During the last 15 years, there has been a resurgence of interest in earth construction, resulting in the development of scientific research on this topic as illustrated by the publication of two recent reviews [3,4]. The research works reviewed in these papers mainly focus on the effect of stabilization (with hydraulic binder or plant fibres) on the mechanical performance, shrinkage and durability of soil blocks or rammed earth.

However, earth and bio-based materials present other advantages that are worth studying, namely their hygrothermal properties [5,6], which describe how the material participates in heat and water vapour transfer. Consequently, studying these properties is a

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Nomenclature

Latin symbols

Cp	specific heat capacity (J kg^{-1} K^{-1})
e	thickness (m)
g_V	vapour flux (kg m^{-2} s^{-1})
h	heat transfer coefficient (W m^{-2} K^{-1})
H	enthalpy (J)
h_{Vap}	mass transfer coefficient (s m^{-1})
m	mass (kg)
p	pressure (Pa)
r	humidity ratio (kg_{Vap} kg^{-1}_{DryAir})
T	temperature (K)
u	moisture content (%)
V	volume (m^3)
w	volumetric moisture content (kg m^{-3})

Greek symbols

δ	vapour permeability (s)
λ	thermal conductivity (W m^{-1} K^{-1})
ρ	density (kg m^{-3})
ψ	relative humidity (–)

Subscripts

M	material
V	vapour
0	dry state

Constants

L_V	latent heat of vapour condensation (2500 kJ kg^{-1})
Cp_V	specific heat capacity of vapour (1.86 kJ kg^{-1})
π_A	water vapour permeability of stagnant air (1.9.10^{-10} kg s^{-1} m^{-1} Pa^{-1})

first step in evaluating the impact of the material not only on energy consumption for heating, but also on indoor comfort, which depends strongly on temperature and relative humidity. This influence, often referred to as the moisture buffering capacity, will be presented further in Section 1.2.

The positive impact of earth on comfort is often mentioned, yet no extensive study is available on this specific topic. In fact, this is not very surprising as it has also been observed that the hygrothermal properties of earth materials were poorly described in the literature until recently. McGregor et al. [7] investigated the moisture buffering effect of unfired clay masonry, demonstrating the strong influence of clay plasters and blocks on indoor humidity. They also observed the marked influence of the clay mineralogy on hygrothermal properties. The hygrothermal characteristics of earth bricks have been measured and their ability to quickly absorb a significant amount of water vapour highlighted [8]. Similar measurements have been carried out to assess the influence of the production process (namely extrusion) on the hygrothermal properties of earth bricks [9]. Strong anisotropy was observed for both thermal and hygric properties due to the orientation of the clay platelets. In numerical simulations achieved to compare the influence of several types of indoor finishing, the advantages of using a clay-based coating rather than gypsum or acrylic stucco plaster have been demonstrated, regarding comfort and energy consumption [10]. Allinson and Hall [11] studied the hygrothermal performance of rammed earth using both experimental and numerical tools. This study concluded on the good moisture capacity of stabilized rammed earth (SRE).

Compared to earth, bio-based materials have lower thermal conductivity and can therefore be used as a thermally insulating material to reduce energy consumption. A glance at the respective advantages of bio-based aggregates and earth shows that they are complementary: earth can be used to maintain a comfortable indoor environment while highly porous bio-based materials can help to achieve efficient thermal insulation by lightening the composites. And, of course, both are highly compatible with the desire to preserve the environment as mentioned above.

The straw-clay construction technique consists of mixing straw with diluted earth found on site. After one night of draining, straw-clay is cast on site and packed by hand between two temporary formwork panels around a wood frame. Formwork is removed the same day. Different dry densities can be reached by modifying the proportions of clay and straw, but common densities range from 400 to 500 kg m^{-3}. The present study results from a project initiated by two construction companies, Ecoterre and Inventerre, located in the south of France and working with the straw-clay technique. According to the builders and to the people living in buildings where straw-clay was used as infill insulating material, a comfortable indoor environment was achieved with no significant increase in energy consumption. However, very few studies could be found in the scientific literature to back up this statement. This is a direct consequence of the lack of data for such mixtures, which results in their poor integration in current thermal regulations and numerical studies. So the first objective of this work was to fill that gap.

To the best of our knowledge, only one scientific study [12] on straw-clay exists in the literature. It used samples with a measured density of 440 kg m^{-3} and a rather high thermal conductivity was obtained (0.18 W m^{-1} K^{-1}). However, no hygroscopic properties were measured. Looking at other types of bio-aggregates, few papers can be found where earth is used as a matrix; they include wood [13–17] corn cob [18], straw [17], oat fibres [19], Hibiscus cannabinus fibres [20,21], coconut coir [22], millet [23], sawdust [24] or phytomass [25]. In these studies, it should be noted that the biomass content was very low in comparison with straw-clay, and this resulted in densities higher than 1000 kg m^{-3} in most cases. As mentioned in Refs. [26], there is a relationship between density and thermal conductivity: thermal conductivity increases linearly with density. Therefore, thermal conductivities higher than 0.5 W m^{-1} K^{-1} were obtained, making the material unsuitable for thermal insulation purposes. A noteworthy exception can be found in Refs. [13,14], where lighter mixes were obtained by incorporating wood aggregate in a higher content. Measured densities were 370 and 621 kg m^{-3} respectively, and thermal conductivities were 0.08 and 0.13 W m^{-1} K^{-1}. The equilibrium moisture content (EMC) of earth plaster incorporating wheat straw, barley straw and wood shavings has also been studied [17]. EMC was found to increase with the plant matter content and to depend on the nature of the plant. Similar results were obtained by Maddison et al. [25], who showed that both the amount of water absorbed and the kinetics of absorption were increased by the presence of phytomass. Concerning water vapour permeability, two references were found for