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Design and multi-physical properties of a new hybrid hemp-flax composite material

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HIGHLIGHTS

- The incorporation of the flax fibers has increased the ductility of the hemp concrete.
- Flax fibers have improved the compressive strength of hemp concrete.
- The hybrid composite appears to have a lower water absorption than hemp concrete.
- Hemp-flax hybrid concretes showed a lower shrinkage of about 15% compared to conventional hemp concrete.

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ABSTRACT

An experimental investigation was conducted in order to study the properties of a hybrid hemp-flax composite material in term of capillary water absorption, mechanical strength, thermal conductivity and shrinkage. The hemp-flax composite material is made with 90% hemp shives and 10% flax fibers. Hemp aggregates have a high water absorption capacity, which led to a reduction of the hemp concrete mechanical performances. Four mixes were made for: shuttered walls, external coating, floor insulation and roof insulation. Firstly, bio-based aggregates were characterized in term of particle size distribution and water absorption. Then, the compressive strength of these four mixes was determined to compare the mechanical behavior of the hybrid composite material with hemp concrete. The capillary absorption and the total shrinkage of these bio-based materials were also measured. Finally, we measured the thermal conductivity coefficient of these materials. The results of the compressive strength show a significant improvement due to the incorporation of flax fibers. Flax fibers improve the compactness of the material, thus increasing its density, which leads to a greater mechanical strength. It was observed that the capillary absorption of hemp concrete seems to be related to the aggregates/paste ratio. Finally, flax fibers have reduced hempcrete shrinkage of about 15%.

1. Introduction

Currently, the construction industry is responsible for 24% of carbon dioxide emissions and 44% of the energy consumption in France [1]. New building insulation standards tend to decrease the amount of energy used for heating, which accounts for almost two thirds of the energy consumption and the main part of the CO_2 emissions in the building sector in France. However, in this context, energy expenditure devoted to the manufacture and the implementation of construction materials is increasing. Regarding France's commitments to the Kyoto protocol for 2050, the development of new materials based on renewable resources is necessary.

Plants have been largely forgotten by modern technologies. The evolution of production processes, the need for materials compatible with sustainable construction, consumer expectations and regulatory requirements mean that bio-based materials are becoming increasingly interesting. Among the plants usable for construction, hemp certainly has a privileged position and can be considered as a model. Hemp stands out because of its environmental assets such as its contribution to the improvement of the soil, its neutral carbon accounting, its low embodied energy expenditure and its end of life without harmful consequences for the environment [2]. From hemp is extracted shiv, which is mostly used as litter for animals thanks to its absorbent properties [3]. However, hemp shiv can be mixed with binders (lime and/or cement) and water to make hemp concrete.

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Hemp-lime concrete is used only for twenty years in construction in France. It is most frequently used in lining or filling to form a construction element having good thermal and sound insulation without structural contribution. For ten years, many researches have been conducted on this material, which now allows a better understanding of its properties [4]. Most published researches are focused on its acoustical, thermal and hygrothermal properties which result from the highly porous structure of hemp shiv [5–8]. Hemp concrete is a lightweight composite insulating material having a dry density ranging from 200 to 800 kg m^{-3} [9]. This low density gives to hempcrete its high thermal properties. Indeed, its dry thermal conductivity is between 0.06 and 0.12 W m^{-1} K^{-1}, depending on mix formulations. However, this porous structure also resulted in low strength and low rigidity of the material after curing. Generally, in most studies, hemp concrete compressive strength remained relatively low compared to other conventional building materials, often less than 1 MPa [10–14]. However, a comparative study realized in 10 different laboratories, on identical hemp concrete formulations, showed that this material has an accurate repeatability regarding the density and the mechanical strength [15].

Given this low mechanical strength, hemp concrete cannot therefore be used as a load bearing material. This material is also characterized by an important mechanical ductility, with a compressive strain higher than 10% [10]. The literature suggests that the high absorption capacity of lignocellulosic aggregates, sometimes greater than 300% by mass, is one of the main causes of hemp concrete low mechanical performances [16]. It induces a decrease of the water available for the binder setting, which leads to poor binder-aggregate interface.

Hemp concrete is often directly implemented on the construction site, or manually into forms or by projection process [12]. These methods of implementation do not allow reaching a sufficiently high compactness. However, previous work has shown that the compaction of hemp concrete at fresh state led to an increase of the mechanical performances [17,18]. Hemp aggregates have a particle size distribution predominantly between 1 and 5 mm [19]. Flax fibers have diameters around 5–80 μm [20]. Flax fibers can therefore be inserted between hemp aggregates and thus increase the compactness of the composite. In addition, the flax fibers can help to improve the behavior of the hemp concrete in large strains and thereby increase its ductility [21].

This experimental work aims to study the effect of incorporating flax fibers on the performances of lime-hemp composite. For this purpose, the physical, mechanical and thermal properties of the hybrid hemp-flax composite were studied and compared to conventional hemp concrete. First of all, the water absorption flax fibers and hemp shives was measured. Then, the particle size distribution of hemp shiv was determined by image analysis. Four formulations were made to study the properties of these bio-based composites. These formulations were based on the French professional execution rules for hemp concrete, published in 2012 [22]. These standard practices provide four hemp-lime concrete mix designs for four different applications: external coating, shuttered wall, floor insulation and roof insulation. Thus, through these four formulations, hybrid hemp- flax composite properties were measured and compared to conventional hemp concretes.

2. Materials and methods

2.1. Raw materials

2.1.1. Hemp aggregates and flax fibers

Hemp shiv used as aggregates for this study was Tradical® HF. It is a hemp aggregate made from the inner woody core of the hemp plant's stem. Hemp is chopped, graded and de-dusted to give a natural, sound and breathable product. This type of shiv is compatible with lime-based binders and is marketed for individual housing construction in hemp concrete. Its absolute density, obtained with a gaz pycnometer, is equal to 1.48. Hemp shiv is characterized by its low bulk density [23], about 110 kg m^{-3}, which additionally gives it a very low thermal conductivity of approximately 0.048 W m^{-1} K^{-1}, determined with the transient hot-wire method [24].

Elementary flax fibers used for this work have a length of 12.7 mm, with a diameter ranged between 43 and 53 μm and were grown in Italy. For this work, only untreated fibers were used. Monofilament flax fibers are used to improve cohesion, holding, mold-ability, and to limit the cracking of cementitious composites.

2.1.2. Mineral binder

The binder used in this study was Tradical® PF70. It has already used in several other researches for making hemp concrete [2,6,18,25]. It is a special lime binder based on aerial lime (75%), hydraulic binder (15%) and pozzolanic binder (10%).

This binder has been chosen for its great capacity to generate carbonation reactions. Indeed, aerial lime contains a large amount of calcium hydroxide $Ca(OH)_2$ [16]. Once mixed with water and aggregates and in the presence of carbon dioxide, carbonation of the lime takes place, converting calcium hydroxide into calcium carbonate ($CaCO_3$). This is a very slow reaction. It starts mainly when lime has sufficiently dried and can last for months or even years. Then, the hydraulic binder (15% of the composition) allows a higher reactivity and better short term resistance. Indeed, dicalcium and tricalcium silicates present in the binder will react with water to form calcium silicate hydrates (C—S—H) and portlandite. Finally, the pozzolanic binder (10% of the composition) will react with calcium hydroxide $Ca(OH)_2$ during the cement hydration and will promote the formation of calcium silicate hydrates [16].

2.2. Methodology

2.2.1. Mix design

According to the French professional execution rules for hemp concrete structures [22], four different mixtures were used throughout this work:

- Mix C: external Coating.
- Mix W: shuttered Walls.
- Mix F: Floor insulation.
- Mix R: Roof insulation.

Amziane and Arnaud provide dosages based on experience for these four applications [9]. Mix proportions by mass and notations used are presented in Table 1.

Two different concrete families have been formulated for this study. The first is a conventional hemp concrete, wherein all the introduced aggregates are hemp shives. This concrete will be noted later HC for Hemp Concrete. In the second hemp concrete, 90% (in mass) of the aggregates are hemp shives and the remaining 10% are flax fibers. Hemp shives are therefore substituted partially (10% in mass) by flax fibers. This second composite will be abbreviated FHC for Flax-Hemp Concrete.

2.2.2. Mixing procedure

One of the main difficulties encountered during the hemp concrete mixing is due to the water absorption of plant aggregates. This water absorption creates a problem for the binder which needs to be hydrated [18]. For this reason, it is essential to take into account the water absorption capacity of the raw natural particles. Thus, hemp shives and flax fibers were first pre-wetted in the mix-

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