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Multi-physical properties of a structural concrete incorporating short flax fibers

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HIGHLIGHTS

- The incorporation of flax fibers in concrete significantly reduces its workability.
- A highly-fluid concrete is obtained using shorter fibers and higher paste content.
- The granular compactness is greatly reduced with the addition of flax fibers.

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ABSTRACT

An experimental investigation was undertaken on the physical characterization of a flax fiber-reinforced concrete (FFRC) in both fresh and hardened state. The objective of this study is to provide guidance for the mix-design of these FFRC. The study was conducted from two points of views: improving the workability of the concrete in a fresh state and improving the flexural strength in the hardened state. Several parameters have been studied independently as fiber length, fiber content, or the paste content. The characterization of flax fibers highlighted a high water absorption capacity which must be taken into account for the concrete mix-design. In addition, the flax fibers significantly impact the compactness of granular skeleton. For the characterization of concrete, testing in the fresh state showed a significant decrease of the workability of concrete with the addition of flax fibers. However, the use of shorter fibers, allows to reduce this damaging influence on the fresh concrete workability. Moreover, increasing the paste content allows compensating this fluidity loss. In the hardened state, the increase of the fiber content enhances the flexural strength, but a decrease of the compressive strength is observed. A greater porosity of the concrete was also observed with the incorporation of flax fibers. An increase in porosity was also observed when increasing the paste content.

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, flax certainly has a privileged position. Flax stands out because of its environmental assets such as its neutral carbon accounting, its low embodied energy expenditure and its end of life without harmful consequences for the environment [2].

In recent decades, there is a renewed interest in plant-based materials in the construction industry [3]. Numerous scientific researches have been conducted to develop the use of these materials. One of the bio-materials for construction on which much researches have been carried out is certainly the hemp concrete, and more generally the bio-aggregate-based concrete [4–6]. This material has good thermal characteristics but it turns to be a

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non-structural material because of its low mechanical performance. Plant fibers have also been studied for the manufacture of cementitious composites [7–9]. Generally, the incorporation of these fibers prevent the production of a composite using standard processes [10].

Fibers are used in cementitious materials to improve the flexural strength and post-cracking behavior. The most commonly used in cementitious composites are steel fibers, glass fibers and polypropylene fibers. Several works aimed at characterizing the behavior of these fiber-reinforced concretes [11–13]. The mix-design of these concretes has also been studied by many authors and now beginning to be mastered [14–17]. A rheological study has also shown that rigid fibers orientation is related to the yield stress of the fresh concrete [18]. This study also showed that the orientation of the fibers was strongly related to the flexural strength of the concrete. It was also observed that a low yield stress concrete leads to a good alignment of the fibers, showing multiple cracking under flexural loading. However, the rheology of fiber-reinforced concrete was studied only in the case of rigid fibers [18,19], with low aspect ratio (length/diameter ratio of the fiber), ranging from 17 to 100. For comparison, flax fibers may have an aspect ratio ranging from 500 to 2000, which explains their great flexibility.

Few authors are interested to the mix-design and the physical characterization of structural concrete incorporating plant fibers. The few existing studies compared the performance of plant fiber-reinforced concrete with ordinary concrete [20,21].

This work proposes to study the mix-design and the physical and mechanical properties of structural concrete incorporating flax fibers. The objective is to provide guidance for the mix-design of these flax-fiber reinforced concretes (FFRC) from two point of view. The first one is to improve the implementation conditions of the material in the fresh state. The second is to improve the mechanical properties of FFRC, particularly in bending, in the hardened state. For this purpose, the influence of several parameters was studied independently as fiber length, fiber content, or the amount of fines and water. First, the flax fibers and the aggregates, have been characterized in order to properly formulate the different concretes. A multi-physical characterization was then carried out on concretes. Firstly, in the fresh state, with the measurement of the slump, the slump flow, the flow time, the fresh density and the air content. In the hardened state, mechanical properties have been studied such as compressive strength, flexural strength and modulus of elasticity. The water accessible porosity and the dry bulk density were also determined.

2. Materials

2.1. Raw materials

A white Portland cement with reference CEM I 52.5 N was used in this study in accordance with EN 196-1 standard. The clinker ratio is 98% (2% of limestone). The compressive strength on standardized mortar at 28 days is 71 MPa, the Blaine fineness is 4250 $cm^2.g^{-1}$, and the density about 3.05 $g.cm^{-3}$.

In addition to cement, a high purity limestone was used (total carbonates equal to 98.7%), in accordance with NF P 18-508 standard. The Blaine fineness of the limestone filler is 5440 $cm^2.g^{-1}$, with a density of 2.70 $g.cm^{-3}$.

A polycarboxylates-based superplasticizer, compatible with the cement used, was added as an admixture with a ratio of 1.0% relative to the mass of cement (i.e. 0.30% solids) to provide a better workability in the fresh state.

In addition, a viscosity-modifying agent (VMA) based on a high-molecular weight bio-polymer was added as an admixture with a ratio of 0.5% relative to the mass of cement (i.e. 0.03% solids) to avoid the segregation phenomenon between the paste and the aggregates.

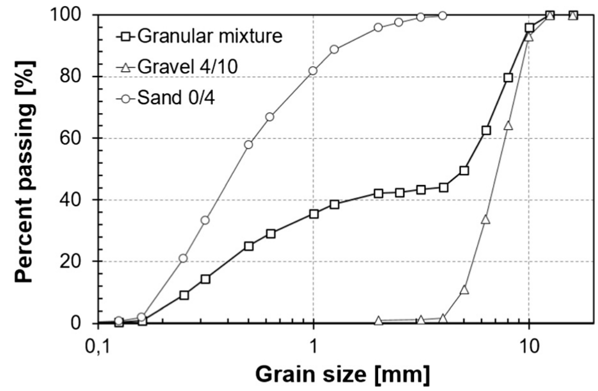

Fig. 1. Grain size distribution of the aggregates.

An alluvial quartz sand with a grain size of 0/4 mm was used. This sand presents a density of 2.69 $g.m^{-3}$, an absorption coefficient of 0.3% and a fineness modulus of 2.10. In addition, a crushed washed gravel with a grain size of 4/10 mm was used to manufacture concretes. This material has a density of 2.64 $g.cm^{-3}$ and an absorption coefficient of 1.3%. These aggregates are in accordance with the French standard NF P 18-545. The particle size distribution of these two aggregates are provided in Fig. 1.

Flax fibers used herein were harvested in Normandy (France) in 2014, cut at a constant length of 12, 24 or 36 mm and provided by Vandecandelaere Company (Depestele Group), specialized in flax farming and scutching. A flax fiber can be described as a 10–20 μm wide cylindrical composite with concentric cell walls which differ in terms of chemical composition and morphology [22]. The thickest cell wall is itself made of cellulose microfibrils, embedded in a polysaccharidic matrix and laying at about 10° from the fiber axis [23]. The high volume fraction of cellulose (about 70% [23–25]) confers to the flax fiber good tensile properties. The diameter and the cross section varies all along the fiber length, which explains the great variability of the properties of the flax fibers.

The physical and mechanical properties of flax fibers are provided in Table 1. The measurement of flax fiber real density was conducted using a helium pycnometer; six samples have been tested. The mechanical tests were performed on 50 samples of elementary fibers, using the protocol described in the French standard NF T25-501-2. The test was performed with an Instron 5566 equipped with a 10 N capacity load, at a crosshead displacement rate of 1 $mm.min^{-1}$ and a gage length of 10 mm. The diameter of flax fibers was measured using an optical microscope in six different points distributed over the length of the 10-mm gage, on 103 samples.

2.2. Mix design

2.2.1. Optimization of the granular skeleton

The concrete mix design was based on the optimization of the granular compactness, which allows adjusting the proportion of each aggregate as desired. In compact concretes (ordinary and self-compacting), the objective is to minimize the intergranular porosity in order to minimize the amount of binder required.

In the actual case, the proportions were selected after the study of the granular compactness in order to obtain a dense granular skeleton. The compactness is a parameter related to the shape and size of the aggregates and corresponds to the ratio of the volume of grains by the total volume [26]. The compactness of the