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Mechanical and thermal properties of an innovative bio based concrete

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Abstract. Generally, bio-based concrete is applied as non-load-bearing insulation. In this work, an innovative material, considered a load-bearing bio based concrete, was developed. Rapeseed concrete is primarily composed of rapeseed straw, with the addition of gravel, sand, and cement-based binders. The formulation of BIP requires the preparation of rapeseed straws, which is called the "inerting" of the straws. It consists of coating the straws with a layer of binders in order to protect the pores of the straws from the destruction of other, more rigid materials. Also protects the hydration of the binders, particularly cement, from the sugars and soluble matters that exist in the rapeseed straws and that are easily released upon contact with water. The mechanical and thermal performances of this novel material are characterized according to its density and by using two different sizes of rapeseed straw. According to the results, the thermal conductivity of these concretes ranges from 0.2 to 0.48 W.m⁻¹.K⁻¹. This concrete has compressive strengths ranging from 2 to 7 MPa and densities ranging from 1150 to 1500 kg/m³, proving that BIP can be used as an insulating, load-bearing bio-based concrete.

Keywords: rapeseed concrete, mechanical strength, bio based concrete, thermal conductivity.

1 Introduction

In France, the building and residential sector is responsible for 45% of energy consumption and 26% of greenhouse gas emissions[1]. Bio-based materials, such as those derived from rapeseed straw, are viewed as a promising solution in the construction industry due to their low thermal conductivity, relatively high specific capacity, and ability to regulate temperature and humidity in enclosed spaces, thereby decreasing the energy consumption of buildings [2,3]. Their transportation and its effect on their carbon footprint is also a significant aspect[4]. This is why we are interested in rapeseed straw, as this bio-based material is readily available throughout France and in practically all regions. In addition, this plant is planted year, ensuring a consistent, local, and speedy supply. After processing, the plant can yield powders, fibers, or aggregates, which can be utilized as insulation or in the composition of bio-sourced concrete by combining the plant with a binder, water, and occasionally additives. These concretes

can also contribute to the improvement of the acoustic comfort of dwellings [5], as well as provide outstanding thermal insulation [6] and hygric performance [7]. However, their primary weakness is their low mechanical performance [8]. Certain elements play a significant influence in determining the qualities of bio-based materials, including the kind of binder, the size of aggregates, the compaction energy, the molding method, and the manufacturing process [9,10]. Due to the plant aggregates, their high porosity, and, of course, their low density, bio-sourced concretes are often lightweight and, through their thermal efficiency, contribute to energy savings.

Rapeseed concretes are part of the family of bio-sourced concretes, which allow for the combination of agro-resources, renewable raw materials, and CO₂ storage, with a binder that has, if possible, a low environmental impact. In order to achieve this goal, load-bearing insulating concrete (BIP), a novel material that combines rapeseed straw with standard concrete components, was developed. Its goal is to increase the concrete's thermal resistance while preserving its good mechanical strength. These results enable the properties of rapeseed straw and its aggregates to be optimized in order to enhance the performance of rapeseed straw concrete.

2 Materials and methodology

2.1 Rape straws

The rapeseed straws used in the study were sourced from the French regions of Somme and Marne and harvested in 2015 and 2016. They were processed by external providers who crushed the straws into various sizes (0.25-20 mm and 0.25-10 mm) using the shearing method. This resulted in 6 different aggregate lots, each identified by the name and year of the harvest region (e.g. Marne 2015 or M15), and the size of the grind (e.g. S16-10 for Somme straw harvested in 2016 and crushed to 10mm)

2.2 Rape straw concrete: BIP (Load-bearing insulating concrete)

The formulation of the BIP is done in two phases. The first phase is the inerting of the rape straw, this step consists in coating the rape straw with a layer of binder in order to protect the pores of the rape straw from destruction during the mixing with other more rigid materials (gravel). The inerting prevents the problems of lack of hydration of the binders, especially the cement binders, due to the intervention of sugars and soluble materials that exist in the rape straw and are easily released when in contact with water. The inerted straws are stored for a minimum period of two weeks before their use for the manufacture of BIP. Table 1 shows the quantities of binder and water used to elaborate the inerting of 200 L of rapeseed straw.

Table 1. Composition of the inerting

Rape straw	Pre-molding Water	Binder	Molding Water
200 L	5 L	12 kg	13 L

Step 2 consists of the final production of the load-bearing insulating concrete. The inert straws are placed in a 20 liter mixer, with the gravel, sand and pre-mixing with a premolding water for 2 min. After that, we add the binders and the final water and mixing lasts for 5 min. The samples are made with several different densities, this density is controlled by the initial settling during the casting of the samples. Table 2 shows the composition of the formulation of the insulating load-bearing concretes.

Table 2. Volume percentage of BIP composition.

Inerted rape straw	$62 \pm 5 \%$
CEM I	$16 \pm 3 \%$
Lime	$5 \pm 2 \%$
Sand	5 %
Gravel	11 %
Water/binder	0,4-0,6

2.3 Mechanical compression test

The compressive strength of rapeseed concrete were studied to differentiate the effect of the type and size of rapeseed straw on the compressive strength, as well as the density of the samples. The compression testing machine (hydraulic servo drive) was used to perform the compressive strength test after 28 days of curing on 15 cm x 15 cm x 15 cm samples with a displacement speed of 0.02 mm/s. Compressive strength tests are performed in accordance with NF EN 12390-2 [11] and NF EN 196-1 [12]. The strength of the cubic samples was calculated by averaging the results of three samples. Figure 1 shows the mechanical test samples of BIP made with rape straws.



Figure1. Mechanical sample of load-bearing insulating concrete made with rape straws (BIP).

2.4 Thermal conductivity test

The thermal conductivity of building materials is determined through thermal conductivity tests, which assess a material's ability to transfer heat under specific temperature and equilibrium conditions. The conductivity of rape-seed concrete was measured using the guarded hot plate method and conformed to standards NF EN 12667 [13] and NF EN 12664 [14]. Samples size is 25 cm x 25 cm x 8 cm, were cured for 30 days, pre-dried at 70°C, and left in an air-conditioned room at 25°C until they reached equilibrium. During testing, the hot and cold plates were set to average temperatures of 10°C, and a thermocouple was placed between the overlapping sample surfaces to prevent any contact resistance.

3 Results

3.1 Mechanical compression behavior

Figure 2 shows the behavior of rapeseed bearing insulating concretes as a function of deformation, using two different sizes of rapeseed straws, 0.25- 10 cm and 0.25- 20 cm. Regarding bio-based materials, the size of the straw plays an important role on the compressive strength of concrete [8]. In a previous study, on a non-bearing insulating concrete made of rapeseed, it's shows that the size of the straws is directly related to the compressive strength, since the latter increases with the size of the straws[15].

In this study, the influence of aggregate size on mechanical performance is less significant than in previous studies, but using larger aggregates still results in better mechanical capacity. The use of 20 mm sized aggregates improves cohesion among different materials. The BIP M20 has a compressive strength of 4.3 MPa, the average density of the samples is 1479 Kg/m³. While the compressive strength of BIP S20 concrete is 3.5 MPa, the average density of the samples is 1360 kg/m³. This great difference is due to the difference in the density of the samples. While the BIP made with the 10 mm straws

have a compressive strength of about 3.2 - 3.7 MPa, and their density is 1282-1320 kg/m³. Regarding to the results, the size of the straws affects the plastic part of the concrete (Figure 2). It can be noticed that the concrete made with 20 mm straws has a higher plasticity behavior than the concrete made with 10 mm straws. In this study, the improved plasticity of the load-bearing insulating concrete with 20mm sized rapeseed straw is attributed to the tight coating of the straw, forming a barrier against cracks in the binder matrix.

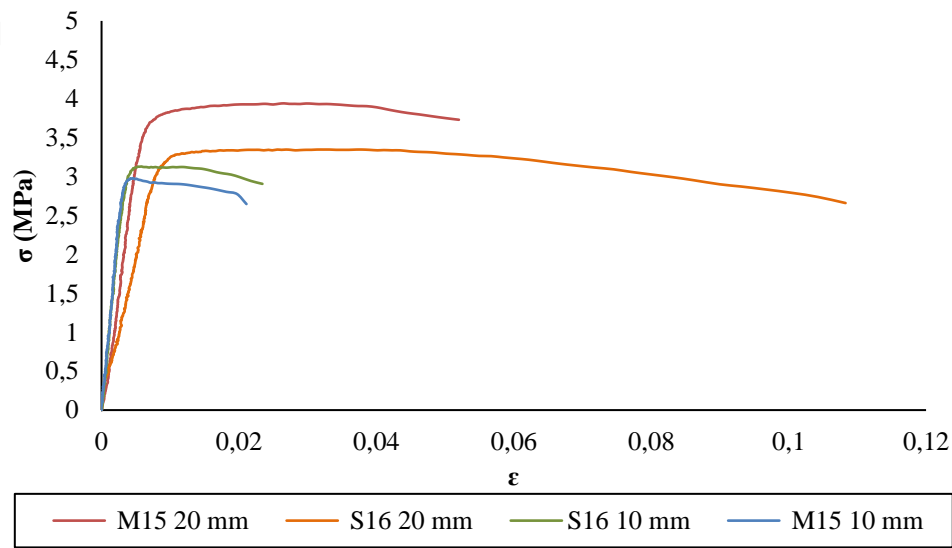


Figure 2. Mechanical compressive strength as a function of deformation of the load-bearing insulating concrete using two sizes of straw.

3.2 Thermal conductivity

Table 3 shows the values of the BIP thermal conductivity as a function of the type of aggregate and its dry density. The thermal conductivities of these materials range from 0.208 W.m⁻¹.K⁻¹ to 0.445 W.m⁻¹.K⁻¹ depending on their apparent densities. BIP is a complex material due to two factors; firstly, the effect of the binder layer with a bond on the rape straws can decrease the thermal performance of these materials. And also the effect of integrating several raw materials makes this concrete very heterogeneous, hence the difficulty in understanding its microstructure and generalizing it.

Table 3. Thermal conductivity of different rape straw concrete in function of the dry density.

	Dry density (Kg/m ³)	Thermal conductivity (W.m ⁻¹ .K ⁻¹)
M15 - 20	1796	0,363
S 16 - 20	1763	0,307
M15 - 10	1627	0,258
S 16 - 10	1683	0,258
M 15 - 20	1804	0,449
M15 - 10	1500	0,208
S16 - 20	1339	0,429
M15 - 20	1299	0,419

Figure 3 shows the thermal conductivity of BIP with 10 mm and 20mm straws, it is clear that the aggregate size plays a very important role in the thermal conductivity of Insulating Concrete Beams. As explained in the previous study on non-bearing insulating concrete[15], this difference is due to the rearrangement of the microstructure of these materials, particularly the pores.

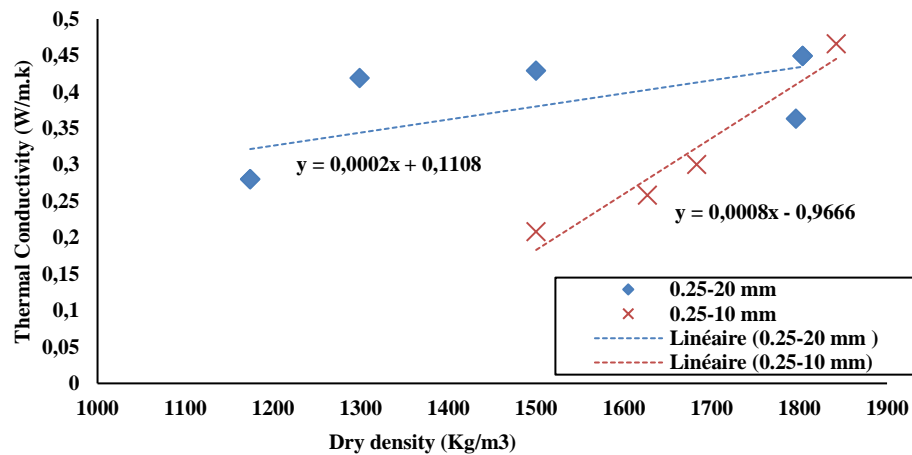


Figure 3. Thermal conductivity of BIP as a function of bulk density of samples made with 20 mm and 10 mm straws.

The Figure 3 presents the thermal conductivity of the Insulating Concrete load-bearing (BIP) based on the dry apparent volume mass of the samples. The samples studied were made with the percentage in Table 2, and straws of size 0.5-20 mm from both Marne and Somme were used. The place of harvest does not influence the thermal conductivity. The thermal conductivity of the concrete varies between 0.265 and 0.45 W.m⁻¹ K⁻¹; the difference in this conductivity is directly related to the apparent volume mass and

the size aggregate. The relationship between mass and concrete depends on each material. A literature review by Asadi [16] on the thermal conductivity of materials and its relationship with volume mass, explains that thermal conductivity is directly related to volume mass, particularly the pores or voids in the material, hence cellular concrete is considered a good insulator, as well as concrete based on plant aggregates. The equation of thermal conductivity with density found for BIP resembles to this found by Liu [17] on cellular concrete integrating geopolymers, as well as Cerezo [10] found a relationship between volume mass and thermal conductivity that is close to the equation found with the BIP samples made with the largest aggregates.

4 Conclusion

The study aimed to improve the mechanical and thermal properties of a new bio-sourced material known as load-bearing insulating concrete (BIP). It was noted that the origin and harvest year of the material did not have any effect on its mechanical and thermal behavior.

The compressive strength ranges between 3.2 MPa and 4.5 MPa, while thermal conductivity varies more greatly, due to the variation in density and aggregate size. These values range between $0.2 \text{ W.m}^{-1}.\text{K}^{-1}$ and $0.4 \text{ W.m}^{-1}.\text{K}^{-1}$ for a density between 1300 kg/m^3 and 1800 kg/m^3 . The size of the aggregates and the density of the material were considered as variables in the optimization process. The results indicated that using 20 mm aggregates provided better mechanical performance and increased plasticity before breaking, and this is due to the good cohesion achieved with the 20 mm straws compared to the breaks in the binder. While using 10 mm aggregates offered better thermal resistance at lower densities. However, when the density increased, the thermal resistance of BIP made with both aggregate sizes was found to be similar. An increase in density carries the risk of damaging the material's pores.

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