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DURABILITY STUDIES ON LIGHTWEIGHT PLASTER AND STRAW FIBER BASED MATERIAL FOR BUILDING THERMAL INSULATION

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Abstract

In this paper, the impact of freezing-thawing and wetting-drying cycles on the thermal and mechanical properties of a new straw-based composite is investigated. The material specimens used for accelerated aging were manufactured with two straw types: wheat and barley. The binder selected for the study was gypsum plaster. Only the optimized mixture was used to perform the accelerated aging tests. The durability of the insulation material was evaluated with accelerated aging through wetting-drying and freezing-thawing cycles in order to reproduce the environmental conditions of outdoor use. The non-aged specimens were characterized after constant curing conditions of temperature and humidity for one, three, and six months. Comparison of the results indicates that freezing-thawing cycles have only a slight effect on the thermo-mechanical behavior of the straw-based composite compared with drying-wetting cycles.

Keywords:

Gypsum plaster; straw; thermal conductivity; freezing; aging; mechanical behavior

1 INTRODUCTION

The growing need to reduce energy consumption in the building sector has prompted scientists and engineers to find materials that both during the manufacturing process and during their lifetime are low cost and have a low energy consumption [Pacheco 2014]. A large number of materials based on natural fibers have therefore been proposed for different applications [Tonoli 2011], [Ramli 2013], [Ali 2013] and more particularly for building thermal insulation [Ashour 2010] [Millogo 2014]. There is a wide variety of natural fibers (flax, straw, hemp, etc.) which can be applied as reinforcements of soil, lime or gypsum plaster matrices. Their low density, low cost, flexural capacity, high porosity, availability and recyclability make them attractive for environmental and ecological considerations. Although there have been considerable developments in the manufacture of these materials for different parts of the building, their long-term performance is still far from demonstrated. Building materials are exposed to changing climate conditions and aggressive environments that are generally responsible for their degradation by interaction with microstructural phenomena. The long-term behavior and durability of these materials are therefore critical if they are to meet the technical and safety criteria of structural use. In order to study the durability of natural fiber based composites and understand the interactions between material microstructure and environmental conditions, accelerated aging conditions are generally used in the laboratory to simulate long-term exposure to variations in the environmental conditions, for example [Toledo 2009]; [Yun 2011] and [Wei 2014]. In this context, one of the major objectives of the scientific project PROMETHE is to study the durability of thermal insulation material using accelerated aging tests. The project, funded by the Region centre (France), focuses on the development of materials with a low environmental impact based on cereal straw for the thermal renovation of existing buildings. The project also aims to exploit this fiber which is an abundant residue of cereal production in the region.

This paper presents a laboratory investigation of the effect of accelerated aging on the properties and performance of plaster-reinforced straw fiber. The composite specimens were prepared at a water-binder and fiber-binder ratio defined in a formulation stage for optimal thermal performance. The specimens were cured for three periods (1, 3, 6 months) and exposed to accelerated wetting-drying and freezing-thawing cycles. The mechanical and thermal characterization was performed after aging cycles. The results show a significant effect of aging cycles on the material behavior with substantial variability that is one of the disadvantages of natural fibers.

2 MATERIALS AND METHODS

2.1 Materials

The use of cereal straw as fiber reinforcement is motivated in this research program by its availability in the region which is the first cereal-producing region in Europe, and its porous microstructure which offers good thermal properties for buildings. It is also an agricultural material produced in excess of requirements, so it is cheap and easily accessible. Cereal straw is generally burned or used as animal bedding to avoid storage. Thus, the use of straw fiber for manufacturing new insulation materials represents a good solution for the valorization of this residue.

Two types of straw were selected for the composite, wheat and barley fibers. Short straw fibers were used after grinding to facilitate the manufacturing process. The selection of the straw type as well as the study of the physical properties required for mix design were the subject of an experimental investigation taking into account parameters such as straw variety, plot and year of harvest [Bouasker 2014]. To prepare the samples for aging tests, the straw was crushed to respect the particle size used for physical characterization. No treatment was used on the straw fibers before mixtures.

In order to obtain good mechanical and thermal properties, simple molding, perfect coating and easy mixing, gypsum plaster was used as binder in this study. In the framework of the PROMETHE research program, other binders have been studied: lime, mixture of cement and pozzolan mixture [Belayachi 2013]. Gypsum plaster is widely used for coating walls and as a restoration material of different parts of historical buildings [Formia 2014]. It has good acoustic and thermal properties and is fire-resistant.

2.2 Composite manufacturing

All the samples for aging tests were prepared using an optimized water/binder (W/B) ratio of 1.1 and straw fiber/binder (S/B) ratio of 0.4. The manufacturing procedure and optimal formulation were initially investigated by [Belayachi 2013] in order to determine the best compromise between thermal and mechanical performance for the straw composite.

To obtain homogeneous samples the process of mixing natural fibers with gypsum plaster is different from the standard method used with mortars. The gypsum plaster used here is the commercial Dial plaster. The procedure consisted in first mixing the straw fibers with 20% of the water for 60s, followed by the addition of the mixed binder-water and mixing for 5 minutes. The binder was mixed with 80% of the water prior to addition in the mixer in order to ensure a good coating of the fibers.

Lastly, the mixture was recovered and placed in molds (300mm x 300mm x 100mm) without compaction. After 1 hour the blocks were removed from the molds and dried in a ventilated oven at 45° until a constant weight was reached. Figure 1 shows straw composite blocks.

Samples measuring (150mm x 150mm x 100mm) were prepared by cutting the blocks for aging and characterization tests. All the samples were stored in the curing chamber at 20°C.

Fig. 1: Manufacture of the composite and straw/plaster blocks.

3 EXPERIMENTAL METHODS

3.1 Accelerated aging tests

Two laboratory aging methods were used in this work, namely freezing-thawing and wetting-drying, to evaluate their effect on the straw composite properties. Accelerated aging was carried out on the blocks after 28 days in the curing room. The freezing-thawing test consisted in exposing the composite samples to temperatures between -10°C and 40°C using a climatic chamber (-12°C to 60°C). For the two wheat and barley straw composites, 5, 20 and 40 freezing-thawing cycles were carried out. Each cycle lasted 12 hours (5h: 40°C to -10°C); (3h at -10°C); (1h: -10°C to 40°C) and (3h at 40°C).

The wetting-drying test was performed on straw/plaster samples for a duration of 72 hours. In order to better reproduce natural conditions, natural drying without an oven was used. Each cycle consisted of 1h immersion in distilled water at 20°C and 71h natural drying. For comparison purposes, samples were exposed to 5, 20 and 40 wetting-drying cycles.

3.2 Mechanical and thermal characterization

As indicated in the introduction, compressive mechanical and thermal properties were used to evaluate the effect of accelerated aging on the behavior of the straw concrete. At the end of 5, 20, and 40 cycles, thermal conductivity and stress-strain response were measured. In addition, in order to evaluate the long-term behavior of the insulation material, the mechanical and thermal characterization was performed for the non-aged samples after 3 and 6 months of curing time.

A uniaxial compressive test was performed using a universal compression machine (IGM 250) in the casting direction of the material. For straw concrete, the machine was equipped with a load cell of 25 KN. Figure 2 shows the controlled displacement test, conducted at a speed of 0.5 mm/min.

Thermal characterization was performed by using the classical hot wire technique following ASTM D5930-97. The thermal conductivity-meter was a NEOTIM FP2C apparatus equipped with a hot wire probe shown in figure 3 between two straw composite samples with the same geometry.

Fig. 2: Mechanical uniaxial compression test

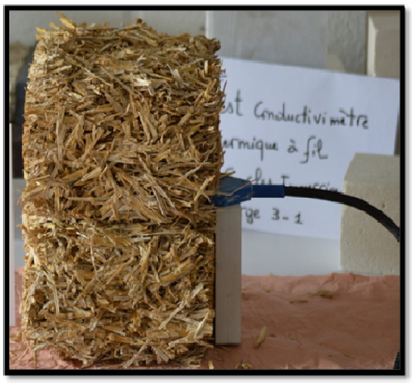

Fig. 3: Measurement of thermal conductivity

The main assumption of this method is to consider the geometry as cylindrical with one dimensional radial heat transfer and infinite length of the wire. The thermal conductivity is identified by considering the evolution of temperature as a function of the logarithm of the time.

4 RESULTS AND DISCUSSION

In order to illustrate the effect of the accelerated aging, all the results were compared with the non-aged behavior for the two composites, wheat/plaster (WP) and barley/plaster (BP). Figure 4 shows the compressive stress-strain curves of non-aged straw composites.

The comparison of the results after 1 month with those of 3 months and 6 months for BP and WP shows a completely different behavior for the two composites. For a given deformation, the stress level is higher after 3 and 6 months curing for the WP and is lower for the BP compared to the stress-strain curve at 1 month. The barley straw has a negative effect on the strength of the plaster, probably because of its very high water absorption [Bouasker 2014].

In figure 5, the stress-strain curve of non-aged composite is compared with 5, 20 and 40 freezing-thawing cycles for the WP and BP composites. It can be seen that freeze-thaw cycling has no effect on the mechanical behavior of the WP composite; the stress level is the same for the aged and non-aged material.

The samples of wheat-plaster material show a good state of preservation without loss of material pieces (Figure 6). For barley-plaster material, a decrease in stress is observed from a strain of 0.2 for the samples undergoing 20 and 40 cycles. This reduction can be explained by the porosity induced by the crystallization of water in the frozen phase or by the loss of barley fiber strength.

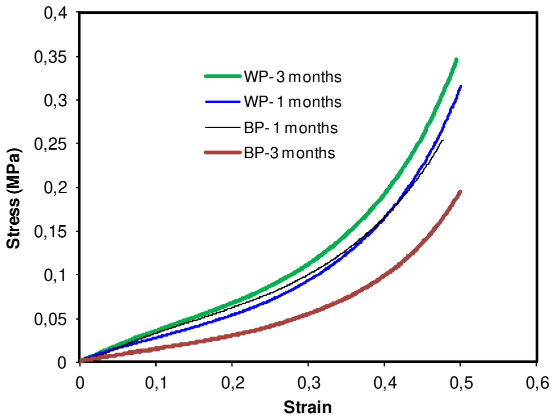

Fig. 4: Stress-strain response of the two composites after different curing times.

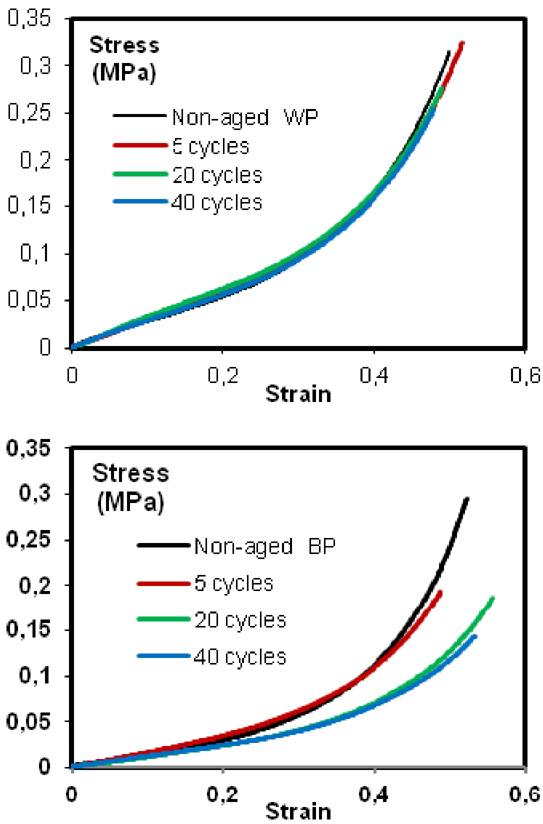

Fig. 5: Stress-strain response of the two composites after freezing-thawing cycles.

Porosity can be also increased by debonding at the straw-binder interface. Although the state of the samples shows no change (figure 6), there is an effect of the freezing-thawing conditions on the mechanical behavior of this composite.

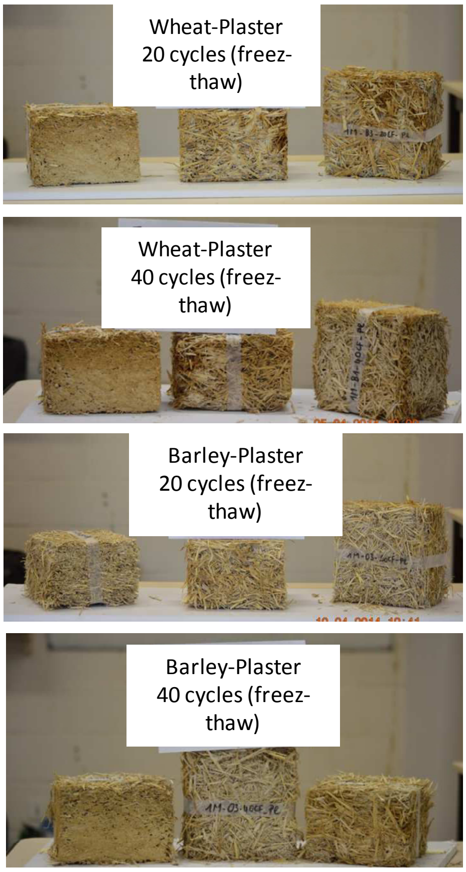

Fig. 6: Illustration of the samples state after freezing-thawing aging cycles.

Figures 7 shows the compressive behavior of the WP and BP composites after the wetting-drying cycles. We can observe the significant effect of these conditions on the mechanical behavior of the two composites. It can also be seen that from 5 cycles the behavior of the materials is the same. The greatest reduction in the stress level is between the non-aged material and the aged material after 5 cycles.

Figure 8 shows the state of samples after 35 wetting-drying cycles for barley and 40 cycles for wheat-plaster. After 35 cycles the barley-plaster samples were very weak and evidenced a substantial mass loss. We can observe leaching of the binder for the two materials with the loss of sample pieces. Because of the degraded state of the barley-plaster samples, the aging was stopped at 35 cycles, in order to perform the characterization tests.

In summary of this first part of the results, the effect of wetting-drying aging is more significant than that of freezing-thawing on the mechanical behavior of the insulation material. The wheat-based composite showed the best potential for successful implementation in building structures.

Concerning thermal conductivity, the results presented in figure 9 for different curing times show that the performance of BP after 1 month was better than that of WP, with a lower thermal conductivity value. This value increases with time, probably due to the moisture content in the material because of the highly hygroscopic nature of barley straw.

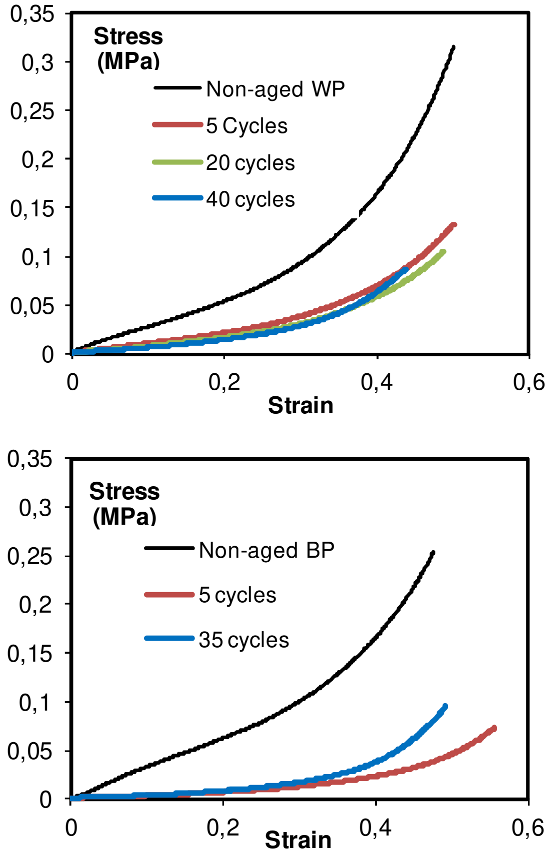

Fig. 7: The effect of wetting-drying cycles on the stress-strain response of the two composites.

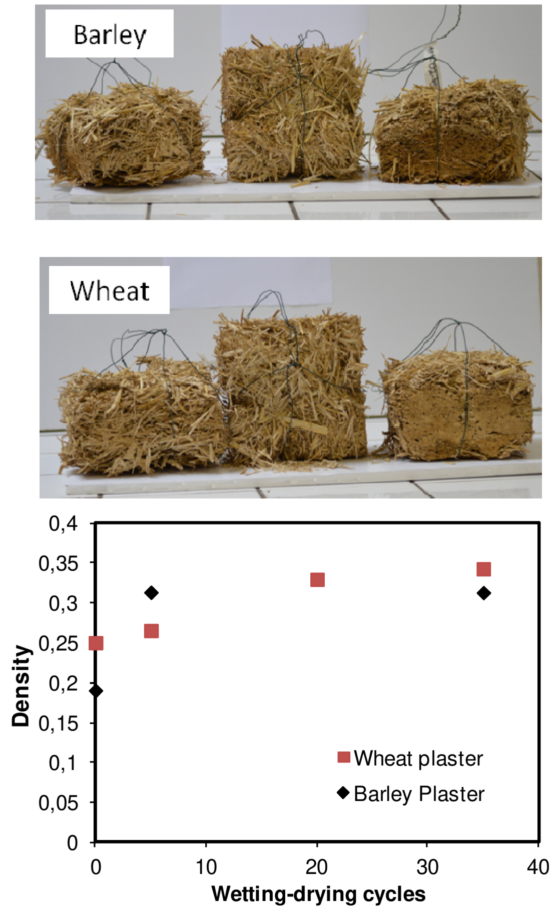

Fig. 8: Samples state after wetting-drying aging cycles for WP and BP composites and the variation of density

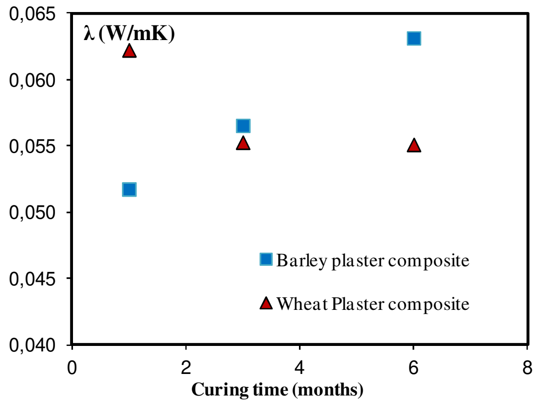

Fig. 9: The effect of wetting-drying cycles on the stress-strain response of the two composites.

The wheat plaster composite again has a better long-term thermal performance.

Thermal conductivity measured after aging cycles was compared with the non-aged material and is illustrated in figure 10. We can observe that the thermal conductivity is twice as large after 5 cycles for both materials. This value remains almost constant for the barley-based composite and is greater for wheat plaster material after 20 cycles. This increase in thermal conductivity may be due to the water content of the materials because of the natural drying process used.

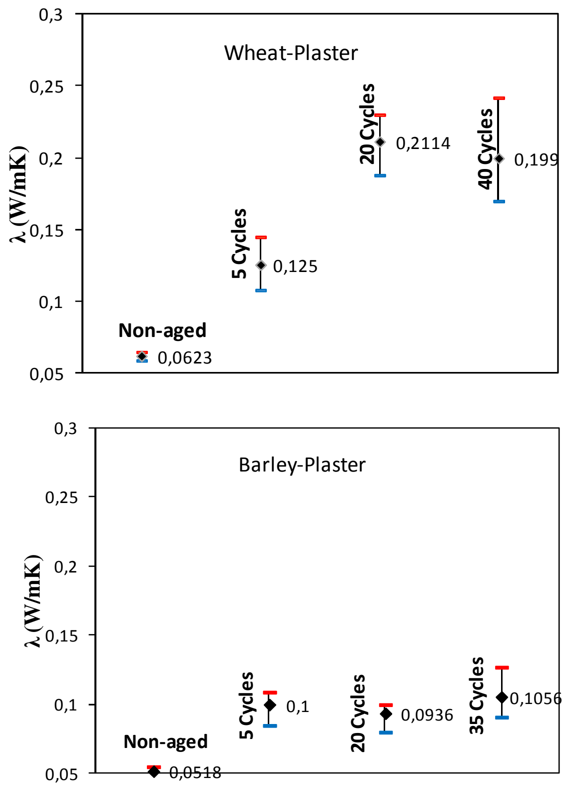

Fig. 10: The effect of wetting-drying cycles on the thermal conductivity of the two composites.

5 CONCLUSION

In this study, the effect of accelerated aging on the thermal and mechanical behavior of a new insulation material based on gypsum plaster and cereal straw has been highlighted. The durability of the material was also evaluated in order to study the properties of the material at different curing times. The results show that the freezing-thawing conditions used in this study have a slight impact on the mechanical behavior of the barley plaster composite and no effect on the behavior of wheat plaster. A significant effect was noted, however, of wetting-drying both for the barley and the wheat based composite. The thermal performance of the non-aged barley composite is more suitable for building insulation.

Based on the results of this work and the aging conditions, the wheat plaster composite has potentially a higher overall durability than the barley composite. The next step in this work will be to investigate the treatment of barley straw so as to reduce its moisture absorption and thereby enhance its performance. Considerable research efforts are necessary to establish standards to study the durability of composites based on natural fibers.

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