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Experimental study on the physical–mechanical durability of innovative hemp-based composites for the building industry

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ABSTRACT

For reducing the environmental impact of the building sector, novel sustainable composites have recently been developed, by bonding hemp hurds with a new hybrid organic–inorganic binder. These composites, designed as substitutes for traditional insulating materials or as substitutes for formaldehyde-bonded wood particle boards, exhibit very promising properties. To ensure that the panel performance is maintained during the building operation phase, durability needs to be specifically evaluated as well. Therefore, in this study three composite types with low, medium and high density (LD, MD and HD, respectively) were subjected to accelerated ageing and the alterations in their physical–mechanical properties were evaluated. Composite resistance to accelerated ageing is strongly correlated with bulk density. HD composites, the only ones actually designed to be directly exposed to rainfall, exhibited almost negligible decreases in mechanical properties and hence a substantially satisfactory behavior. MD and LD composites, designed to provide thermal insulation and hence to be sheltered by HD panels, were affected to a larger extent by accelerated ageing, which however was definitely more severe than the real exposure conditions of the composites during their service life. Further studies are currently in progress to optimize the composites formulation and physical–mechanical durability.

1. Introduction

In developed countries, the energy consumption in the building sector accounts for about 20–40% of the total energy use, thus exceeding industry and transport, and it is predicted to significantly increase in the future [1]. Such an enormous energy consumption makes the development of innovative strategies for energy efficiency a priority in the building sector. Two main strategies have been followed: (i) reducing energy consumption during the building *service life*, for instance by adopting the “Zero Energy Building” approach [2]; (ii) reducing energy consumption also in the building *pre-service life*, including raw materials extraction and manufacturing [3], for instance by developing new building materials based on renewable resources (such as hemp) and/or involving less energy-consuming manufacturing processes [4–7].

Following this latter approach, novel sustainable composites for the building industry have recently been proposed by the authors [8–10]. These composites, obtained by bonding hemp hurds with a new hybrid organic–inorganic binder [10], were designed for different applications:

- low density composites (LD, 330 kg/m^3, thickness 50 mm) were developed for building thermal insulation, as substitutes for traditional materials such as glass/rock wool, extruded/expanded polystyrene or polyurethane foam;
- medium density (MD, 640 kg/m^3, thickness 30 mm) and high density composites (HD, 1210 kg/m^3, thickness 10 mm) were developed for substitution of formaldehyde-bonded wood particle boards (currently used in the building and furniture industry), for creation of exterior insulation and finishing systems and to be used as structural walls for one-storey social housing in developing countries.

With respect to alternative traditional materials, the new composites exhibit: (i) a better environmental impact (both in the manufacturing and disposal phase) and a lower production cost,

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thanks to renewability of hemp hurds and the vegetable fraction of the binder; on the contrary, traditional insulating materials (such as extruded/expanded polystyrene, glass/rock wool and polyurethane foam) require petroleum-derived raw materials, high processing temperatures and/or cannot be recycled [11,12]; (ii) a better impact on human health, as they are free from any toxic organic binder (such as formaldehyde), unlike building materials such as mineral wool and wood particle boards [13,14].

The new composites also exhibit very promising thermal, physical and mechanical properties [10], comparable to those of hemp-based composites bonded with cement [15] and in some cases even superior to those of alternative natural fiber-based products available in the market [16,17]:

- LD composites have a low thermal conductivity ($\lambda = 0.078$ W/m K, in line with values reported for composites of similar density based on wood wool, wood fibers and wood chips [16]), a quite good reaction to fire (class "C–s2–d0") and relatively good mechanical properties (flexural strength ~1 MPa). For comparison's sake, commercial cement-bonded wood wool composites with comparable bulk density (360 kg/m^3) exhibit slightly lower thermal conductivity ($\lambda = 0.063$ W/m K) but about half as much flexural strength (~0.5 MPa) [17].
- MD and HD composites, although having a higher thermal conductivity ($\lambda = 0.138$ W/m K for MD), are characterized by very good reaction to fire (class "B–s2–d0" for MD, at least the same class for HD) and mechanical properties (flexural strength ~7 MPa for MD and ~16 MPa for HD) [10]. For comparison's sake, commercial cement-bonded wood chipboards with 1000 kg/m^3 bulk density exhibit flexural strength ~9 MPa [17].

The above-reported characteristics make the novel composites highly promising for substituting commonly used materials with higher environmental impact. In particular, among other applications, the possible use of the new composites for creating a multi-layer wall plug for concrete, steel or wood structures (where the inner LD layers provide thermal insulation and the external MD/HD layers provide resistance against physical–mechanical actions and protection against fire) has been proposed [10].

In any case, before the composites can be introduced into the market and actually employed in buildings, their durability needs to be specifically evaluated, to ensure that the panel performance is maintained during the building service life. Durability actually involves resistance to a multitude of weathering factors that may threaten the panel performance, e.g. moisture, freeze–thaw or bio-organisms. Which weathering factors may be active in a specific situation actually depends on the panel operation conditions (indoor/outdoor, possible exposure to direct rainfall, possible contact with the ground, possible presence of rendering layers, etc.), which, in turn, depend on the panel function.

As a first step towards a 360-degree assessment of the new composites durability during their service life, in this paper the resistance against water-related deterioration was experimentally evaluated, by determining the alterations in physical–mechanical properties after accelerated ageing. In the lack of an international standard describing a specific accelerated weathering method for hemp-based panels, the European Standard for wood-based panels EN 321 [18] was followed. The weathering conditions involved by this standard (i.e. cycles of immersion in water, freezing and thawing) can be considered as definitely severe, because it is extremely unlikely that, in their service life, the new composites will be subject to complete saturation with water. Indeed, the multi-layer wall plug made of hemp-based panels (similarly to wall plugs made of wood-based panels, currently available in the market) is designed to be protected from rising damp from the ground (by using an impermeable basement element), so that the only direct source of liquid water is expected to be rainfall. However, among the different composite types, the only panels that are expected to be subjected to direct contact with rainfall are HD panels, designed as the external layer of the multi-layer wall plug, over which also a traditional rendering layer may be present.

Consequently, the weathering conditions adopted in this study are actually relevant *only* for HD composites. On the contrary, in the case of MD and LD composites, the investigated weathering conditions are *not* representative of the real conditions that the composites will have to face in their service life. Different deterioration processes (such as fungi growth, possibly favored by interstitial humidity condensation) are expected to be more relevant for these kinds of composites. However, investigating how does mechanical resistance to accelerated ageing change as a function of the composite physical–microstructural properties is very interesting from a materials science point of view, hence also MD and LD composites were subjected to the same weathering tests, although not representative of the composites exposure conditions during their service life. Additional tests to evaluate the composite resistance against bio-deterioration (fungi, termites, etc.) will be addressed in future steps of research. Anyway, considering the basic environment of the composites (as detailed later in the paper), a good durability to bio-deterioration is expected.

2. Materials and methods

2.1. Hemp-based composites

Three composite types with low, medium and high bulk density (LD, MD and HD, respectively) were produced according to the procedure described in detail in [10]. In brief, the composites were obtained by bonding hemp hurds with a novel hybrid organic–inorganic binder, comprising a vegetable fraction and a magnesium-based mineral fraction [10]. For each composite, the hemp hurds size, the binder/hemp hurds ratio and the press compression ratio are reported in Table 1. Notably, with respect to MD and LD composites, HD panels were obtained by using hemp hurds with smaller size (length 2–5 mm instead of 10–30 mm, diameter 1–2 mm instead of 2–6 mm) and by adopting a lower binder/hemp hurds ratio (1:1.25 instead of 1:1). At the end of the manufacturing process, involving hot pressing at 80 °C for 3 min, panels with 150 × 50 cm^2 dimensions and thickness (t) ranging from 10 to 50 mm (depending on composite type, Table 1) were obtained. These panels were then sawn to obtain specimens for the different physical–mechanical tests performed to assess the composite durability. In particular, composite characteristics were determined before and after exposure to accelerated ageing, carried out as described in the following paragraph.

Table 1
Characteristics and manufacturing parameters of the investigated hemp-based composites.

	Low density (LD)	Medium density (MD)	High density (HD)
Density [kg/m^3]	330	640	1210
Thickness (t) [mm]	50	30	10
Hemp hurds length [mm]	10–30	10–30	2–5
Hemp hurds diameter [mm]	2–6	2–6	1–2
Binder/hemp hurds ratio [wt./wt.]	1:1	1:1	1:1.25
Compression ratio	1:1.7	1:3.3	1:4