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# Novel sustainable hemp-based composites for application in the building industry: Physical, thermal and mechanical characterization

Enrico Sassoni [a,b,*], Stefania Manzi [a,c], Antonio Motori [a,b], Matteo Montecchi [d], Max Canti [e]

[a] Department of Civil, Chemical, Environmental and Materials Engineering (DICAM), University of Bologna, via Terracini 28, Bologna 40131, Italy
[b] Centro Interdipartimentale di Ricerca Industriale (CIRI) Edilizia e Costruzioni University of Bologna, via Lazzaretto 15/5, Bologna 40131, Italy
[c] Centro Interdipartimentale di Ricerca Industriale (CIRI) Meccanica Avanzata e Materiali University of Bologna, Viale Risorgimento 2, Bologna 40136, Italy
[d] CMF TECHNOLOGY S.P.A., Via Bottegone 73, Pavullo nel Frignano (Modena) 41026, Italy
[e] C.M.F. GreenTech, Via Di Vittorio 423/A, Cavezzo (Modena) 41032, Italy

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ABSTRACT

In this study, novel hemp-based composite materials, designed for building application as components of a multi-layer wall plug for concrete, steel or wood structures, providing both thermal insulation and physical–mechanical resistance, are presented and characterized. Composite panels were produced by bonding hemp hurds with a novel hybrid organic–inorganic binder. The panels were then characterized in terms of physical–microstructural properties (bulk density, water absorption, swelling in thickness and weight loss after immersion in water, microstructural features by means of scanning electron microscope and stereo optical microscope observation), thermal properties (thermal conductivity, reaction to fire) and mechanical properties (compressive strength, flexural strength, tensile strength, resistance to axial withdrawal of screws). The panels exhibited promising physical, thermal and mechanical characteristics, generally comparable to those of commercially available products. In addition, the novel composites have the advantage of a significantly low environmental impact (thanks to the nature of both the dispersed and the binding phase) and no negative effects on human health (contrary to many commercial materials, responsible for emission of formaldehyde). All things considered, the novel composites seem like very promising materials for application in the building industry. Further tests to assess the physical–mechanical durability of the panels are currently in progress.



## 1. Introduction

Because of the strong impact of the building industry onto the environment, developing new materials with a reduced environmental impact has become a very important and urgent issue [1]. A possible strategy is reducing the use of not renewable resources. For instance, in the case of structural concrete, recycled aggregates from construction and demolition waste have been investigated as possible substitutes for natural aggregates [2]. In the case of composite materials used for building thermal insulation, the possible substitution of inorganic mineral fibers with natural ones from agricultural resources is one of the studied routes [3,4].

Indeed, traditional materials used for building thermal insulation, e.g. glass/rock wool, extruded/expanded polystyrene, polyurethane foam, exhibit significant limitations with regard to their environmental impact, both in the production phase and in the waste disposal phase. These materials require petroleum-derived raw materials (e.g., extruded/expanded polystyrene) and/or very high processing temperatures (e.g., glass/rock wool) and in many cases they cannot be recycled (e.g., polyurethane foam) [5,6]. Consequently, in recent years possible alternative materials with enhanced environmental sustainability have been investigated. Composites containing natural fibers from agricultural resources (e.g., jute, flax, hemp, cotton, cellulose) have been extensively studied, as natural fibers exhibit several positive characteristics: low thermal conductivity, low density, good specific tensile properties [3,7,8]. Moreover, natural fibers are obtained from renewable resources, which makes the environmental impact of natural fiber-based composites sensibly lower than that of traditional insulating materials [3,5].

Among others, hemp (*Cannabis sativa*) has received a lot of attention because of its good thermal insulation properties, good mechanical properties, rapid growing (only 3.5 months), high dry biomass production (4–5 times higher than that produced by a forest of the same extension in one year) and high carbon storage potential [9,10]. Because of the above described characteristics,

* Corresponding author. Tel.: +39 051 2090363; fax: +39 051 2090322.
*E-mail address:* enrico.sassoni2@unibo.it (E. Sassoni).

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several studies [7,9–12] have investigated the insulating properties of hemp fibers and hemp hurds (i.e. the non-fibrous fraction), bonded by either organic or inorganic binders, and several hemp-based products, in the form of flexible mats and boards, have recently been introduced in the market. The environmental benefits of hemp-based composites for building thermal insulation, in place of traditional materials such as rock wool, have been quantitatively assessed by Life Cycle Assessment (LCA) [10]. Moreover, hemp is currently used to create the so-called "hemp concrete" (i.e., a mix of hemp particles, lime, water and, in some cases, sand), utilized for wall infilling, floor and roof insulation and insulating plasters and renders [13]. While hemp concrete is used for its thermal insulating ability and not for bearing loads, the possible exploitation of hemp fibers tensile strength was investigated as well, with the aim of developing hemp fiber-reinforced concretes [14] and pozzolanic matrix-hemp fiber composites for structural retrofit applications [15].

In this paper, novel hemp-based composite materials for application in the building industry are presented and the results of a preliminary physical, thermal and mechanical characterization are reported and discussed. The composites were obtained by bonding hemp hurds with a new hybrid organic-inorganic binder, based on magnesium oxide and a reactive vegetable protein, in the form of a flour. Five composite types, with density ranging from about 300 to 1300 kg/m$^3$, were produced: low density panels were designed for building thermal insulation, while medium and high density panels were designed as possible substitutes for formaldehyde-bonded wood particle boards, used in the building and furniture industry. In addition to the cited general uses, the new composites were specifically developed for creating a multi-layer wall, to be used as a wall plug for concrete, steel or wood structures: the inner, lower density layers are expected to provide thermal insulation and the external, higher density layers are expected to provide resistance against physical–mechanical actions, as well as protection against fire.

Compared to traditional materials used in the building and furniture industry, the new composites are expected to have:

(1) a better environmental impact, both in the production and disposal phases. Indeed, the hemp hurds used as the dispersed phase and the vegetable protein used for the binding phase are obtained from renewable resources, while production of magnesium oxide requires lower temperature than production of other inorganic binders (e.g., lime or cement). As for the end-of-life disposal, the hemp-based panels are completely recyclable, as they can be ground to powder and used for production of new panels, by mixing with the binder and some new hemp hurds.
(2) a better impact on human health, as they are free from any toxic organic binder, such as formaldehyde; the latter, classified as "carcinogenic to humans", can in fact be emitted in the indoor environment by formaldehyde-bonded building materials, such as mineral wool and wood particle boards [16,17]; on the contrary, the newly developed composites will be entirely formaldehyde-free.
(3) a remarkably lower production cost, thanks to the low-cost and renewability of the raw materials from agricultural resources and to the low processing temperature for magnesium oxide production. This aspect makes the novel hemp-based panels highly competitive from an economic point of view and particularly suitable for low-cost buildings construction, especially in developing countries.

Therefore, considering the promising properties of the new composites in terms of environmental sustainability, impact on human health and economic competitiveness, this paper focuses on the physical, thermal and mechanical properties of the new composites.

## 2. Materials and methods

### 2.1. Samples

Five composite types were studied, as detailed in Table 1. Low density (LD) and medium density (MD) composites were produced by using coarse hemp hurds (about 10–30 mm in length and 2–6 mm in diameter), while high density composites (HD-1, HD-2 and HD-3) were produced by using thin hemp hurds (about 2–5 mm in length and 1–2 mm in diameter). For all the composite types, hemp hurds were bonded by means of a new hybrid organic–inorganic binder, currently under patent [18]. The binder is based on magnesium oxide, which reacts when an aqueous magnesium sulfate solution is added, and a reactive vegetable protein. For composite production, magnesium oxide was mixed with water, then the vegetable protein, in the form of a flour, and the magnesium sulfate solution were added. Suitably pre-treated hemp hurds were then added to the so-prepared binder and then mixed at 80 r.p.m. for 3 min. In total, the addition of the various components and mixing lasted 10 min. As reported in Table 1, the binder/hemp hurds ratio differed as a function of composite density, ranging from 1:1 to 1:5. The fresh binder/hemp hurds mix was then poured into a $150 \times 50 \times 5$ cm$^3$ wood frame; the frame was then removed and the fresh composite was pre-heated at 80 °C in a micro-wave unit for 3 min, to allow for uniform heating all through the panel thickness. Finally, the composite was pressed at a temperature of 80 °C for 3 min, the compression ratio (i.e., the ratio between the final and the initial thickness of the panel) varying as a function of composite density, as specified in Table 1. At the end of the process, panels having $150 \times 50$ cm$^2$ dimensions and thickness ($t$) ranging from 1 to 5 cm, as a function of composite density (Table 1), were obtained. The final appearance of the five composites is illustrated in Fig. 1. To perform the characterization tests described in the following, specimens with suitable dimensions were obtained from the panels by sawing or, in the case of fire reaction test, by assembling two panels.

### 2.2. Characterization techniques

#### 2.2.1. Physical–microstructural properties

*2.2.1.1. Bulk density.* Bulk density ($\rho$) was measured on the same samples used for the physical–mechanical tests, as the average for at least 15 specimens. According to European standard EN 1602 [19], the bulk density was calculated as the ratio of sample weight

**Table 1**
Nominal characteristics of the five composite types and corresponding technological parameters.

| Sample | Label | Nominal density [kg/m$^3$] | Nominal thickness [mm] | Binder/hemp hurds ratio [wt./wt.] | Compression ratio |
|---|---|---|---|---|---|
| Low density | LD | 300 | 50 | 1:1 | 1:1.7 |
| Medium density | MD | 600 | 30 | 1:1 | 1:3.3 |
| High density-1 | HD-1 | 1100 | 10 | 1:1 | 1:4 |
| High density-2 | HD-2 | 1200 | 10 | 1:1.25 | 1:4 |
| High density-3 | HD-3 | 1300 | 10 | 1:1.50 | 1:4 |