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Natural fiber nonwoven reinforced cement composites as sustainable materials for building envelopes

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HIGHLIGHTS

- Mechanical performance and durability of OPC/flax nonwovens composites for façade pieces is explored.
- The effect of two pozzolanic additions combined with nonwoven treatment is evaluated.
- Significant improvements in the durability using treated nonwovens.

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ABSTRACT

This experimental research analyzes the mechanical performance and durability of façade pieces based on Portland cement matrix and flax nonwovens as reinforcement. Two types of pozzolanic additions (silica fume and metakaolin) combined with nonwovens subjected to different treatments to decrease their water absorption are analyzed as potential materials for fiber-cement sheets for building envelopes with high strength and durability. For this purpose, on the one hand, the mechanical performance and chemical composition of various ternary compositions were studied. On the other hand, various treatments were performed on the nonwovens and the nonwoven–matrix adherence was also analyzed. Finally, composites were prepared from some selected treated nonwovens and matrix mixtures, and their mechanical properties and durability were evaluated under four-point bending tests after 28 days of curing in a humidity chamber and after accelerated aging. The composites developed with the treated nonwovens presented very high performance combined with enough durability to be potential candidates for the development of sustainable materials for building envelopes.

1. Introduction

It is widely known that the rising carbon dioxide level in the atmosphere is causing an increase of the global temperature of the earth that demands an urgent global response. In this sense, the atmospheric concentration of CO_2 has increased from a pre-industrial concentration of about 280 ppm to around 390 ppm at present. Although the Stern review advises that the CO_2e should be stabilized between 450 and 550 ppm to avoid the worst impacts of climate change, global emissions have grown at a rate of 3.7% during recent years [1].

Approximately 50% of these emissions are produced by the building sector, during both the construction and the operational phase of buildings. The building sector is responsible for about 40% of the European Union total final energy consumption and 36% of its total CO_2 emissions [2]. Innovations to improve the energy efficiency of buildings are thus of practical importance.

To reduce CO_2 emissions, the involvement of the construction sector is necessary in all possible areas, that is to say, both during the operational lifetime, which accounts for over 80% of the gas emissions, and during the manufacture and transport of materials, construction, maintenance, and demolition, which generally account for 10–20% of the energy consumption [3].

With respect to the manufacture of the materials, the use of more environmentally friendly materials obtained from renewable sources with sustainable processes could be an interesting solution for the reduction of CO_2 emissions [4].

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Concerning the lifetime use of the building, the design of new construction solutions combined with adequate energy consumption management can lead to a significant reduction of the energy expenditure for lighting and air conditioning. More concretely, the construction solution known as the "ventilated façade" system has experienced a significant increase in use in Europe, especially the Mediterranean countries, due to both its good performance and its ease of construction and in both new buildings, especially offices and residences, and the rehabilitation of buildings [5].

Ventilated façades are multi-layered building envelopes consisting of an outer layer mechanically connected to an inner layer and a ventilated air gap that usually contains thermal insulation in contact with the inner layer. Each of the layers has a specific function, as can be seen in Fig. 1. The provision of an external discontinuous protective envelope, separated from the insulation layer, allows air ventilation and prevents heating by direct sunlight or by transmission through the coating layer surface, thus improving the internal comfort of the building, especially in hot climates with intense solar radiation. This outer envelope, apart from its aesthetic function, should protect against heat radiation, rain, and wind and should form an air chamber. So, the material used for this outer layer has to fulfill certain requirements such as strength, flexibility, ductility, lightness, permeability, thermal and acoustical insulation, and durability, among others.

Currently the materials most commonly used for these envelopes are ceramics, natural stones, wood-resin and aluminum-resin composites, and, increasingly, fiber cements. Each of these materials has advantages with regard to some requirements but not all of them. For example, ceramics and natural stones have excessive weight and high stiffness, which limits their size and necessitates a complex supporting structure. Furthermore, partial breaking, which can lead to objects falling on public roads, can be dangerous. Wood and aluminum composites are more flexible and lightweight but are less durable, have lower hardness, and are much more expensive and less sustainable compared to conventional building materials. For these reasons it is of practical importance to develop new materials for envelopes with the maximum aforementioned characteristics: primarily strength, ductility, flexibility, and durability, using environmentally friendly and low-cost raw materials and processes.

One possible solution is the use of vegetable fiber cement reinforced composites. The use of cellulosic or vegetable fibers has emerged during the last decades as an interesting option to substitute for asbestos, allowing the development of materials with good performance at relatively low cost [6–9]. Cellulosic fibers provide adequate stiffness, strength, and bonding capacity to cement-based matrices, enhancing their flexural strength, toughness, and crack resistance. Moreover, vegetable fibers are nonhazardous, renewable, and biodegradable, allowing the development of more sustainable construction materials.

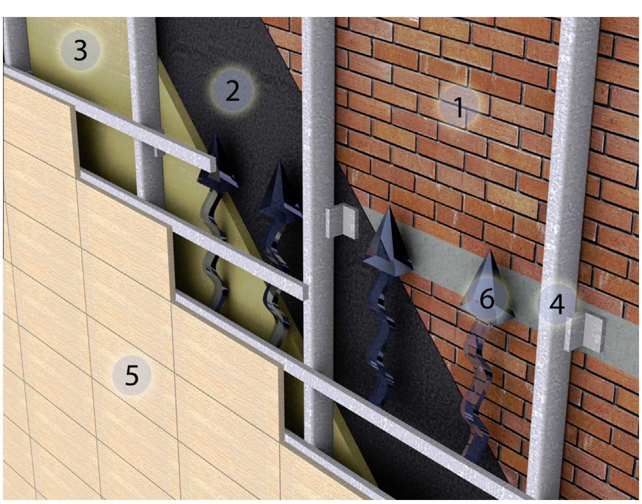

Fig. 1. Image of layers of a ventilated façade system: (1) inner wall; (2) breathable and waterproof sheet; (3) continuous insulating layer; (4) load-bearing structure; (5) joined building wall; (6) ventilated air gap.

Many studies describing the use of cellulose-based fibers as a reinforcement for cement-based composites have been published [10–17]. Nonetheless, in most of these papers the fibers are used in pulp or staple forms, limiting the improvement of the flexural strength and ductility of the composites, owing to the short length of the fibers, and the maximum quantity that it is possible to mix with the cement matrix (around 4–6 wt %). In order to overcome these problems, Toledo Filho et al. [18] used unidirectional sisal strands to reinforce cement-based composites, which significantly improved the tensile strength and toughness [19–21]. Although interesting results are obtained with these strands, it is difficult to produce these composites industrially using an automated laminating process. Therefore, recently Claramunt et al. [22,23] developed composites reinforced with nonwovens made of flax fibers. These structures allow handleability and easier applicability for automated processes [24].

Despite all the aforementioned advantages of these composites, one of the main drawbacks is the loss of mechanical properties after accelerated aging. It is well known that this lack of durability is mainly caused, on the one hand, by the calcium hydroxide (portlandite) of the matrix, which degrades the fibers, and, on the other, by changes in environmental moisture, which induce dimensional changes in the vegetable fibers and hence loss of physical contact with the matrix [25–27]. To overcome the problem of the calcium hydroxide component, several strategies have been used, such as pozzolanic additions to precipitate the portlandite as calcium silicate hydrate [28–35] or carbonation treatments with CO_2 to precipitate the portlandite as calcium carbonate [9]. Concerning the pozzolanic additions, Cyr et al. [36] stated that the reactivity of the pozzolan depends on the alkalinity of the matrix and on the fineness of the particles of the mixtures. This indicates that it is important to analyze the reactivity of every system.

To minimize the dimensional changes of the fibers, chemical or physical modifications can be carried out. One successful treatment is to subject the fibers to wetting and rewetting cycles in water, causing shrinkage of the fibers and a reduction in water-retention values due to the formation of hydrogen bonds in the cellulose. This irreversible effect [37–39], known as "hornification" and quantified as the percentage reduction in the water-retention value (WRV), occurs in the cell wall matrix of the fibers, resulting in intensely bonded structures [40]. This simple and ecofriendly treatment, which uses water as the reagent, has been used successfully to obtain more durable cement composites reinforced with cellulose pulps [41,42], or sisal strands [43].

The aim of this work it to analyze the mechanical performance and durability of façade pieces based on Portland cement matrix and cellulosic fiber nonwovens as reinforcement. Two types of pozzolanic additions (silica fume and metakaolin) combined with nonwovens subjected to different treatments to improve their dimensional stability are analyzed as potential materials for fiber-cement sheets for building envelopes with high strength and durability. The mechanical properties and durability are evaluated under four-point bending tests after 28 days of curing in a humidity chamber and after subjecting the sheets to accelerated aging.