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Studying the hardening and mechanical performances of rice husk and hemp-based building materials cured under natural and accelerated carbonation

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HIGHLIGHTS

- Rice husk and hemp concretes are cured under natural conditions up to 10 months.
- Mechanical strength and lime-based binder hardening are monitored over time.
- Carbonation and hydration degrees of both concretes are equivalent.
- Outdoor exposure (45% < RH < 75%) promotes carbonation.
- CO_2 curing led to an increase of the short term compressive strength (1–2 months).

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ABSTRACT

The purpose of this paper is to investigate the mechanical properties and the lime-based binder hardening of green concretes made of rice husk or hemp hurd. Concrete specimens were subjected to different curing conditions. Under natural carbonation, specimens were cured during 10 months either in a climate-controlled room (20 °C – 50%RH) or exposed outdoors. The work also focused on an accelerated carbonation curing (CO_2 curing) aiming to improve the short term compressive strength (1–2 months) of the concrete materials.

Compressive strength tests were conducted at different dates until 10 months of natural carbonation and after CO_2 curing. Powdered matrix samples were collected in the bulk and on the surface of the specimens to investigate carbonation and hydration of the binder by thermal analysis and a phenolphthalein test was used to provide information about the carbonation depth.

Under natural carbonation, the results indicated that the lime-based binder was almost hardened in the same way for both concretes with a similar rate of carbonation. However, the rice husk concrete was characterized by a ceiling effect of mechanical performances over time, which was attributed to the lower bonding strength between rice husks and lime. Concerning specimens exposed outdoors, the strength gain over time was more significant owing to more favorable humidity conditions for carbonation. The accelerated carbonation curing led to an increase of mechanical properties of the concretes in the short term. The compressive strength after CO_2 curing was approximately equivalent to those obtained after 10 months of outdoor exposure under natural carbonation.

1. Introduction

Buildings are the largest consumers of energy worldwide and sustainable development has become a serious concern in this sector. The major challenge is to reduce the energy consumption linked to heating and cooling throughout the life of the building system. At the same time, the need to select raw materials with lower embodied energy is growing. The development of eco-friendly concrete materials using plant aggregates has increased significantly for the last 15 years. In this field, lime and hemp concrete (LHC) is an example worth following. It is a carbon negative building material [1] with attractive hygrothermal properties [2]. The combination of water, hemp hurd aggregates and a lime-based binder produces a building material with an excellent thermal and sound insulation. LHC buffers temperature and

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humidity, prevents condensation and allows buildings to breathe. Moreover, it is a natural and solvent-free material that provides a comfortable healthy environment and a good air quality [3,4].

The diversification of renewable and easily available lignocellulosic resources helps to popularize bio-based concretes. This work follows our previous research about the use of whole rice husk as plant aggregate to develop an insulating lightweight concrete like LHC for building envelopes [5]. The recovery of this crop residue without any burning or grinding to design such a material was almost unexplored.

Mechanical performances obtained after 2 months of setting showed that our rice-husk-based material was suitable for infilling walls. However, it cannot be used as a load bearing material because of its compressive strength being only slightly over 0.30 MPa at early ages [5]. Since the mechanical strength of this kind of building material is very low, some authors especially focused on the improvement of LHC compressive strength. The main parameters influencing the mechanical properties of bio-based building materials like LHC are binder type and binder content, intrinsic characteristics of aggregates and their bonding strength with the binder, curing conditions, age of concrete and process used for concrete manufacturing [6–10].

The works of Nguyen [9–10] highlighted a significant increase of compressive strength when specimens are placed with a high compaction load. However, this process can be detrimental to the hygrothermal properties.

Many authors have studied aggregate surface treatments in order to restrict the release of hydro soluble components and make aggregates hydrophobic, with the purpose to improve the cementitious matrix hydration and the interface. This method is fairly effective when Portland cement is used [11–14]. However, when lignocellulosic concretes are designed with a lime-based binder, results are more controversial [8,15,16]. For instance, it has been reported a degradation of surface wettability which has yielded a negative impact on mechanical properties [8]. Moreover, the process is often heavy, costly and not very suitable for building industry.

The type of binder and the contribution of its hydraulicity to the final strength of LHC give diverging views. The presence of calcium silicate phases can contribute to early age reactivity and promote strength as long as hydration can be well performed. However, according to some authors, using a binder with a high hydraulicity like cement leads to an important powdering effect due to hydration disrupting [17,18]. It also must be pointed that for lime-based binders, carbonation contributes towards strength as the concrete ages [6].

The materials studied in this work are made up of rice husk or hemp hurd with a lime-based binder (hydrated and hydraulic lime). Arnaud and Gourlay [7] have well reported the evolution of LHC compressive strength with time using a lime-pozzolan binder. The latest was increased from 0.35 MPa to 0.85 MPa between 21 days and 24 months of setting and was largely attributed to slow carbonation.

The main weakness of lignocellulosic concretes using lime as binder is the long time they require to cure when cast in-situ. Therefore, the improvement of mechanical performances of the lime binder at early ages is certainly a path that needs to be explored. For lime-based mortars designed for restoration works, slow carbonation times and low mechanical strength at early age are also inconveniences. Some studies focused on improving hardened properties of aerial lime-based mortars with adequate proportions of pozzolanic additives (such as metakaolin) and specific admixtures, especially water-retaining, water-reducing agents or even plasticizers [19–22]. Pozzolans can improve durability and mechanical strength in medium-term [19]. The use of admixtures is rather tricky as the fresh state properties are also influenced and the dosage has to be precisely contained [20–22].

Another attractive possibility is to accelerate carbonation process of lime. This was investigated by the use of chemical additives in the works of Medici et al. [23–24]. The presence of an amine-based resin that reacts very well with acid gas like CO_2 accelerated the carbonation of aerial lime-based mortars and pastes, thus enhancing their short-term compressive strength. Accelerated carbonation using a CO_2-rich atmosphere is more widespread for all cementitious materials [25–28]. It has been studied on lime mortars and pastes by some authors [29,30] and compared to natural carbonation by Cultrone et al. [31]. In the latter work, 90 wt.% Portlandite-calcite transformation was achieved in over one week by subjecting lime mortars to a CO_2-rich atmosphere. Reaction mechanisms of lime carbonation are well described by Cizer [29]. It is a natural process whereby $Ca(OH)_2$ reacts with atmospheric CO_2 to form calcium carbonate $CaCO_3$ which is denser and stronger. Carbonation under ambient conditions is very slow, as a consequence of the relatively low concentration of CO_2 in the atmosphere (0.03–0.04%) [25]. Hence, the development of accelerated carbonation through exposure to high CO_2 concentrations for shorter periods of time. The extent and quality of carbonation depend upon several parameters. CO_2 reactivity is linked to the nature of binder phases and CO_2 diffusivity is linked to pore network and exposure conditions, in particular relative humidity [25,29]. Using accelerated carbonation appears very promising with particularly porous lignocellulosic concretes designed with an important part of $Ca(OH)_2$. Some studies have dealt with the effect of accelerated carbonation on vegetable fiber reinforced composites. They are presented as a good initiative to CO_2 sequestration and an interesting way to decrease alkalinity and porosity within concrete. A smaller average pore diameter associated with a densification of the matrix by higher precipitation of $CaCO_3$ results in increased bulk density, improved mechanical properties and interface and enhanced durability [32–34].

The first objective of the current paper is to monitor the mechanical strength of rice husk and hemp concretes until 10 months in two kinds of curing conditions as an extension of our previous study [5]. Mechanical performances are investigated for specimens cured in standard curing conditions (20 °C – 50%RH) and compared with those of specimens cured outdoors. The evolution over time of the chemical nature of lime-based binder phases is characterized and discussed in order to better understand the way in which carbonation and hydration perform in this mixture of lime depending on curing conditions. Moreover, the purpose is also to follow and compare LHC with LRC (lime and rice husk concrete) in terms of quality of the lime binder in relation to other parameters, which may affect the mechanical strength of the final concrete.

The second objective is to characterize specimens after accelerated carbonation in a CO_2 curing enclosure in a similar way to the characterization under natural carbonation. This is carried out in the prospect of moving towards a load-bearing material for single-storey houses using precast bricks as structural elements.

2. Materials and methods

2.1. Raw materials

Two different crop residues were used to design bio-based building materials: as received whole rice husks coming from a nearby rice field (Biosud, France) and a commercial hemp hurd (FRD, France).

2.1.1. Lime binder

The binder used in this study was a 50/50 wt.% combination of natural hydraulic lime NHL3.5 from Lafarge and hydrated calcic lime CL90-S from Saint-Astier (EN 459-1 Standard). Hydrated lime is obtained by slaking of quicklime (CaO) derived from burning of limestone and is mostly composed of calcium hydroxide (Table 1). Hydraulic lime results from calcination of chalky siliceous limestone, thereby giving rise to reactive silicates. After slaking, hydraulic lime consists of $Ca(OH)_2$ and belite C_2S (Table 1).