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Influence of binder characteristics on the setting and hardening of hemp lightweight concrete

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HIGHLIGHTS

- The impact of lime on the shiv-binder compatibility in hemp concrete was studied.
- Lime improves the hydration of hydraulic phases in presence of shiv extracts.
- The "protective effect" toward extractives is enhanced by finer lime.
- Washing hemp by water, and moreover by NaOH solution, improves its compatibility.
- None of the treatments or binders used allow a perfect shiv-matrix interface.

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ABSTRACT

Hemp concrete is an alternative building material used for insulation in low energy constructions. Experiments conducted with pure cement have generally led to poor binding properties, hence, commercial binders are often composed of a mix of hydraulic binder with lime. However, empirical observations in laboratories or onsite indicate that setting problems still may occur. This paper attempts to identify the phenomena that can explain the properties of mixed binders. With regard to hydration and mechanical performances, the results show that the addition of lime, especially fine lime, can reduce detrimental effects of hemp, but does not fully suppress them.

1. Introduction

Hemp concrete is a composite building material obtained by mixing a binder, shiv (hemp woody particles) and water as a reactant. This kind of lightweight concrete is often used in renovation projects, as well as in new constructions, for wall, floor or roof insulation [1]. In addition to having low thermal conductivity and good acoustic absorption properties [2–6], hemp concrete presents the advantage of enabling the valorisation of shiv, a byproduct of hemp long fibre production [7,8]. In fact, during the defibering process, the inner woody part of the hemp stalk is fragmented into small prismatic particles (average dimension $2 \times 0.5 \times 0.2\ \text{cm}^3$ [4]); they present a low bulk density ($110\ \text{kg/m}^3$), offering the good insulation properties reported.

The choice of binder is of the utmost importance in order to obtain a material that is easy to handle on the construction site and which will achieve sufficient final cohesion after setting. Indeed, the addition of hemp particles to a binder, as with many plant aggregates, can lead to some implementation problems, resulting in poor quality concrete. The main problem reported is the potential physico-chemical incompatibility between plant aggregates and hydraulic binders. Several authors have observed a delay in cement setting caused by particles originating from various plants, including bagasse fibre, wood, oil palm frond or hemp [9–12]. This incompatibility results in concrete with low mechanical properties; it can even be observed that the cement does not set at all.

The compatibility level of the aggregate depends upon diverse factors, such as the plant species (e.g., hardwood or softwood)

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[13], harvesting time [14–16], the particle shape (e.g., coarse residue, fibre, powder) [17], origin (e.g., heartwood or sapwood) [13,14,18], or physical state (e.g., degradation by treatments or by microorganisms) [14,15,19]. Several studies have shown that the incompatibility of wood with cement is largely due to extractive compounds like sugar (e.g., glucose), tannins or starch [15,20,21]. Moreover, cell wall polysaccharides, in particular hemicelluloses, can be degraded by the high alkalinity of cement into saccharinic acids which can hinder cement hydration along with other degradation products like carboxylic acids (e.g., glycolic, pyruvic or malic acid) [9,22,23]. Different action mechanisms are suggested to explain the negative impact of molecules extracted from the plant; most of them are based on the adsorption of those molecules onto the unhydrated cement grains or their hydration products (e.g., portlandite or C-S-H), thus "poisoning" the nucleation or growth of these hydrates [24,25]. Likewise, the chelation or precipitation process of calcium ions could decrease its concentration in solution, preventing C-S-H formation.

To overcome these technical problems, different improvement strategies based on granulate pretreatment or optimization of the concrete production have been investigated [26–28]. Also, most binders employed onsite to produce hemp concrete are composed of both hydraulic and aerial phases, while pure cement is rarely used (see also [3,6,29,30]). These two phases can be naturally present in the binders, as with hydraulic lime, or can be the result of mixing lime and cement. The most common hemp concrete binders reported being used are also often supplemented with filler, such as finely ground limestone or pozzolanic materials [3,31,32]. Non hydraulic lime is added to cement for the positive impact of its carbonation, which can provide mechanical properties if there is a hydraulic setting failure in the cement due to the compatibility problems mentioned above. However, lime could also improve the hydraulic setting of cement and perhaps even control and/or enhance shiv compatibility.

Aerial lime can produce chemical effects on cement hydration. First, lime reduces the C_3S dilution rate [33] and the number of C-S-H nuclei, which increases the initial hydration period [34]. However, a high lime concentration leads to greater hydration rate at the end of the free growth period by impacting the C-S-H growth mode [35,36]. A high lime concentration also affects C-S-H composition as it increases the C/S ratio [37].

Calcium carbonate is frequently combined with lime in binder formulations. It is commonly considered as an inert filler; however, some studies have shown that a small proportion of calcium carbonate can play a direct role in certain hydration reactions involving aluminate phases to produce monocarboaluminate [38].

Besides producing these chemical reactions, lime and calcium carbonate can show common filler effects. Thus, when minerals with little (e.g., lime) or no (e.g., calcium carbonate) binding properties are added to the cement phase, they may reduce the mechanical properties of the material by a dilution effect of the active components in cement. Inversely, these mechanical performances can be improved by an optimization of particle size distribution as a result of the filler characteristics. Another direct impact of adding fillers is that the Water to Cement ratio (W/C) must be increased to obtain the same paste consistency. Studies have shown that a higher W/C ratio tends to decrease the hydration rate during the nucleation period [39] but accelerate it thereafter [40,41]. Conversely, fillers are able to promote nucleation by offering more nucleation sites [42–44], especially in the case of high Specific Surface Area (SSA) fillers. It has also been suggested that this high SSA counters the set retarding agent effect. As mentioned above, set retarding agents can be adsorbed on to cement particles; as such, it has been suggested that a high SSA filler can lead to preferential adsorption of those molecules on to filler particles rather than on to cement particles [45].

This study seeks to more precisely describe the effects and action mechanism of lime when mixed with cement in a binder intended for use with plant aggregates. The emphasis is placed on determining whether the characteristics of lime can improve cement hydration kinetics, plant aggregate interfaces and the final mechanical properties of hemp concrete. Several parameters related to the chemical or physical features of shiv and lime have been also studied to assess their impact on the setting of different binder types.

For this purpose, model studies were first performed on the impact of water extractable compounds from hemp shiv on setting and the development of mechanical properties of the binders containing different lime qualities. In a second phase, hemp concrete was used to validate the results obtained. Hypotheses on how lime with specific properties may enhance setting by limiting the inhibition range of the shiv extracts at the interfaces between shiv and matrix in the concrete material will be proposed.

2. Materials and methods

2.1. Raw materials

2.1.1. Binders

Five binders were used for this study; their characteristics are shown in Tables 1 and 2 and Fig. 1:

- A commercial Portland cement CEM I 42.5 R-HS (Schwenk) called CB.
- Three mixed binders called MBr, MBf and MBc which derived from a commercial specific hemp concrete binder (Tradical PF70). These mixed binders "MB" were produced by mixing together 43% cement, 40% aerial lime (designated as CL 90 S according to [46]) and 17% finely ground calcium carbonate. The three MB binders contain the same cement and calcium carbonate, but different aerial limes having different porosity (Table 2) and particle size (Fig. 1). They were used in order to study the influence of lime characteristics in the binders. The "reference" lime, Lr (average particles diameter 7.2 μm; BET surface area 13.54 cm^3/g), was used to produce the "reference" mixed binder, MBr. The

Table 1
Phase composition calculated by the Rietveld method from X-ray diffraction data [47]. Legend: CB = Cement Binder; MB = Mixed Binders; LB = Lime Binder; n.d. = not detectable.

Phases (% in mass)	CB	MB	LB
C_3S	43.40	29.35	n.d.
C_2S	25.80	5.99	n.d.
C_3A	0.50	1.45	n.d.
C_4AF	19.80	4.53	n.d.
CaO	0.30	0.28	n.d.
Gypsum	0.30	0.96	n.d.
$Ca(OH)_2$	0.00	40.14	96.00
$CaCO_3$	2.40	17.29	2.00
SiO_2	0.10	0.00	n.d.
Anhydrite	3.70	0.00	n.d.
Bassanite	1.60	0.00	n.d.

Table 2
Specific surface area and porosity of the different binders and constituent limes obtained by N_2 sorption and Brunauer–Emmett–Teller (BET) method [48]. Legend: CB = Cement Binder; MBr = reference Mixed Binder; MBf = fine Mixed Binder; MBc = coarse Mixed Binder; LB = Lime Binder; Lr = reference Lime; MBf = fine Lime; MBc = coarse Lime.

Binder	BET surface area (m^2/g)	Cumulative pore vol. (cm^3/g)	Average pore width (Å)
CB	1.51	0.0046	111
MBr	5.47	0.0257	182
MBf	16.57	0.0759	167
MBc	4.05	0.0194	165
LB	12.1	0.0632	176
Lr	13.54	0.0643	171
Lf	39.63	0.1898	170
Lc	6.85	0.0315	166