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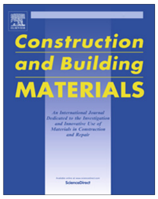

Experimental investigation of the shear behaviour of hemp and rice husk-based concretes using triaxial compression

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HIGHLIGHTS

- Plant-based concretes were tested under triaxial compression after 60 days of curing.
- Both shear banding and localised bulging occurred for hemp concrete.
- Shear banding was a consistent failure mode for rice husk concrete.
- The predominant influence of the aggregate type on the peak friction angle was highlighted.
- The cohesion was found to be correlated with the binder strength.

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ABSTRACT

Lime and hemp concretes are used as infill materials manually tamped in timber stud walls or more recently in the form of precast blocks. In either case, the structural design practice of wood frame construction associated with hemp concrete does not assume any contribution of the plant-based concrete whereas it may contribute towards the racking strength of the wall.

This work is intended to evaluate the shear behaviour of two different bio-based concretes by means of triaxial compression.

Hemp shives and whole rice husks were mixed with a lime-based binder according to the same mix proportioning and mixes were vibro-compacted in cylindrical forms. Then, samples were cured at 23 °C – 65%RH before being tested under unconfined and triaxial compression. The triaxial shear test was performed after 60 days of curing on unsaturated specimens under drained conditions at air pressure and for increasing effective confining pressure (from 25 to 150 kPa).

It was possible to estimate the shear strength parameters (peak friction angle and cohesion) of the two plant-based concretes. Comparing results, it appears a consistent value of cohesion but a different friction angle related to the binder and the aggregate contributions respectively. This leads to a first analysis of the relationship between the composition of the concrete (plant aggregates cemented with a binder) and its shear strength. Furthermore, the ductility of plant-based concretes is markedly enhanced as the mean effective pressure increases. Finally, the shear strength of plant-based concretes should be considered as part of the design practice of building envelopes.

1. Introduction

Buildings account for one-third of final energy consumption and global carbon emissions in the world [1]. Construction industry is therefore able to provide a significant potential for the reduction of greenhouse gas emissions. Energy efficiency of buildings tends to improve over time as a result of increasingly advanced insulating materials. However, it is essential to pay close attention to the carbon footprint of selected materials. Conventional construction systems used for residential buildings mostly combine an insulating layer with a load bearing structure. In order to keep buildings free from the risk of condensation in walls, self-insulating blocks like autoclaved aerated concrete or lightweight clay bricks are growing on the market of wall-building materials. These load-bearing blocks have rather low thermal conductivity [2–10]

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Table 1
Properties of some building materials at the hardened state (ρ: bulk density, CS$_{1\text{-}2}$: compressive strength after 1 or 2 months, λ_{dry}: dry thermal conductivity).

	ρ (kg m^{-3})	CS$_{1\text{-}2}$ (MPa)	λ_{dry} (W m^{-1} K^{-1})	
Autoclaved Aerated Concrete (AAC) [3–6]	415–600	2.6–5	0.12–0.16	
Burnt clay bricks (hollow–solid) [7–10]	850–1780	11–60	0.24–0.96	
Manually tamped LHC [18–21]	250–500	0.1–0.45	0.08–0.11	
Precast elements of LHC [24–27]	600–670	2–2.8[a]	λ_P[c]	0.10–0.13
			λ_O[c]	0.14–0.18
	670–870	1.4–4.7[b]	–	

[a] Compressive stress reported for 7.5% strain.
[b] Yield stress according to Tronet et al. [26].
[c] λ_P and λ_O are measured such that the thermal flow is parallel and orthogonal to the compaction direction respectively.

(Table 1) but they use non-renewable resources and their carbon footprint remains high, especially that of fired-clay bricks [11]. Recent decades have witnessed the emergence of bio-based concretes mixing hemp shiv (aggregate coming from the woody part of hemp stems) with lime-based binders. This return to old building methods aiming at associating plant-derived aggregates with mineral binders is arousing great interest. Walls including Lime and Hemp Concretes (LHC) constitute relevant alternatives to traditional building envelopes.

LHC are characterised by a low environmental impact due to carbon sequestration during hemp growth and lime carbonation during the hardening of concrete [11,12]. These materials are designed with a high volume fraction of hemp shives providing an important porosity to the hardened material. Therefore, the latter exhibits very attractive hygrothermal properties (insulation, thermal comfort, water permeability) [13–15] and acoustic absorption [16,17].

Most of the time, LHC is manually tamped into a wooden framework (cast on the building site). In these conditions, its mechanical properties are very low. Compressive strength values obtained by a number of authors [18–21] are reported in Table 1. For a bulk density ranging from 250 to 500 kg m^{-3} and a binder-to-aggregate (B/A) mass ratio less than 2, compressive strength after 2 months of natural curing remains under 0.5 MPa. It is therefore obvious that LHC cast by manual tamping is a filling material that needs load-bearing timber studwork.

Using precast blocks is another option for hemp-lime construction. This method opens up interesting ways of improving mechanical strength of LHC. Previous studies [21–23] have shown that its strength development is strongly dependent on curing conditions. Accelerated carbonation curing (cyclic CO_2 exposure) at 20 °C and 65%RH was found to be effective to increase the short term compressive strength of slightly compacted LHC [22]. Furthermore, mechanical behaviour of LHC is heavily impacted by the casting process. Nguyen et al. [24] investigated the compaction of freshly-mixed concrete under static loading. After hardening, compacted LHC exhibits improved compressive strength (Table 1). In addition, stress-strain behaviour of highly compacted LHC shows an increase in rigidity and ductility (large strain hardening area) [24–26]. This is due to the reduction of macroscopic intergranular voids and better arrangement of hemp aggregates in concrete [26]. However, high compaction pressure generates a layered concrete with anisotropic thermal conductivity [24] (Table 1). Tronet et al. [25,26] have studied highly compacted specimens of LHC as part of precast industry. Thanks to a specific compaction device, it was possible to apply a compaction pressure up to 7 MPa. Authors have succeeded in achieving compressive strength close to that of autoclaved aerated concrete blocks for a very low B/A (=0.5) but a relatively high bulk density (Table 1). In the work of Dinh [27], LHC was compacted by means of vibro-compression. With this method commonly used for granular soils, compaction results from combined effect of axial loading and vibration in order to reduce the internal friction. Vibro-compacted LHC studied by Dinh showed equivalent performances to those obtained by Nguyen [24] with static loading and close bulk density.

LHC can also be cast around a timber frame through a spraying process. In the same way as for precast blocks, the force of projection used for sprayed LHC induces an anisotropic arrangement given that hemp shives are elongated in form and tend towards stratified planes that are perpendicular to the compacting force [28].

Whether it is cast in-situ or in the form of prefabricated blocks, LHC is only considered as an insulating material. As a matter of fact, the structural design practice of wood frame walls associated with LHC does not assume any contribution of the plant-based material. In view of their properties, it makes sense to consider that plant-based concretes could contribute to the mechanical performance of the structure. In particular, some authors [29–32] have shown that LHC provides in-plane racking strength to the timber frame. According to Munoz and Pipet [29], the mechanical behaviour of a timber stud frame with LHC infill is enhanced compared to that with diagonal bracing. The studwork frame with LHC exhibits higher stiffness, racking strength and strain capacity at failure. Gross and Walker [30,31] studied the racking strength of a timber studwork encapsulated with low density LHC (320 kg m^{-3}). They concluded that even with a low strength (compressive strength was about 0.4 MPa after 5 months), manually tamped LHC improves the racking performance of timber studwork frames. An illustration of the racking strength test and failure of timber wall is presented in Fig. 1. Another author [32] has found that hemp concrete prevents weak axis buckling of timber columns by acting as a continuous lateral elastic support. Regarding high density LHC (715 kg m^{-3}), it is stated that the latter can add strength to the wall by partly contributing to its load-bearing capacity. High density was performed by increasing the binder content in this study. These works show that timber sections could be reduced and some design practice of timber frame wall panels should be reviewed without noggins and diagonal braces. In this context, it seems necessary to study the shear behaviour of plant-based concretes since it is currently unknown. No studies have been conducted to date on the shear strength of these bio-based materials apart from that of Youssef et al. [33]. These authors investigated the shear behaviour of highly compacted cubic specimens of LHC by means of a direct shear box test. An explicit strength criterion could not be determined due to the absence of peak in the shear response. This is certainly related to the strong ductility of the mixes and the slenderness ratio of specimens. Shear strength parameters of soils are usually determined either by this method or by the triaxial shear test. The direct shear test is widely used in geotechnical engineering due to its ease application. Nonetheless, it is known that the plane of failure is more governed by the test itself than the properties of the material. The triaxial test gives access to the state of stress up to failure and shear strength parameters.