Cement and Concrete Composites 67 (2016) 60–72

Contents lists available at ScienceDirect

Cement and Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Study of lime hemp concrete (LHC) – Mix design, casting process and mechanical behaviour

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A R T I C L E I N F O

Article history:
Received 11 March 2014
Received in revised form
25 September 2015
Accepted 26 December 2015
Available online 2 January 2016

Keywords:
Lime-hemp composite
Mix design
Compression moulding
Rigid die
Compressive strength
Compressive stiffness

A B S T R A C T

This paper deals with the mechanical behaviour of lime hemp composites. LHC blocks have been produced by compression in a rigid die at a relatively high compression pressure. This process allows the production of LHC with a high proportion of hemp shiv. New mechanical parameters are proposed to compare experimental results of this study with those found in published literature. This paper shows that a high compaction pressure enhances the compressive strength and can offset a reduction of binder. Consequently, a new formula is proposed to predict the strength of LHC which depends on both the binder content and the compaction state of the shiv particles. The study leads to recommendations for the mix design of such composites.

1. Introduction

The high environmental impact of the construction and building sectors leads to a focus on green or alternative materials such as bio-aggregate-based concretes. Nowadays the most developed bio-aggregate-based building material in Europe is Lime-Hemp Concrete (LHC) or Hempcrete; these lime-hemp composites were first designed and tested in the early nineties. This material is comprised of a mineral binder, often a combination of hydraulic and non-hydraulic lime, with a plant-based aggregate, mostly consisting of shiv with or without small residual fibers. Shiv is produced from the woody core of hemp stems; it is ground and graded to 5–40 mm long particles [1]. Due to the environmental advantages of non-hydraulic lime and of hemp cultivation, LHC presents, during its life cycle, a weaker ecological impact [2,3] compared to traditional building materials. However, LHC has properties that differ from those of conventional concrete. It is lighter and has good insulation properties; heat transmission ranges from 0.06 to 0.19 W m^{-1} K^{-1} for apparent dry densities between 200 and 840 kg/m^3 [4–6]. This means that in a masonry application, no additional insulation is needed. However, the strength of LHC is very low compared to usual building materials. The compressive strength of this material is less than 2 MPa [6–11]. This low compressive strength, in combination with the low Young's modulus of LHC composites (see Table 1) indicates that this material in its present form cannot be used as a load-bearing material. For this application increased rigidity and higher compressive strength are needed.

According to Bouloc et al. [12], the low compressive strength of LHC is due to the high flexibility of the aggregates, and to the imperfect arrangement of these particles. Currently LHC walls can be made on site, the material being poured into a formwork and tamped manually; alternatively it can be sprayed using a projection process [9]. These processes neither achieve a high compaction nor any precise control of conditions of maturation of the material. Consequently, its resistance is very low. For example, French professional LHC building rules [13] give a compressive strength of 0.3 MPa for tamped LHC walls and floors. LHC can also be used to make bricks or hollow blocks [5–7]. The main advantage of this method is to permit a better control on the packing and arrangement of shiv particles; this is the process that is developed in the present work.

Two main methods are studied to improve the strength of hollow blocks made of plant-derived aggregates and cementitious binders. The first method is the use of an admixture, for example: Nozahic and Amziane [14] treated the surface of sunflower

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http://dx.doi.org/10.1016/j.cemconcomp.2015.12.004
0958-9465/

Table 1
Strength and stiffness values of LHC taken from literature (W/B = Water to binder mass ratio; B/S = Binder to shiv mass ratio).

	W/B	B/S	Density *(hardened state)* [kg/m3]	σ_c [MPa]	$\sigma_{1.5\%}$ [MPa]	$\sigma_{7.5\%}$ [MPa]	E [Mpa]
Nguyen [5]	0.55	2.15	850	–	1.58	3.57	131
	0.86	2.15	670	–	1.34	2.65	113
Arnaud & Gourlay [10]	1.5	2.4	460	0.18	0.08	0.22	5
Kioy [11]	1.1	3.14	610	1.88	0.70	1.65	43
	0.8	3.14	830	1.98	0.86	1.82	52
	1.3	8	356	0.3	0.21	0.35	14
Cerezo [4]	1.3	6.7	391	0.35	0.22	0.39	44
	1.4	5.3	504	0.7	0.57	–	15

aggregates to improve fibre-matrix bonds. Kazhma et al. [15] used sucrose to treat flax shiv by cement–sucrose coating. This method gives promising results, but requires an additional stage of processing and additives to be achieved. The second method to improve the material properties is to control compaction of the fresh mix during casting. Nguyen et al. [5,16,17] have shown that the compaction of fresh material can significantly increase the compressive strength of hemp concrete by reducing the volume of voids within the material. Such a process improves mechanical strength while using lower binder content; furthermore it also increases the strain capacity before failure. Compacted LHC is pressed during casting to make bricks or hollow blocks. The aim of this is to achieve a structural or load-bearing function, while maintaining good thermal insulation properties. Fig. 1 shows typical curves, taken from published works, of uniaxial compressions of LHC cylinders. These curves clearly show the improvement of both rigidity and ductility due to the compaction process. For compacted LHC blocks, determining a value of yield stress or strength is not as easy as for classical building materials, which pass through a maximum value. Some studies on LHC [3,4,11] report more easily discernable strength values because the mix designs used in these studies are lightly pressed and so rich in lime that the hardened material maintains a brittle behaviour or a maximum stress, thus making it easier to characterise resistance (Fig. 1). Some of these compressive strengths σ_c are reported on Table 1. Any collapses have been observed in some compacted LHC specimens (with a compressive stress lower than 30 MPa [5]). As a consequence, arbitrary characterisation values have been selected: stresses for a strain of 1.5%, close to the end of the linear elastic area and 7.5% in the strain hardening area. Table 1 sets out the principal

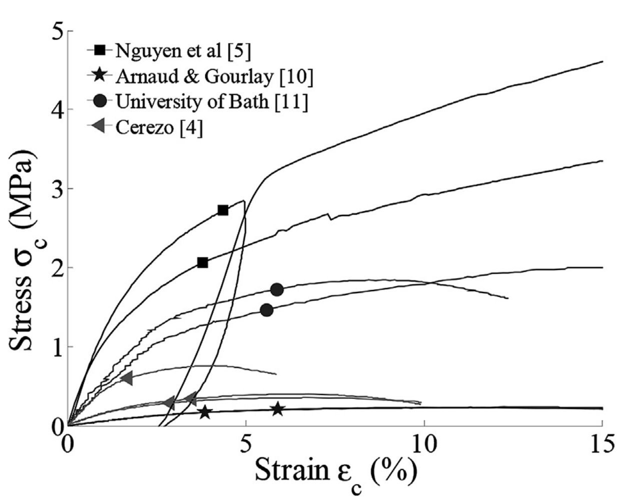

Fig. 1. The different compression curves of LHC taken from literature: lightly compacted LHC [10,4,11] behave as lightweight concretes, with a stress softening and densest LHC [5] having a large hardening area.

results for strength taken from literature and computed with these arbitrary characteristics. The compaction process clearly shows promising results for both rigidity and strength.

The pressure applied by the upper punch of the compression cell by Nguyen et al. [5,16,17] and in former studies [6–12] was never higher than 2.5 MPa. This upper limit was due to the design of the compression cell (generally made of polymeric materials such as PVC). Higher compressive stresses are required to limit the proportion of binder, which is the main environmental impact component of LHC, and to improve a hollow block's resistance and rigidity. Nozahic et al. [18] made prismatic 40 × 40 × 160 mm^3 specimens by applying an upper punch pressure of 5 MPa on bio-aggregates, pumice and lime mixtures; however the binder/aggregate mass ratio was 18, and the specimens are narrow compared with the size of the longest particles (40 mm). This is the reason why Tronet et al. [19] developed a rigid cylindrical die, enabling the application of upper pressures on fresh mixes up to 10 MPa and producing 10 cm diameter and 20 cm high specimens. Tronet et al. studied the influence of mix design, particularly moisture content and lime paste proportion on the compressive behaviour and frictions on the cell walls. It is this friction that influences the homogeneity of loading. Tronet's research showed that a high level of compression can be a good way of limiting heterogeneity inside a precast block, and that for high levels of compression the mix design does not greatly influence the heterogeneity of loading. In this study, the same device used by Tronet et al. [19] is used to produce cylinder blocks (10 cm diameter, 20 cm high) from several mixes. Their compressive behaviour is then studied at the ages of 28 days and 90 days.

Decreasing the binder proportion would probably be detrimental to the tensile strength; however building materials such as bricks or concrete blocks essentially work in compression. Therefore applying a high pressure and limiting the binder quantity should be a good way of improving hempcrete blocks from a mechanical and environmental point of view. Limiting the thermal bridges within the lime should also improve the thermal insulation properties. Some published literature proposes that the strength of hardened LHC is essentially due to the properties and proportion of the binder chosen for its formulation. Lanos et al. [20] noted that the mechanical results for mineral binders can be modelled by a power law based on the volume fraction ϕ occupied by the hardened binder in the sample.

$$\sigma = \sigma_0.\phi^a \tag{1}$$

where σ_0, when $\phi = 1$, is the intrinsic binder strength without any porosity. Nguyen et al. [5] found a σ_0 of 126.2 MPa by studying the effect of the water/binder mass ratio (W/B) on lime paste resistance (the lime in question was Tradical ® PF 70). The parameter a usually takes a value of around 2 for cementitious materials. Nguyen et al. [5] proposed a value of 2.98 for the Tradical ® PF 70 and Nozahic et al. [18] a value of 3 for a pumice-lime binder. For hardened mixes