Construction and Building Materials 165 (2018) 17–27

Contents lists available at ScienceDirect

Construction and Building Materials

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

Performances of flax shive-based lightweight composites with rapid hardening

V. Dubois *, A. Leblanc, O. Carpentier, G. Alhaik, E. Wirquin

Univ. Artois, EA 4515, Laboratoire de Génie Civil et géo-Environnement (LGCgE), F-62400 Béthune, France

HIGHLIGHTS

- The materials are designed to bring insulating to structures built from 3D printing.
- The mixes include flax shives, foam agent, and for some of them, earthern materials.
- The studied mixes give a rapid hardening and low mechanical strengths.
- Acoustic absorption coefficient of one mix is from 0.3 up to 0.55 (100–1500 Hz).
- The measured lowest thermal conductivity is 0.085 $W.m^{-1}.K^{-1}$.

ARTICLE INFO

Article history:
Received 3 May 2017
Received in revised form 22 December 2017
Accepted 29 December 2017

Keywords:
Foam composite
Rapid hardening
Insulating materials
3D printing

ABSTRACT

This research work aims to develop a rapid hardening lightweight composite including flax shives, foaming agent and earthern materials. The results show a satisfying workability just after the mixing step and a rapid hardening of about less than thirty minutes. The mixes with a large amount of flax shives show a thermal conductivity inferior to 0.1 $W.m^{-1}.K^{-1}$ and porous-like acoustic absorption coefficients. Even if the mechanical performances are low ($fc_{28\ days}$ = 0.1–1 MPa), the developed mixes, in association with a structural material, can be used with advantage the 3D printing technique.

1. Introduction

Growing in the field of construction, 3D printing consists of joining materials layer upon layer to obtain part or all of a building from a 3D model developed by CAD software. The 3D printing allows the building of various shapes. By significantly reducing useful matter to build, 3D printing allows to optimize resources [1,2]. This technique is the subject of several pieces of research including the development of printing materials such as concrete, metal or earth. In most current applications, the printed material serves as the structural part of bearing walls [3–5]. But, to bring thermal or acoustic comfort to the user, a wall must also have insulating performance, which is given by insulating materials. In most common 3D printing projects, these materials are not included during the process.

In conventional techniques, lightweight concretes have been developed both to meet varying levels of mechanical strengths as well as to simultaneously provide thermal and acoustic performances. Lightweight concretes can be obtained by including lightweight aggregates and/or foaming agents. Lightweight aggregates can be natural (e.g. pumice, volcanic cinder) or artificial (e.g. expanded perlite, polystyrene, fly ash cenospheres or aerogel) [6,7] while foaming agents are surfactant molecules that entrap air voids in the solid components during the mixing. In its fresh state, foam concrete must have a stable consistency to avoid segregation observed with insufficient foaming agent content or collapse due to the lack of aggregates to entrap [6].

At hardened state, the performances of lightweight concretes are variable according to their composition, the fabrication mode and their density. Table 1 shows characteristics of foam concretes with various densities. Several pieces of research work show the link between compressive strength and density. Liu et al. [8] have studied lightweight concrete containing perlite aggregate and the results have shown that the compressive strength is a function of oven-dry bulk density according to a power law. Horpibulsuk et al. [9] have developed an empirical relation between unconfined compressive strength and void/cement ratio. The intrinsic porosity

---

* Corresponding author.
E-mail address: vincent.dubois1@univ-artois.fr (V. Dubois).

https://doi.org/10.1016/j.conbuildmat.2017.12.239

Table 1
Performances of foam concretes.

Type of concretes	References	Range of f_c (MPa)	Range of λ ($W \cdot m^{-1} \cdot K^{-1}$)	Range of density ($kg \cdot m^{-3}$)
Foam concrete including expandable polystyrene, Portland cement or aluminate cement, silica fume, polypropylene fibers, foaming agent	[6]	3–13	0.09–0.25	400–800
Lightweight cementitious composite incorporating aerogels and fly ash cenospheres	[7]	17–24	0.32–0.41	1000–1300
Shotcrete including cement, sand and expandable perlite	[8]	2–4.6	0.1–1.44	620–2080
Foam including gypsum, cement, superplasticizer and surfactant	[10]	0.03–5.03	0.08–0.2	247–819
Lightweight concrete without foaming agent and including expandable perlite	[12]	0.1–1.1	0.13–0.21	392–673
Autoclaved cellular concrete	[13]	2–4.6	0.08–0.2	300–500

of lightweight aggregates and/or the pores generated by foam agents also induce interesting thermal and acoustic performances by reducing heat transfer and by increasing absorbing sound. Testing various surfactants, Samson et al. [10] show that the thermal conductivity varies linearly with the dry density regardless of the surfactant employed, with values similar to autoclaved cellular concrete (Table 1). As regards acoustics, Hung et al. [11] show that the sound absorption of foams increases as its relative density decreases. With a density of 400 $kg \cdot m^{-3}$, the acoustic absorption coefficient of their materials is between 0,48 and 0,9 for a frequency interval of 100 5000 Hz, with transmission losses between 16 and 42 dB.

In addition to performances, foam concretes are interesting from an environmental point of view because of the low amount of aggregates required for a given volume in comparison to conventional concretes, which allows to preserve natural resources. However, cement, which is a traditional component in the mix design of foam concrete, needs large quantity of energy to be manufactured. When the requested mechanical performances are low, cement can be replaced by lime, gypsum or natural prompt cement, for example, which are generated at lower temperatures than ordinary cement. Besides, gypsum and natural prompt cement offer a rapid setting to the material which can be interesting for the 3D printing.

To accentuate further the green side of a building product, clay earth can also be chosen as a binder such as in the traditional earthen buildings. This is a mineral resource that can come from to the building site, therefore not requiring transportation. Besides, its energy requirements remain limited. Two-thirds of the worldwide population live in homes made with unfired earth such as compressed earth bricks or adobe bricks. Considering only the manufacturing phase, Maskell et al. [14] explain, relying on the ICE and Ecoinvent databases, that the choice of unfired extruded clay brick induces an embodied energy saving of 86% compared to fired clay and of 25% compared to concrete blocks. The CO_2 emissions decrease, respectively, by 86% and 72%. Furthermore, the grey energy of earth plaster is considered around 30 $kWh \cdot m^{-3}$ while those of gypsum plaster and cement plaster are around, respectively 750 $kWh \cdot m^{-3}$ and 1100 $kWh \cdot m^{-3}$. One disadvantage of unfired earth techniques is the long drying time.

In order to further decrease the environmental impact of concrete, another solution derived from eco-construction techniques is the use as aggregates of vegetable co-products (e.g. straw), which are renewable materials and offer interesting thermal and acoustic behaviour whether on their own or combined with unfired earth materials (e.g. cob) thanks to their multi-scale porosity. Dubois et al. [15] have manufactured and tested blocks containing earthern materials, lime and hemp straw. Some of those blocks have thermal and acoustic performances which are better than the traditional gypsum block. However, from a mechanical point of view, the use of vegetable coproducts in the design of concretes generally induces a decreasing of strengths. Vercelheze et al. [16] have thereby designed baked foams including sugarcane fibres and show that fibres not only decrease the density but also the strength at failure and increase the deformation level. Treatments of vegetable coproducts are developed and improve their mechanical performances. Thus, Khazma et al. [17] show treatments using linseed oil for flax-shives cementitious composites which multiply the compressive strengths by ten and the flexural strengths by six to eight in comparison to composites without treatment of flax shives.

By allowing the use of locally available and inexpensive materials, earth materials and vegetable co-products have a decisive role to play in the development of 3D printing applied to the building sector. Russel [18] demonstrates the great potential of earth materials to be an innovative solution to the housing shortage the developing world is facing. Some examples of the use of earth materials in 3D printing have been developed in Italy with the WASP project or also the ICAA project Pylos in Spain.

In this context, this research work aims to develop a lightweight composite with insulating performances and including eco-materials, for the 3D printing in the building domain. This composite has to be used in addition to structural material. In a fresh state, a satisfying workability and a rapid hardening are targeted to obtain extrudable and buildable materials. For a rapid hardening, gypsum and natural prompt cement have been chosen as binders. Gypsum and natural prompt cement request lower grey energy during the fabrication process compared to standard rapid hardening cement. Flax shives have been chosen as aggregates. To reduce the grey energy of the foam composites, quarry fines chosen as earth materials replace part of the hydraulic binder. Quarry fines coming from the washing of aggregates are presently poorly re-used and need large storage capacity. Finally, a foaming agent is used to ensure good workability and reinforce low density, already enhanced by the incorporation of straw, for high thermal and acoustic performances. The experimental campaign includes the study of 18 mixes corresponding to various proportions of each component. Influential parameters are searched for to understand the impact of each component on the performances of foam composites (workability, mechanical strengths, acoustic and thermal performances).

2. Experimental details

This part describes the materials and the mix proportions chosen for the experimental campaign. Several laboratory samples have been made according to a process developed hereafter. All the tests procedures are also detailed such as the type of equipment used and the test parameters.

2.1. Materials

The gypsum (G) used in this research work is known as plaster of Paris. This plaster is mainly compounded of beta hemihydrate ($CaSO_4$, $1/2H_2O$) and anhydrite ($CaSO_4$). The natural prompt cement (PC) is siliceous cement, formed between 800 and 1200°C, includ-