

French Polytech network form for PhD Research Grants from the China Scholarship Council

This document describes one of the PhD subjects proposed by the French Polytech network. The network is composed of engineering schools/universities. The document also provides information about the supervisor.

Supervisor information	
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Country	France

PhD information	
Title	Bio-based binders and mineral additives for improving the rheological and mechanical performances of 3D printed earthen materials.
Main topics regards to CSC list (3 topics at maximum)	Sustainable development engineering and lower cost manufacturing, New theory and technology of manufacturing, Biomaterials and polymer materials

Required skills in science and engineering

Material characterization and formulation, experiment plan, programming and automated analysis, scientific writing and reporting, team working

Subject description (two pages maximum including biblio)

The construction industry is one of the largest consumers of energy and natural resources [1], while lagging behind other sectors in digitalization [2, 3]. To address these challenges, the sector must adopt more sustainable practices eventually based on digital fabrication [2]. Large-scale additive manufacturing or 3D printing offers significant potential as a key technology for this transformation [2, 3].

Extrusion-based technology [4], consists of depositing layer by layer a material that is pumpable, printable, buildable and with a controlled curing time [5]. Compared with reinforced concrete, it offers formal freedom at low cost [6, 7].

Cementitious materials currently dominate 3D printing, with additives and cement being the main environmental impact factors [8]. Reducing cement consumption and replacing these materials with eco-friendly alternatives can mitigate environmental impact [9, 10]. In this context, raw earth offers sustainable properties [11] consistent with circular economy principles [12,13] and earth 3D printing has known growing interest in the use of raw earth in 3D printing since 2018 [14, 15]. However, the use of raw earth in 3D printing is still limited due to its low mechanical performance and high water sensitivity [14]. The development of new formulations with improved mechanical performance and reduced environmental impact is therefore a major challenge for the scientific community.

In the literature, two strategies are adopted to enhance the mechanical and/or the hygrothermal performances : the use of binders and the addition of plant fibers. The formulations developed have been used either to print specimens [14, 16], walls [16] or filler material for pre-existing formwork [15], construction elements or even houses. A recent comprehensive review of 3D clay printing can be found in the article by Fahfouhi et al. [17].

A variety of binders are used to accelerate the hardening of the clay or improve its mechanical performance, including gypsum [15], prompt cement [15], bio-polymers [18–23], geopolymers [24, 25], calcium hydroxide [21], sodium hexametaphosphate [21]. Authors focused on the rheological properties of clay composites used in 3D printing, such as Maierdan et al. [20, 22], Soda et al. [26], Asaf et al. [27] and Biggerstaff et al. [19], Ji et al. [28] and Perrot et al. [14]. Among these works, some of them propose a thorough analysis of the interactions between clay phases and bio-based binders considered as alternatives to cement replacement [19, 20, 22, 29].

Printed materials can also contain plant additives (plant fibres or aggregates) in order to improve their thermal properties, tensile strength or ductile behaviour, such as flax straw [15], flax fibres [18, 21], straw [16,30], sisal [23,31–33], kenaf [30], banana fibers [30] or hemp shiv [30]. The integration of plant fibers into formulations has an impact on rheological properties and can lead to difficulties in pumping materials, which may be detrimental to the printing process. The distinctive feature of the study by Carcassi et al. [30] is the establishment of a formulation method enabling the maximization of fiber content without compromising material pumpability.

Numerous scientific challenges still need to be addressed, particularly those related to :

- the variability of earthen materials ;
- the effect of natural binders, as well bio-based as mineral, on the stiffness development and the rheological and mechanical properties
- the effect of fiber type and content on the pumpability and buildability.

The aim of this PhD thesis is to study the effect of low-impact binders and fibers on the various properties of 3D printing materials at the different stages of the printing process (mixing, pumping, printing, curing and printed structure lifetime).

The work will be split into different work packages dedicated to :

- The bibliographic review on earth 3D printing and on the bio-based or low-impact mineral binders and fibers by focusing on the issues related to the use of these materials in 3D printing (impact on rheological and mechanical properties) ;
- The design and formulation of low carbon materials – This part will be dedicated to the design and formulation of 3D printing materials incorporating various binders (bio-based or mineral binders). The materials will have to be in compliance with the requirements of 3D printing materials. Several formulations will be proposed, based on the model tested in Ali Muhammad Nurad PhD thesis [24]. The addition of plant fibers will lead to deviation from the model, that will be pointed out.
- Printing tests – Printing tests of small-scale walls will be carried out on chosen formulations and compared to formulations previously designed in Yameng Ji's PhD thesis [21] and Ali Muhammad Nura PhD thesis [24]. These tests will be necessary to assess the viability of the designed materials in a printing process. This part will use the experiment plans methodology to catch the influence of the different parameters on various output properties.
- Early-age behavior – The early-age behavior of the printed materials will be studied by assessing the evolution of the rheological and mechanical properties according to the age of the materials. The influence of the curing conditions (temperature and relative humidity of the ambient air) will be analyzed. The measured properties will be the yield stress (cone penetrometer) and the Young's modulus (uniaxial compression test). These parameters will be used to determine the parameters of hardening models inspired by models developed for concrete 3D printing.
- Stability tests – The walls printed by 3D printing techniques must be stable once printed and several models exist to assess the stability of these walls according to the mechanical and rheological properties of the materials at the fresh state and to their evolution at early-age. In this aim, the model developed during Yameng Ji's PhD thesis [21] will be further developed to take into account these various parameters. Moreover, experimental measurement will be necessary to assess the properties of the fresh material during the drying/hardening phase (sorption isotherm, setting time, transition between the fresh state and the hardened state...). This work will help better understand and optimize the printing process, and in particular the structure buildability.
- Artificial Intelligence – The use of AI will be considered to optimize the printing process and the design of the materials. The AI will be used to predict the properties of the printed materials according to the printing parameters and the formulation of the materials. The AI will be trained on the data collected during the printing tests and the early-age behavior tests. This will be a first attempt to demonstrate the potential of AI in the field of 3D printing of earthen materials, because of the limited size of the dataset. This work will be supervised by **Nabil Issaadi, Nordine Leklou, Philippe Poullain, and Stéphanie Bonnet.**

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