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Formulating and optimizing the compressive strength of a raw earth concrete by mixture design

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HIGHLIGHTS

- Economical, ecological and workability constraints used to build the mixture design.
- Statistical validation: quadratic model for short curing times, linear one for 90-day.
- Drying process study from response trace plots: negative role of silt pointed out.
- Optimization from surface response plots: minimizing cement and water proportions.
- Validation of model with a raw earth concrete implemented on a construction site.

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ABSTRACT

Earthen construction is one of the most common construction technique used since the earliest times. The raw material is abundant, requires very low energy to manufacture and does not generate waste. Building today with raw materials, requires noticeable mechanical performance. For this, a raw earth treatment using the binders is one of the methods used to improve its durability and strength. This paper presents the use of mixture design as a tool to optimize a raw earth concrete formulation to reach a desirable compressive strength. The results show that the mixture design approach can be an important tool to help develop and optimize a raw earth concrete formulation.

1. Introduction

From the first centuries of human civilization, the raw earth, by its properties and performances, was used as a building material at different levels of complexity [1,2]. The prodigious constructions made of raw earth by our ancestors have proved a resistance and a durability that have crossed through the centuries. Nowadays, contemporary building materials (concrete, steel, etc.) are very energy-intensive in terms of grey energy, responsible for the emission of large quantities of greenhouse gases. Hence the need to develop new ecological and economical materials, known as eco-geomaterials of construction, mainly raw earth-based materials with low energy consumption [3,4]. These raw earth materials as a natural building material have received increasing attention. Some of the main advantages of these materials, made from the earth, are: i) Natural materials are everywhere in the world, available in large quantities with a low and affordable cost. ii) In comparison with industrial building materials such as concrete, earth material needs approximately 99% less energy during the production process [5]. iii) They are recyclable, then they prevent or reduce the amount of waste. iv) There is no need to use a very advanced technology for their in-situ implementation, when it is not the case for materials such as concrete or steel. v) They contain a fraction of clay which provides the natural cohesion of the material and contribute to the strength. In contrast, for a concrete, cohesion requires an amount of cement which is very energy-intensive.

Some important properties of earth material are the mechanical strength, the shrinkage and swelling, the cracking and the hygrothermal properties [6].

It is not always adequate to meet the performance required from a building material and stabilizers are used to enhance the properties [7]. Among them, when the mechanical strength is con-

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cerned, stabilizers such as lime, cement and gypsum can be added. Reinforcement can also be assured by an addition of strong fibers. Some studies explore the influence of these binders on the raw earth properties [6,8–10]. As was reported by Delgado and Guerrero in a review paper on earth construction in Spain [7], for unstabilized soils, the compressive crushing strength varies in the range 0.60–1.80 MPa for rammed earth and between 0.75 and 2.25 MPa for Adobe. It can be enhanced by a factor 3.6–5 when cement is used as a stabilizer, 2.6–3.6 when a mixing of lime and cement is used and a factor 2–3 when lime is used alone [7]. The given ranges correspond to different dosages of the stabilizer and different initial compressive strengths of the unstabilized tested earth material. Zak et al. [5] studied the influence of reinforcement by natural fibers, gypsum and cement on compressive strength of unfired earth bricks materials. They pointed out that the mixing of earth with gypsum has no favorable influence on the compressive strength. Pakbaz and Farzi (2015) [11] studied the effect of mixing methods (dry vs. wet) on the mechanical and hydraulic properties of treated soil with cement or lime. They showed that the strength of wet cement treated samples was higher than dry cement treated samples and this was opposite for lime treated samples. Minke [12] proposed that for dry building elements made of raw earth materials, a compressive strength value between 2 and 5 MPa should be considered.

A new concrete based on raw earth material was developed by a firm from Normandy called Cematerre, in collaboration with the University of Le Havre, Normandie. Its originality is its ability to be cast in place like a traditional concrete. For the tested raw earth concrete, preliminary studies according to an experimental protocol under CSTB (Building scientific and technical center (FR)) specifications have led to the so-called "ATEx A" official qualification.

Traditionally, in the great majority of studies dealing with the characterization of materials resulting from mixing, the chosen experimental design is built on varying successively the different components of the mixture. However this method requires a great number of tests to finally obtain the desired product characteristics. Design of Experiments (DoE) method is an alternative methodology [13]. Based on statistics analysis, it provides the maximum amount of relevant information with a selected number of experimentations. Different families of DoE exist: full factorial, fractional, composite and D-optimal designs. The application of these methods in the field of civil engineering is recent. Full factorial, fractional and composite designs are specifically used for regular experimental regions where every corner of the region of experiments is accessible [14]. For example they make it possible to study mortar composition [15] or the influence of Nano-Silica on the compressive strength and water absorption of mortar mixes [16]. A factorial design was also built for assessment of properties of recycled concrete for optimization of the compressive strength of rubberized concrete [17] and for development of self-compacting concretes [18]. Concerning the composite design, it was used for statistical research on phase formation and modification of alite polymorphs in cement clinker [19]. D-optimal design is a computer-aided design, more specifically used for irregular experimental regions [20,21]. This irregularity is due to restrictions of the experimental region imposed by specific constraints [14].

The mixture design is a particular design, adapted to study responses depending on the proportion of mixture components. Such a design originally developed in the fields of chemistry and agronomy [22,23] was also recently used in civil engineering. Some authors used mixture design to develop formulations of low-strength materials containing polymer concrete [24] or mine tailings [25]. Enhancing the properties of ceramic and pozzolanic products through mixture design was studied by Nardi et al. [26]. More application of mixture design in civil engineering can be found in Yeh et al. [27], Chen et al. [28], Senff et al. [29]. In the search for economic and ecological materials, Kupaei et al., [30] used the mixture design to produce geopolymer lightweight concrete using locally available waste materials.

The main objective of this paper was to optimize the formulation of raw earth concrete with the aim of improving the mechanical strength. To fulfill this objective, the statistical combinations of four-constituent mixtures composed of Portland cement, silt, lime and water were formulated by a D-optimal mixture design to study unconfined compressive strength. The experimental domain was defined based on different constraints and choices that are presented. The mixture design of experiments used to establish model formulations after 7, 28 and 90-day of curing times. The derived models were validated. The influence of each mixture component on the unconfined compressive strength of raw earth concrete was then studied with the contour plots. Finally, results were analyzed to improve and optimize formulations of raw earth concrete materials with two binders (cement and lime) using silt and water.

2. Materials and experimental methods

2.1. Materials

2.1.1. Soil material

The used material is natural silt, chosen because it is a local material, available in abundance at the site of the planned construction.

Concerning particle size, the analysis is carried out by different methods, depending on the particle diameters:

- by sieving (dry after washing according to NF P 94-056 standard [31], or wet according to XP P 94-041 standard [32]) for particles with diameters between 80 μm and 100 mm.
- by sedimentation for particles with diameters less than 80 μm according to NF P 94-057 standard [33].

Table 1 and Fig. 1 show the grading size curve, the effective diameter (D_{10}), the size of the 60% passing granulates (D_{60}), the Hazen uniformity factor ($C_u = D_{60}/D_{10}$) and the curvature factor ($C_c = D_{30}^2/(D_{60} \times D_{10})$). The results highlight a sandy loaminess material. The sands (0.06 mm–2 mm) are largely predominant with a content of around 67%. There is also a silt fraction of less than 25% and a small gravel fraction of less than 8%. Moreover, the material has a spreading grading size curve.

Concerning the liquid limit, and given the presence of a large silty fraction, the test required the use of the Casagrande box with a rough cup.

Concerning the plastic limit, it is almost impossible to measure it according to the NF P 94-051 standard [34]. To estimate the plastic limit parameter, one of the methods consists in using the correlation of Biarez and Favre (1975) [35] which gives the plasticity index value according to the following expression:

$$I_P = 0.73(W_L - 13) \quad (1)$$

where I_p is the plasticity index and W_L is liquid limit.

Based on grading size curve and Atterberg limits, and according to LPC-USCS (ASTM D2487-11) standard [36], this material is classified as silty sand (SM).

2.1.2. Binders

Two binders are used, lime and cement. The lime used comes from the Proviacal® DD range, produced by Lhoist group, according to the European standard EN 459-1. It is a calcic quicklime CL 90-Q (R5, P3), containing 90.9% available CaO and reactivity t_{60} = 3.3 min [37]. The cement is CEM I 52.5 N, according to the NF EN197-1 [38], NF P15-318 [39] and NF EN196-10 [40] standards. It is a Portland

Table 1
Silt properties.

Grain distribution	Fines content (<80 μm)	35%
	Clay particles (<2 μm)	0
	Effective size D_{10} (μm)	32
	Uniformity coefficient $C_u = D_{60}/D_{10}$	4.37
	Gradation coefficient C_c	0.94
Atterberg limits	Liquid limit w_L	20%
	Plasticity index I_p	6%
Clay	Methylene blue test value VBS	0.5

D_{60}: Diameter corresponding to 60% finer in the particle-size distribution.