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Use of by-products as additives in adobe bricks: Mechanical properties characterisation

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HIGHLIGHTS

- Six by-products from agricultural, transport and appliances are added into adobe.
- A three-level design of experiments is done to evaluate the effect of the additives.
- Flexural and compressive strength of optimised formulas are tested and evaluated.

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ABSTRACT

Six by-products are used as additives in adobe bricks to study the variability of mechanical properties by a three level design of experiments and to evaluate optima formulations. Corn plant, fescue, straw, and grounded olive stones are agricultural by-products; and rubber crumbs and polyurethane are wastes used as transport and appliances by-products. Results show that the three-level design of experiments defines properly the governing equations of flexural and compression strength, furthermore it shows the interaction between them. A maximum improvement of 89% and 26% of flexural strength in corn plant and fescue types, respectively, is achieved.

1. Introduction

According to Gonzalez et al. [1], by the selection of low environmental impact construction materials a 27% of CO_2 emissions can be reduced. Nearly zero energy buildings are one of the goals to achieve by the EU Member States in 2020 [2] because it is well known that the building sector is one of the highest energy consumers in the world, representing 32% of the total global energy use being one of the largest end-use sectors worldwide [3].

Nowadays, buildings are composed by conventional materials which have high embodied energy. The reduction of the energy consumption in buildings can be achieved [4,5] by using local materials as Morel et al. [6] which successfully achieves a reduction of 215% and 285% of the buildings embodied energy by using local materials (stone and rammed earth, respectively). Furthermore, if materials with high environmental impact are replaced by more environmental friendly materials, the energy consumption of building can be reduced remarkably [1]. In Spain, ceramics are the second most used material in a building, representing around 20% in weight of the whole building after stone and granular materials (which represents a 53%) taking into account a study carried out with 200 buildings in Spain [7]. The production of ceramics present high environmental impact in the extraction zones and consumes high amounts of energy, water and resources. Ceramics represents a 21.5% of the primary energy demand and a 20.3% of the CO_2 emissions associated with the manufacture of the materials needed in the construction of 1 m^2 in a Spanish standard block of flats [8]. By using non-fired bricks (adobe), the demand of bricks in buildings can be reduced and even covered; in addition, the impact during the manufacture is substantially reduced due to their low-tech process.

The Spanish Legislation 22/2011 defines "valuation" as any operation to replace other materials by a waste thus, the aim of the valuation is to use wastes as a useful material without processing it; "recycling", as any disposal operation to transform wastes in new products, materials or substances; and finally "by-products", as a substance or object, resulting of a manufacture process, when it can be used without any transformation (it is the results of another production process, environmentally friendly and does

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not harm human health). To build sustainable and affordable housing for the future it is advantageous to create links between local agriculture and the construction industry [9,10]. Sustainability can only be possible when construction uses renewable materials or materials recycled from construction wastes [11].

There are some studies where mechanical and physical properties of adobe bricks are studied. In [12], the compressive strength of adobe bricks with different stabilizers (plastic and straw fibres) is tested and the results show an improvement on the compressive strength by the addition of fibres. Otherwise, in [13] the authors conclude that compressive and tensile strength decreases by adding and increasing fibres content.

In the present study, six by-products from several fields are selected to be used as adobe bricks additives and they can be classified by its shape as fibres and pellets. Four of them are agricultural by-products, corn plant, fescue, straw (fibres) and grounded olive stones (pellets). Rubber crumbs from pneumatic tyres and polyurethane from refrigerators insulation are used as by-products (pellets). The aim of the investigation is to study the variability of mechanical properties of adobe bricks with different by-products used as additives within a design of experiments (DoE) by using percentages between 1–3% of fibres and 5–15% of pellets (in weight). Finally, the last part of this study consists on calculating and evaluating the optima formulations by maximising only the flexural strength, and by maximising the flexural strength and the amount of additives. Moreover, compressive strength of optima formulations is also measured and evaluated.

2. Materials

Adobe bricks samples are composed by clay, sand and one type of additive. Six different by-products, which are fibres and pellets, are used as additives in order to evaluate the variability of mechanical properties of adobe bricks Fig. 1. Different percentages of additives are used depending on their shape because their densities are notably different, using lower percentages of fibres than pellets. Table 1 shows the range (maximum and minimum) of materials used in each sample during the experimentation. The sand is named as the matrix of the adobe bricks. For this reason, the percentage used in both cases is the same. The clay used is commercialised by Ceràmica Almacelles S.A. and it is composed by quartz (25–39%), illite (17–25%), chlorite and kaolinita (21–25%), feldspar (10–11%), calcite (13–21%), and others (3–5%), according to technical characteristics provided by the supplier. The sand is marketed by Nordvert of Grup Sorigué with a particle diameter of $1 > \phi > 4$ mm. In this study, corn plant, fescue and straw are the fibres used and they are commercialised by Farratges La Noguera SL. Rubber crumbs from pneumatic tyres are commercialised by GMN S.A., polyurethane pellets from refrigerators are provided by RAEES, and grounded olive stones were provided by Cooperativa Agrícola d'Almoster SCCL.

Straw, fescue, corn plant and olive stones are four by-products from the agricultural industry which are local, abundant and economic. The selection of these materials was done in order to revalue some agricultural by products which could be perfectly reintegrated into the earth once the building has been demolished. The addition of rubber crumbs and polyurethane could improve the thermal properties of adobe bricks, moreover, they are two abundant local wastes and a revalorisation could be also a good option. Even though the reintegration of adobe bricks with these types of wastes into the earth is not possible, the reutilisation of the material once the building is demolished could be an interesting option because there are no chemical reactions in the material.

Some parameters were fixed as the mass of each sample (sand, clay and additive) and the amount of water, which were 500 g and 120 g, respectively. The amount of water represents around 20% of the total mass (sand, clay, additive, and water).

Straw is an additive popularly used in adobe bricks composition. For this reason, adobe brick with straw as additive is used as the reference material during the experimentation in order to compare the results obtained by the other five additives which have never been tested before.

Table 1
Adobe bricks composition.

	Fibres		Pellets	
	Min.	Max.	Min.	Max.
Sand [% in wt.]	15	40	15	40
Clay [% in wt.]	57	84	45	70
Additive [% in wt.]	1	3	5	15

3. Methodology

3.1. Design of experiments

In order to evaluate how additives affect on the flexural and compressive strength of adobe bricks, a design of experiments is carried out using Design Expert® software. This methodology allows maximum information with minimum number of experiments.

A three-level design (*3k* factorial design) was chosen in this study. It means that *k* factors are considered, each at 3 levels (0, 1, and 2) which are referred to as low, intermediate and high levels. A third level for a continuous factor facilitates investigation of a quadratic relationship between the response and each of the factors [14]. In this case two-factors with centre points were used (3^2) as Fig. 2 shows. Factor A is represented by sand and Factor B is represented by additives.

The addition of centre point runs (see number 11 in Fig. 2) in a design of experiments has two purposes: to provide a measure of process stability and inherent variability and to check for curvature. In this three level factorial design four centre point runs are added interspersed among the experimental setting runs, therefore each design of experiments has 13 runs.

3.2. Optimisation process

The optimisation process is done in order to evaluate the variability of compressive and flexural strength due to the incorporation of additives in the ranges selected and thus, to select the optima formulations: (1) with mechanical properties maximised, without controlling the amount of additives; and (2) with mechanical properties also maximised and maximising the amount of additives.

Flexural strength and compressive strength were tested using Incotecnic MUTC200 equipment following the standard UNE-EN 196-1 [15]. Flexural strength was calculated following Eq. (1) where R_f is the flexural strength (N/mm^2), F_f is the maximum force at break point (*N*), *b* is the squared section of the prism (mm) and, *l* is the distance between the holders (mm).

$$R_f = \frac{1.5 \cdot F_f \cdot l_f}{b^3} \quad (1)$$

Compressive strength was calculated by Eq. (2) where R_c is the compressive strength, F_c is the maximum force at break point, and *A* is the area of the plates used in the assay (1600 mm^2).

$$R_c = \frac{F_c}{A} \quad (2)$$

The equipment Incotecnic MUTC200 has an associated error of ±0.2 kN. Samples of 40 × 40 × 160 mm were made in the laboratory with a constant temperature, around 20–22 °C.

4. Results and discussion

4.1. Optimisation process

Flexural strength of three types of adobe bricks with vegetable fibres was analysed by the DoE and the results of each run are listed in Table 2. Fescue samples have the best flexural strength behaviour achieving between 0.330 and 0.605 N/mm^2. On the other hand, the lowest results were obtained with straw samples,