# Use of by-products as additives in adobe bricks: mechanical properties characterization

Susana Serrano, Camila Barreneche, Luisa F. Cabeza.

GREA Innovació Concurrent, Edifici CREA, University of Lleida, Lleida, Spain, Phone: 34-973003576, Fax: 34-973003575, e-mail: lcabeza@diei.udl.cat

## 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.

**Key words:** sun-dried brick, compressive strength, flexural strength, design of experiments, vegetal fibres, pellets.

## 1. Introduction

According to Gonzalez et al. 2006 [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 [7]. 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 [8]. 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 [9]. 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 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 [10,11]. Sustainability can only be possible when construction uses renewable materials or materials recycled from construction wastes [12].

There are some studies where mechanical and physical properties of adobe bricks are studied. In [13], 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 [14] 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 maximizing only the flexural strength, and by maximizing 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. 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 commercialized 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 revalorization 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 reutilization of the material once the building is demolished could be an interesting option because there are no chemical reactions in the material.

**Figure 1. Fibres (up) from left to right: straw, corn plant and fescue. Pellets (down) from left to right: olive stones, rubber crumbs, and polyurethane.**

**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 |

Some parameters were fixed as the mass of each sample (sand, clay and additive) and the amount of water, which were 500 g and 120g, 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.

## 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 [16]. In this case two-factors with centre points were used ($3^2$) as Figure 2 shows. Factor A is represented by sand and Factor B is represented by additives.

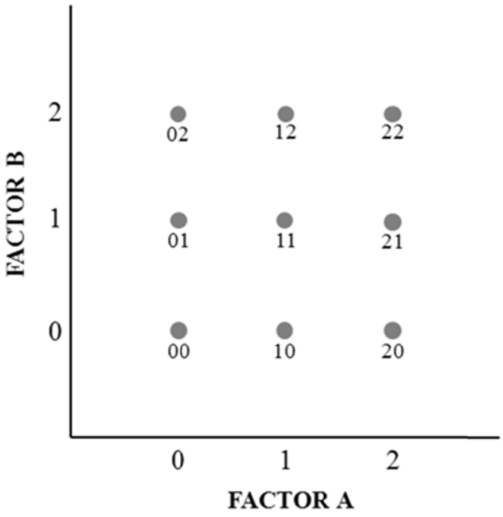


**Figure 2. $3^2$ design schematic**

The addition of centre point runs (see number 11 in Figure 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. Optimization process

The optimization 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 maximized, without controlling the amount of additives; and (2) with mechanical properties also maximised and maximizing the amount of additives.

Flexural strength and compressive strength were tested using Incotecnic MUTC200 equipment following the standard UNE-EN 196-1 [17]. 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).

$$R_f = \frac{1.5 \cdot F_f \cdot l_f}{b^3} \qquad \text{Eq. (1)}$$

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$^2$).

$$R_c = \frac{F_c}{A} \qquad \text{Eq. (2)}$$

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

## 4. Results and discussion

### 4.1. Optimization 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 – 0.605 $N/mm^2$. On the other hand, the lowest results were obtained with straw samples, between 0.157 – 0.299 $N/mm^2$. Furthermore, it can be seen that the results of compressive strength were very similar. Adobe bricks with fibre corn plant (CP) achieve from 1.980 to 3.253 $N/mm^2$, with fescue (F) between 1.937 – 2.884 $N/mm^2$ and, with straw (S) 2.047 – 2.908 $N/mm^2$.

**Table 2. DoE Flexural and compressive strength results of adobe bricks with fibres.**

| Run | Sand (%) | Clay (%) | Fibres (%) | Corn plant (CP) | | Fescue (F) | | Straw (S) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Rf ($N/mm^2$) | Rc ($N/mm^2$) | Rf ($N/mm^2$) | Rc ($N/mm^2$) | Rf ($N/mm^2$) | Rc ($N/mm^2$) |
| 1 | 27.5 | 70.5 | 2.0 | 0.314 | 2.149 | 0.578 | 2.585 | 0.279 | 2.569 |
| 2 | 40.0 | 58.0 | 2.0 | 0.306 | 2.365 | 0.486 | 2.405 | 0.196 | 2.071 |
| 3 | 27.5 | 70.5 | 2.0 | 0.395 | 2.157 | 0.562 | 2.365 | 0.275 | 2.696 |
| 4 | 40.0 | 57.0 | 3.0 | 0.347 | 3.253 | 0.487 | 2.338 | 0.271 | 2.908 |
| 5 | 27.5 | 70.5 | 2.0 | 0.346 | 2.612 | 0.549 | 2.425 | 0.287 | 2.090 |
| 6 | 27.5 | 70.5 | 2.0 | 0.361 | 2.309 | 0.555 | 2.367 | 0.287 | 2.047 |
| 7 | 40.0 | 59.0 | 1.0 | 0.251 | 2.610 | 0.605 | 2.884 | 0.157 | 2.141 |
| 8 | 15.0 | 83.0 | 2.0 | 0.396 | 3.226 | 0.373 | 2.248 | 0.251 | 2.281 |
| 9 | 27.5 | 70.5 | 2.0 | 0.322 | 2.209 | 0.519 | 2.310 | 0.271 | 2.265 |
| 10 | 15.0 | 84.0 | 1.0 | 0.295 | 1.980 | 0.330 | 2.483 | 0.196 | 2.483 |
| 11 | 27.5 | 71.5 | 1.0 | 0.302 | 1.998 | 0.468 | 2.187 | 0.177 | 2.560 |
| 12 | 15.0 | 82.0 | 3.0 | 0.381 | 2.982 | 0.436 | 1.937 | 0.299 | 2.438 |
| 13 | 27.5 | 76.5 | 3.0 | 0.314 | 2.584 | 0.420 | 1.972 | 0.285 | 2.059 |

On the other hand, results of mechanical properties of adobe bricks with pellets as additives are listed in Table 3. As expected, flexural strength decreases in the three cases of adobe with pellets if results are compared with straw adobe bricks.

Flexural strength results are very similar in olive O, R and PU being between 0.074 – 0.164 $N/mm^2$, 0.095 – 0.164 $N/mm^2$, and 0.78 – 0.173 $N/mm^2$, respectively. The same behaviour than in flexural strength is observed in compressive strength results (results listed in Table 3), and lower results are obtained by the addition of pellets. The results are between 0.986 – 1.619 $N/mm^2$, 1.206 – 2.521 $N/mm^2$, and 1.233 – 2.627 $N/mm^2$ for O, R and PU, respectively. Rubber crumbs and polyurethane shows similar results but, the addition of olive stones decreases notably compressive strength of the material.

The DoE is statistically significant if p-value is lower than 5% that means that, there is a chance less than 5% that a calculation done by this model can occur due to noise. Compressive and flexural strength results are analysed and DoE show that, the model is statistically significant for flexural strength in the case of S, CP, F and O; however, in the case of R and PU are not significant in the range studied. This result is because of the flexural strength does not change with the percentage of R and PU addition. Hence, the flexural strength will not be dependent neither related with those percentages.

On the other hand, compressive strength is statistically significant in the case of CP, F and O; but, S, R and PU are not statistically significant in the range studied due to the same reason explained before.

**Table 3. DoE Flexural and compressive strength results of adobe bricks with pellets.**

| Run | Sand (%) | Clay (%) | Pellets (%) | Olive stones (O) Rf ($N/mm^2$) | Olive stones (O) Rc ($N/mm^2$) | Rubber crumbs (R) Rf ($N/mm^2$) | Rubber crumbs (R) Rc ($N/mm^2$) | Polyurethane (PU) Rf ($N/mm^2$) | Polyurethane (PU) Rc ($N/mm^2$) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 15.0 | 70.0 | 15.0 | 0.089 | 1.282 | 0.107 | 1.524 | 0.090 | 1.776 |
| 2 | 27.5 | 67.5 | 5.0 | 0.164 | 1.551 | 0.142 | 1.605 | 0.163 | 1.839 |
| 3 | 27.5 | 62.5 | 10.0 | 0.141 | 1.455 | 0.095 | 1.254 | 0.103 | 1.709 |
| 4 | 27.5 | 62.5 | 10.0 | 0.132 | 1.512 | 0.103 | 1.261 | 0.101 | 2.031 |
| 5 | 40.0 | 45.0 | 15.0 | 0.074 | 1.082 | 0.108 | 2.013 | 0.078 | 1.233 |
| 6 | 27.5 | 62.5 | 10.0 | 0.141 | 1.447 | 0.118 | 1.239 | 0.110 | 1.748 |
| 7 | 15.0 | 80.0 | 5.0 | 0.160 | 1.619 | 0.105 | 2.521 | 0.104 | 2.627 |
| 8 | 40.0 | 55.0 | 5.0 | 0.109 | 1.358 | 0.117 | 1.704 | 0.110 | 1.333 |
| 9 | 27.5 | 62.5 | 10.0 | 0.125 | 1.227 | 0.136 | 1.882 | 0.142 | 2.144 |
| 10 | 27.5 | 62.5 | 10.0 | 0.137 | 1.294 | 0.158 | 1.805 | 0.173 | 1.550 |
| 11 | 27.5 | 57.5 | 15.0 | 0.102 | 0.986 | 0.164 | 1.206 | 0.131 | 1.611 |
| 12 | 40.0 | 50.0 | 10.0 | 0.110 | 1.105 | 0.102 | 1.400 | 0.137 | 1.573 |
| 13 | 15.0 | 75.0 | 10.0 | 0.120 | 1.035 | 0.138 | 1.621 | 0.137 | 1.455 |

Moreover, p-values and higher and lower flexural and compressive strength obtained in models statistically significant in the range studied are listed in Table 4,

**Table 4. P-value, maxima and minima flexural and compressive strength of DoE.**

|  | Flexural strength |  |  | Compressive strength |  |  |
|---|---|---|---|---|---|---|
|  | **FIBRES** |  |  |  |  |  |
|  | **CP** | **F** | **S** | **CP** | **F** | **S** |
| **p-value** | 0.0318 | 0.0259 | 0.0014 | 0.0375 | 0.0092 | - |
| **$R_{max}$** | 0.395 | 0.605 | 0.299 | 3.253 | 2.881 | - |
| **$R_{min}$** | 0.251 | 0.330 | 0.157 | 1.980 | 1.937 | - |
|  | **PELLETS** |  |  |  |  |  |
|  | **O** | **R** | **PU** | **O** | **R** | **PU** |
| **p-value** | 0.0034 | - | - | 0.0326 | - | - |
| **$R_{max}$** | 0.164 | - | - | 1.619 | - | - |
| **$R_{min}$** | 0.074 | - | - | 0.986 | - | - |

The equations defining the behaviour and, therefore, the optima formulations of adobe bricks with fibres as additives are given by Eq. (5) and (6) for CP type, Eq. (7) and (8) for F type, and Eq. (9) for S type (where $R_c$ is compressive strength, and $R_f$ is flexural strength).

$$R_{f(CP)} = 0.31809 - 1.87371 \cdot 10^{-003} Sand + 0.032299 \cdot CP \qquad \text{Eq. (5)}$$

$$R_{c(CP)} = 2.4950 \qquad \text{Eq. (6)}$$

$$R_{f(F)} = -0.27171 + 0.0336 \cdot Sand + 0.27099 \cdot F - 4.4819 \cdot 10^{-3} \cdot Sand \cdot F \\ - 3.424 \cdot Sand^2 - 0.039395 \cdot F^2 \qquad \text{Eq. (7)}$$

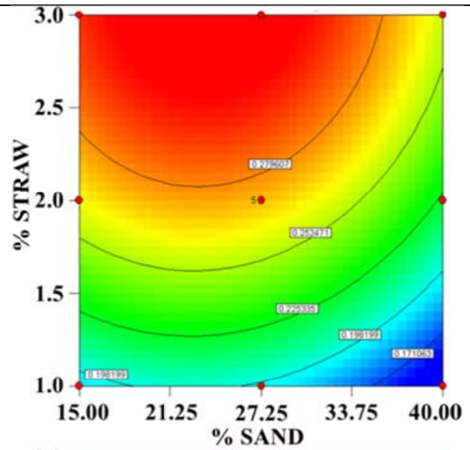
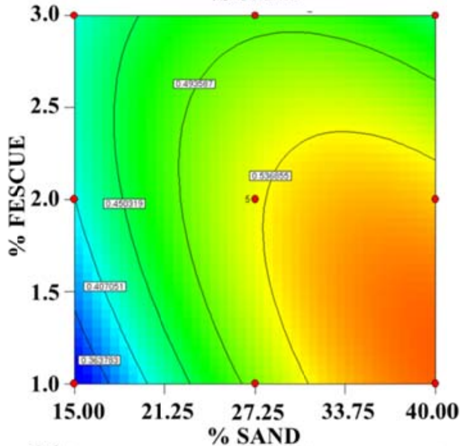
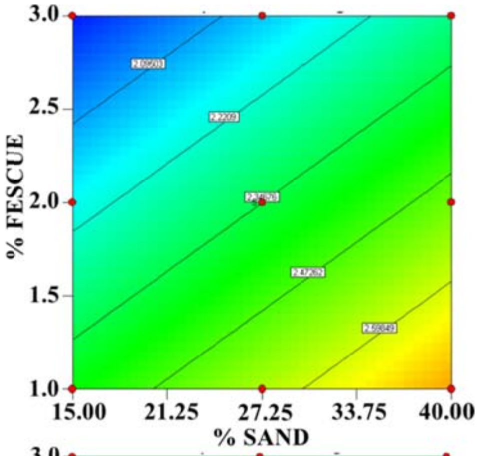
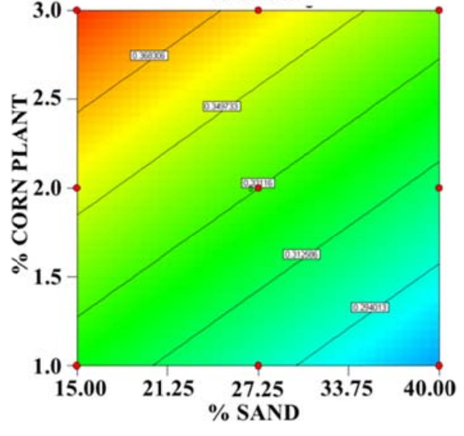
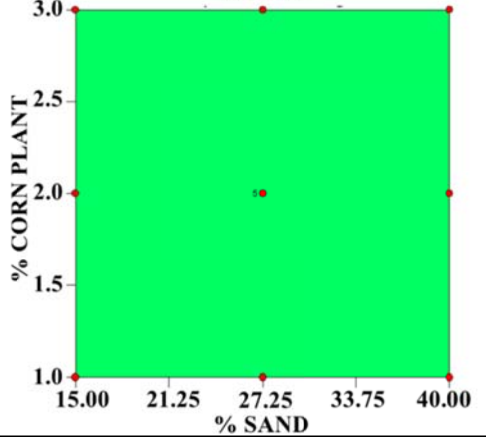
$$R_{c(F)} = 2.43083 + 0.01278 \cdot Sand - 0.2178 \cdot F \qquad \text{Eq. (8)}$$

$$R_{f(S)} = -5.97 \cdot 10^{-003} + 8.0627 \cdot 10^{-003} \cdot Sand + 0.13548 \cdot S + 2.354 \cdot Sand \cdot S - 1.847 \cdot Sand^2 - 0.0219 \cdot S^2 \quad \text{Eq. (9)}$$

Eq. (10) and (11) defines the optima formulations of O type.

$$R_{f(O)} = 0.20733 - 5.59987 \cdot 10^{-003} \cdot O - 1.02269 \cdot 10^{-003} \cdot Sand \quad \text{Eq. (10)}$$

$$R_{c(O)} = 1.84086 - 0.039305 \cdot O - 5.22546 \cdot 10^{-003} \cdot Sand \quad \text{Eq. (11)}$$

| **FLEXURAL STRENGTH** | **COMPRESSIVE STRENGTH** |
|---|---|
|  | |
|  |  |
|  |  |

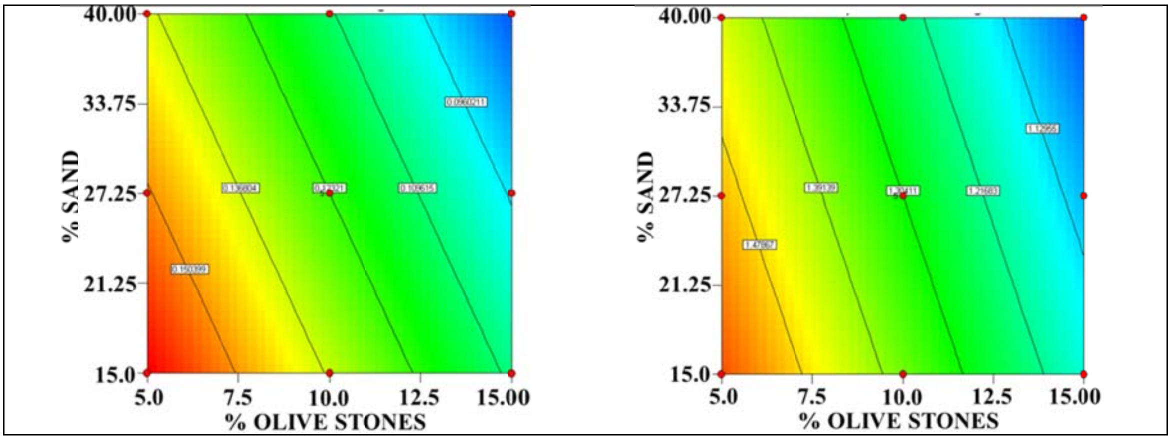


**Figure 3. Flexural and compression strength behaviours of adobe bricks compositions**

The behaviour of flexural and compressive strength of adobe bricks with additives is shown in Figure 3 by a colour scale (warm colours mean higher results and cold colours lower results). Straw and fescue flexural strength show a quadratic behaviour.

Straw type shows an enhancement of flexural strength if the amount of straw is maximized and the amount of sand is minimized. In fescue case, flexural strength is maximized by decreasing the amount of fibres and increasing the amount of sand.

On the other hand, flexural strength of corn plant and olive stones adobe bricks shows a linear behaviour where, in the case of corn plant flexural strength is maximized by increasing the amount of fibres and decreasing the amount of sand and, in the case of olive stones, flexural strength is maximized if sand and olive stones are minimized.

Compressive strength shows a linear behaviour with fescue and olive stones types but fescue type increases compressive strength if sand is maximized and fibres minimized, while olive stones has its maximum compressive strength by minimizing the amount of fibres and sand. Compressive strength of corn plant type remains constant in the range studied with affecting neither the amount of sand nor the amount of fibres.

The optima formulations listed chosen have: (1) flexural strength maximized (Table 5) and (2) the additive content maximized as well as flexural strength (Table 6). Furthermore, compressive strength results obtained with optima formulations are also calculated.

**Table 5. Optima formulations by maximizing flexural strength.**

| | Rf ($N/mm^2$) | Desirability | Sand (%) | Clay (%) | Additive (%) | Rc ($N/mm^2$) | Desirability |
|---|---|---|---|---|---|---|---|
| **S Type** | 0.3067 | 1.00 | 23.95 | 73.05 | 3.00 | - | - |
| **F Type** | 0.5801 | 0.91 | 40.00 | 58.84 | 1.16 | 2.6818 | 0.98 |
| **CP Type** | 0.3869 | 0.94 | 15.00 | 82.00 | 3.00 | 2.4950 | 0.74 |
| **O Type** | 0.1640 | 0.99 | 15.00 | 80.00 | 5.00 | 1.5660 | 0.97 |

**Table 6. Optima formulations by maximizing flexural strength and additive.**

| | Rf ($N/mm^2$) | Desirability | Sand (%) | Clay (%) | Additive (%) | Rc ($N/mm^2$) | Desirability |
|---|---|---|---|---|---|---|---|
| **S Type** | 0.3067 | 1.00 | 23.12 | 73.88 | 3.00 | - | - |
| **F Type** | 0.4984 | 0.75 | 30.44 | 66.70 | 2.86 | 2.0730 | 1.00 |
| **CP Type** | 0.3869 | 0.97 | 15.00 | 82.00 | 3.00 | 2.4950 | 0.74 |

|  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|
| **O Type** | 0.1189 | 0.63 | 15.00 | 71.94 | 13.06 | 1.2491 | 0.64 |

The optima formulations with flexural strength maximized show that F type achieves the highest flexural strength (0.5801 N/mm$^2$), followed by CP (0.3869 N/mm$^2$) and S type (0.3067 N/mm$^2$). The lowest results are obtained with olive stones as additive (0.1640 N/mm$^2$). Compressive strength has the same trend.

When flexural strength is maximized as well as the amount of additives, F type shows the higher results (0.4984 N/mm$^2$) and O type the lowest (0.1189 N/mm$^2$). However, in compressive strength CP type has the higher value (2.4950 N/mm$^2$).

## 5. Discussion

In the present study, six types of additives with two different shapes (fibres and pellets) are added into adobe bricks. The fibres used are straw “S” (used as the reference material), corn plant “CP” and fescue “F”; on the other hand, the pellets used as additives are olive stones “O”, polyurethane “PU” and rubber crumbs “R”. Four of them are agricultural by-products and, the others, transport and appliances wastes. Mechanical properties as flexural and compressive strength are evaluated by three level designs of experiments. The optima formulations of the statistically significant models are calculated by using different equations given by the models. The results of optima formulations are achieved by fixing different parameters: (1) maximizing the flexural strength and, (2) maximizing the flexural strength and the percentage of additives. Finally, compressive strengths are calculated by using the equations of the model and by using the dosages of the optima formulations previously calculated. The non-statistical-significant models are discarded in the study because the response is not related with the by-product percentage added.

Before the optimization process[1] it is noticed that flexural strength is notably improved by the addition of F (0.330 – 0.605 N/mm$^2$) if results are compared with S type as the reference (0.157 – 0.299 N/mm$^2$), and slightly improved (0.251 – 0.395 N/mm$^2$) in the case of CP type.

On the other hand, compressive strength obtained with F (1.937 – 2.884) and CP (1.980 to 3.253) is similar to the reference S (2.047 – 2.908 N/mm$^2$)[1] type. However, the addition of pellets into adobe decreases notably the flexural strength in all cases (O (0.074 – 0.164 N/mm$^2$), R (0.095 – 0.164 N/mm$^2$) and PU (0.078 – 0.173 N/mm$^2$)) as well as compressive strength (O (0.986 – 1.619 N/mm$^2$), R (1.206 – 2.521 N/mm$^2$) and PU (1.233 – 2.627 N/mm$^2$)), obtaining the lowest results by O type.

The three level designs of experiments show that the models are statistically significant in the range studied in all cases, except R and PU types. Both, F and CP, are statistically significant in flexural and compressive strength; and S type in compressive strength. This means that the flexural and the compressive strength of each type can be defined by an equation with a maximum error of 5% in the range studied. The no-statistically significant types have been discarded due to possible unreliable results.

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[1] Minimum and maximum value obtained of flexural and compressive strength in the 13 runs of the DoE

The optimization process provides the equations of the optima formulations (Eq.5-11) and, in addition, shows the behaviour of the materials. The optima formulations with flexural strength maximized show that flexural strength of F and CP are improved 89% and 26%, respectively. However, flexural strength of O type decreases 46%. On the other hand, the higher compressive strength is achieved by F type (2.6818 N/mm$^2$), followed by CP Type (2.4950 N/mm$^2$) and O type (1.5660 N/mm$^2$). The behaviour of the materials follows the same trend if flexural strength and the amount of fibres are maximized, by improving 62% the flexural strength of F, 26% CP type and, decreasing 61% the flexural strength of O type.

Taking into account results of compressive strength, the maximum values are obtained by CP type (2.4950 N/mm$^2$) and F type (2.0730 N/mm$^2$), and the lower results by O type (1.2491 N/mm$^2$).

## 6. Conclusions

It can be concluded that the three level design of experiments used during the present work is appropriate to define the equations of the material behaviour of F, CP and O for flexural and compressive strength and, for flexural strength in the case of S, with a maximum error of 5% in the ranges studied. Nevertheless, in further studies this model can be used in order to study different ranges.

Furthermore, by observing the behaviour of the materials it can be concluded that flexural and compressive strength of F type increases if the amount of fibres is minimized and the amount of sand is maximized. Otherwise, flexural strength of S type is maximized by increasing the amount of fibres and decreasing the amount of sand and CP type follows the same behaviour. In the case of O type, flexural and compressive properties are maximized if the amount of pellets and sand are minimized.

Finally, the optima formulations evaluated shows that and improvement of flexural strength can be achieved with F and CP type if results are compared with the reference S. However, flexural strength decreases by the addition of olives stones (O). Compressive strength behaviour follows the same trend than flexural strength.

To sum up the most relevant conclusions obtained in the present experimentation, flexure strength can be improved by the addition of S and CP but, contrary, F and O are not recommended to increase flexural strength of the adobe bricks. On the other hand, the addition of additives is, in general, not recommended to increase compressive strength, except in CP, where compressive strength remains constant in the range studied.

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