Analysis on the mechanic resistance and water absorption capacity of prototype mortar with residual coconut mesocarp and fiber aggregates

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Abstract. Material physics has traditionally been used in the area of mechatronics and aeronautical engineering. However, in recent years, bioclimatic architecture has used physical principles and conservation of matter to evaluate the performance of buildings where the comfort and safety of its inhabitants are sought, with the mortar being an adequate alternative in minimizing heat transfer. However, this material is fragile and has a high risk of fragmentation. This problem has been addressed through the incorporation of inorganic aggregates to maximize their mechanical properties but the cost of production is high compared to the traditional process. This work proposes the analysis of cement-sand modules with coconut endocarp and mesocarp (coconut fiber) aggregates, by evaluating their mechanical resistance, under a compressing force, and permeability and comparing to current regulations. The results showed that coconut fiber has a large impact on the mechanical resistance of the prototypes: a proportion of fiber greater than 3% compromises the mechanical resistance of the prototypes due to the water adsorption capacity of coconut fiber. Whereas, the prototypes identified under the endocarp to fiber ratio of 10% to 1% showed the highest performance in the deformation tests under compression with respect to the modules without the presence of this waste material. The resulting mixture meets the Mexican standard for mortar and could be an alternative for avoiding the burning of plant residues in regions with an active coconut industry.

1. Introduction
In recent years, climatic change has become a problem with worldwide scale. Evidence of it’s impact has began to be observed in many aspects of our common life at mid and long term [1]. To minimize these effects has become the task of scientist, technologist and specialists from a wide variety of areas, who have proposed diverse strategies that go from actions like encouraging an energy saving life style to the creation of energy plants that are able to benefit from using clean energy and renewable resources [2].

Architecture is an area of human knowledge that has the potential of becoming very important to minimize the negative effects of climatic change, by proposing diverse strategies: Bio-climatic Architecture developed new ways in which the environmental conditions around a construction site can be used to benefit the life and activities of its occupants, ensuring thermal conform but, at the same time, minimizing energetic costs [3]. Domotics focuses on the incorporation of new technologies into existing buildings to maximize energy saving within their interiors [4]. Despite,
some of these proposals have demonstrated to be promising alternatives, their fabrication cost is still too high for emerging countries [5].

This problematic can be reduced by the use of green materials. These materials should able to conserve the desired properties of conventional building elements while adding a considerable reduction on the contamination levels involved in their making (e.g. the fabrication of materials like concrete and mortar 8% of worldwide man-made CO$_2$ emissions [6]). Also, if these green materials come from typical residues, that are already being produced by socioeconomic human activities, within a certain region, their use as construction materials would greatly benefit construction industry in underdeveloped countries [7].

Within construction industry, mortar, a mixture between sand, cement and water, is very relevant due to its adhesive properties (serving as a bounding material for bricks, blocks and other types of structural elements), being water proof (thus, helping to insulate structural elements from damage by water), being workable (that facilitates its capacity to fill any kind of empty spaces that could debilitating structure and requiring less setting time [8]). Recent studies have found that the mechanical resistance of mortars and their water insulation capacity can benefit by adding all kinds vegetable residues coming from a wide variety of sources [9–12].

Coconut residues are one of the most abundant fruit residues in in México. The Coconut fruit (Cocos Nucifera) is very popular since hydrating water and oil can be extracted from it; its pulp is used in the preparation of food and candies and its shell is a traditional material used to manufacture handicrafts since the pre-Columbian age [13] and, since last century, it is shredded and used as furniture fiber [14]. The elimination of residues from the coconut market usually implies transportation costs, plague proliferation within storage sites and high contamination, due to the large CO$_2$ emission produced by their incineration [15].

Coconut like other fibrous materials such as straw, wood chips, coconut shells, corn stalks have the function of controlling the effect of expansion, retraction, or contraction during setting, that is, these fibers will create networks that will improve the adhesion of the material. In addition to this, these fibers have a stabilizing function as they prevent the appearance of cracks, allowing the structure to be more flexible against seismic movements [16].

In the open literature, the use of coconut fiber to improve physical and mechanical characteristics has been reported; for example Crisanto [17] used different proportions of coconut fiber ash and corn to partially substitute the amount of cement in the concrete construction. The results showed that when using 3% coconut fiber ash and 7% corn cob, the compression capacity of the specimens was reduced compared to the control tests, probably because these organic residues do not comply with the binding properties of cement. González and Lizárraga [18] evaluated the physical-mechanical properties of annealed clay bricks based on organic residues such as coffee, corn, and coconut fiber. These residues were dried and ground; later they proposed different proportions for the creation of blocks and the capacity of adsorption and compression was evaluated. The results showed that the incorporation of coconut fiber with and without other aiding materials do not comply with the Mexican Standard NMX-C-173-ONNCCE-2010 [19], due to the low granulometry of the coconut (which has to be smaller than 1.08 mm).

Since the use of coconut mesocarp residues has not shown promising results; The use of walnut’s shell has been proposed to improve the physical and mechanical properties of building materials [20]; for example, Acosta et al. [21] evaluated the compression of lightweight concrete by partially substituting silicon for the walnut shell. These authors determined that using proportions less than 15% of walnut shell and without the presence of silica, low resistance was obtained. On the other hand, when incorporating silica and 15% shell, a significant increase in the strength of the material was observed, therefore, the incorporation of these materials shows a synergistic effect on the product. Miron et al. [22] proposed the use of the walnut shell as an element to increase the compression and adsorption of gypsum-based blocks. The results
showed that the use of organic residue reduces the mechanical resistance under compression and the adsorption capacity, limiting the use of this proposal. Therefore, the use of walnut’s nutshell used for the creation of compressed earth blocks (CEB) is not recommended. Marte on [23] evaluated the incorporation of walnut’s shell to reduce the proportion of gypsum in the production of CEB. In that work, the shell was ground under different granulometric sizes of 2 mm, 4 mm, and 5 mm. Once separated; The partial replacement of the plaster was carried out under the proportions 5%, 10%, 15%, and 20%. The results showed that the particle size of the walnut was an important factor for the mechanical resistance of the blocks.

Following the successful cases of the use of walnut shell, this work proposes a exploratory study for analyzing and evaluating the mechanical resistance of and water absorption capacity of mortar with residues from coconut fiber and endocarp aggregates, as a part of a larger investigation on the mechanical and thermal properties of mortars with fiber and shell aggregates from residues of different kinds of fruit typical for the occidental region of Mexico

2. Methodology

Apart from common gray cement powder and water, the prototype blocks were manufactured from the following materials.

- River Sand: The size of the granule should not exceed 5 millimeters and any kind of contaminant matter was removed, like vegetable residues or clay granules.
- Coconut shell (endocarp) granules: Made from the mesocarp of coconuts. Should be previously thermally dried out and any fruit residues should have been cleaned. Granules had a size between 2 and 10 millimeters, a an intermediate range between the average size of sand grains and gravel used in typical mortar [24].
- Coconut fiber (mesocarp): Should be previously cleaned and shredded into fine threads. The typical thread longitude was reduced to between 10 mm and 20 mm.

Four kinds of prototype blocks were manufactured. The main difference among them was the proportion of the materials used to prepare the mixture. Table 1 shows the volume percentage within each mixture, compared against a conventional mixture used to make mortar (labeled as witness). Although each group of prototype blocks had increasing percentage proportions of coconut aggregates, all emulated the sand to cement ration of 2-1 from the witness group.

| Group          | Witness | Proto 1 | Proto 2 | Proto 3 | Proto 4 |
|----------------|---------|---------|---------|---------|---------|
| Coconut fiber (%) | 0       | 1       | 2       | 3       | 5       |
| Coconut shell (%)  | 0       | 10      | 5       | 20      | 15      |
| Sand (%)          | 66.0    | 59.6    | 62.0    | 51.3    | 53.4    |
| Cement (%)        | 34.0    | 29.4    | 31.0    | 25.7    | 26.6    |

The proportions of materials shown in Table 1 were weighted with the aid of a digital scale and then put within a plastic container to be mixed. Water was added gradually until a homogeneous mix formed, on the instances in which lumps formed within the mix, the context was discarded and the process was repeated, slowing down the velocity in which water was being poured. After this, the mixture was put within cubic containers with sides of 5 centimeters. The size of the cubes was chosen to follow the Mexican norm NMX-C-173-ONNCCE-2010 [19], care was taken that no air bubbles were formed within the mixture. Once the mixture was put within the cubic containers, they were set by 72 hours and water was poured over the containers at intervals of 3 hours to avoid the formation of cracks on the block’s surface.
The two properties of interest in this work were resistance to mechanical deformation and percentage of water absorbed by the block, after the saturation process was done. The results of blocks made following recipes 1 to 4 (labeled as prototypes 1 to 4) were compared to blocks made up with conventional mortar (labeled as witness). The first test was designed to evaluate the mechanical resistance of each prototype to a compressing force. For this propose, sets of 5 cubes for each prototype and the witness group, like the ones described above, were put within a universal testing machine. For each cube, the universal testing machine applied a compression force until an structural fail within the cubes was measured.

The water absorption test followed the procedure described in [19]. After being set, all the blocks were washed to remove any kind of particles, drained within an oven at 100°C and immersed in distilled water at a temperature around 25°C, for about 24 hrs. After that time period, the blocks were removed from water, allowed to drain and left to rest away from sunlight until their surfaces appeared to be dry. After the surface was dry, the blocks where weighted using a digital scale and the weight of each block ($W_{\text{wet}}$) was recorded. After that, all the blocks were put inside an oven and left to desiccate by about 24 hrs at a temperature around 110°C. The dry weight ($W_{\text{dried}}$) was recorded a second time, after removing them from the oven and left to cool down at ambient temperature as shows Equation (1).

$$\Delta W[\%] = \frac{W_{\text{wet}} - W_{\text{dried}}}{W_{\text{dried}}} \times 100$$  \hspace{1cm} (1)

Equation (1) allows to calculate the percentage of water that was absorbed by the blocks after they were made. The two tests were repeated five times for each prototype group and for the witness group.

3. Results

Table 2 shows the average density of blocks from each prototype group, the force required to produce a fracture when submitted to a load (measured in kilogram-force) and the resulting deformation, measured in millimeters, at the moment of fracture. The second column shows the results for the witness group while the third to sixth column shows results for each prototype group. The blocks from the witness group proved to be more resistant to compression (almost tripling up the effort required to produce an structural fail for blocks within the four prototype groups). This can be understood by looking at their average density, which is about 30% higher than most dense prototype group (prototype group 1).

| Parameter | Witness | Proto 1 | Proto 2 | Proto 3 | Proto 4 |
|-----------|---------|---------|---------|---------|---------|
| Density (g/cm³) | 2.44 | 1.92 | 1.76 | 1.80 | 1.16 |
| Force (kgf) | 392.30 | 124.70 | 122.47 | 83.92 | 0.00 |
| Deformation (mm) | 1.25 | 2.00 | 1.00 | 0.75 | 0.00 |

In Table 2, the blocks from the prototype 1 and 2 groups showed very similar resistances under compression, requiring an average force around 125 and 122 kilogram-force to produce an structural failure. In contrast, those from the third and fourth groups proved to be weaker: group 3 produced blocks that were 75% weaker than those from groups 1 and 2, while blocks from group 4 broke down almost immediately. In terms on the measured deformation, up to the instant in which a structural fail was detected, the blocks from prototype 1 and 2 groups proved to be 60% more flexible than those within the witness group. Blocks from group 2 and 3 were less flexible than the control group, as the measured deformations were 80% and 60% smaller.
Figure 1 shows the average performance of each prototype and witness group to the deformation under compression test. As can be seen, the witness group shows a very steep slope, as a result of its large density and small flexibility. In contrast, blocks from the prototype group 1 presented a deformation about 60% higher than the witness group before failing, with a much less steep slope, thus delaying the break. Blocks from the prototype groups 2 and 3 broke under a similar force but their response to the load, in terms of the slope, was much faster.

![Figure 1. Results for the test for resistance to deformation under a compression force. On the plot, the vertical and horizontal axes correspond to the force.](image)

Table 3 shows the results for the water absorption test (with values obtained at each repetition being averaged). The blocks within the witness group showed to have the smallest retention of water, as their weight varied by around 1.3%. Among the prototype groups, the blocks from groups 4 and 1 showed the highest absorption of water (with a difference in weight of around 38% and 10%).

| Parameter | Witness | Proto 1 | Proto 2 | Proto 3 | Proto 4 |
|-----------|---------|---------|---------|---------|---------|
| ∆W (%)    | 1.3     | 10.4    | 6.8     | 8.8     | 37.9    |
| Coconut fiber (%) | 0 | 1 | 2 | 3 | 5 |
| Coconut shell (%) | 0 | 10 | 5 | 20 | 15 |

4. Conclusions
In this work, the deformation under compression and water absorption capacity of mixtures with coconut’s fiber and mesocarp aggregates was compared that of conventional mortar. Over all, the best mixture (group 1) was able to resist a load of 124.7 $Kgf/cm^2$ (30% of the results from the witness group). Even when this mixture was less resistant to break under a compressing force, it still meets the Mexican norm for two out of three types of common mortars, requiring the mini mun break force to be around 110 $Kgf/cm^2$ (for type 2 mortars) and 60 $Kgf/cm^2$ (for type 3 mortars). In terms of water absorption, all prototype groups showed larger dry to wet differences in weight that the conventional (witness) group, with blocks from group 1 having a difference of around 10%.
Since there are not reported works in which the combination of endocarp and mesocarp have been used for the preparation of mortar a direct comparison of results is difficult to make. However, some of the previous of other works in which vegetable residues have been added to concrete blocks: that the addition of vegetable residues reduce the mechanical resistance; that blocks with vegetable residues are lighter in weight than those made from only from cement and sand (both results obtained from studies with walnut shell or coconut fiber aggregates) and that coconut fiber allows the resulting blocks, submitted to a compressing force, to deform more than blocks made from conventional mortar.

An interesting result of this work is the apparent effect of large fiber proportions over the mechanical resistance of the experimental mortars. Even when blocks from groups 3 and 4 had very similar proportions of the conventional ingredients for the mixture (cement and sand), their shell to fiber ratio was around 6 and 3, respectively. This difference made that while, on average, blocks from group 3 were able to resist a load around $84 \text{ Kg/cm}^2$ (what would made them suitable for being used as type 3 mortars) those from group 4 were extremely fragile, as they were broken just by transportation movement. This results could be explained by the effect of the high porosity of coconut fiber (absorbing large amounts of water that evaporated afterwards, when the blocks were dried out). When absorbed by cement, water aid to increase its strength. However the addition of coconut fiber provides with a material that prevents water in the mixture from being absorbed by cement, thus debilitating the resulting block. If one looks at the difference in weight before and after the blocks were set, blocks from group 4 had the largest difference. Blocks from group 1 had the second largest weight difference, but in their case, this could be explained by the evaporation of the remaining water after the saturation of the mixture. On a future work these apparent dependencies between the mechanical properties of mortars and their volume proportions of fiber and shell materials will be further explored and complemented with thermal tests, to analyze their insulating capacity.

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