Analysis of the mechanical resistance of cement with aggregates of petrous endocarp from macadamia nut

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Abstract. This research evaluates if adding crushed macadamia nutshell to a mixture of cement and sand could result in lighter and more resistant constructive materials. The mechanical resistance under compression of cement blocks made from two different experimental mixtures, in which a certain amount of sand is replaced with crushed nutshell, is compared against two control groups. Results show that blocks made from one of the proposed mixtures got an average resistance around 50% above the controls group while being 3% lighter. Additionally, the physical dependence of the strength of the blocks on the granulometry of the aggregated endocarp fragments, and their percentage to the volume of cement, was studied thanks to contour plots developed from a factorial design of the data.

1. Introduction

In recent years the use of organic waste materials in the construction industry has increased, as a strategy for environmental and economic improvement [1]. Unlike traditional inorganic materials, organic waste has a shorter biodegradation time, and its manufacturing process is designed to minimize pollution [2], while their intrinsic properties (like hardness or porosity), along with their relative abundance, present a clear advantage for being employed in construction industry. Thus, various investigations have resulted in efficient constructive elements with organic aggregates that match or improve some characteristics of common industrialized materials [3].

Some examples are: bamboo as a building material [4], agave fiber as a reinforcement of concrete [5], ixtle fiber for the reinforcement of a polymer matrix for concrete [6], coconut fiber as complement for mortar [7], the petrous endocarp of indian nut in concrete [8], nano-palm oil fuel ash and nano-eggshell powder on concrete [9]. Some authors have proposed the use of petrous endocarp of pecan nut [10] and the petrous endocarp of chandler walnut [11] as a substitute for river sand in cement mixtures as an alternative to reduce the weight of the constructive elements, while not risking the mechanical resistance under compressive stress.

Cement is produced by incurring its natural components, using large amounts of fuel and thereby causing environmental pollution [12]. The manufacturing of constructive materials made from cement involves a high demand for sand, often providing bulk, strength, and stability to other materials like concrete, cement, and mortar. However, sand extraction usually involves several forms of environmental contamination like the change in natural channels,
water contamination related to the movement of the earth or the discharge of by-products, deforestation, and destruction of habitat.

In contrast to sand, the petrous endocarp is a by-product of macadamia nut industry, an inert and safe surplus. The hardness and porosity of the petrous endocarp of the macadamia nut make it a promising candidate to improve the mechanical resistance of cement blocks while also reducing their weight, make them less prone to retain water or to conduct heat without affecting the chemistry of the mixture. This could result in resistant structural elements for the construction industry which could offer mechanical and thermal advantages.

This work describes the design and creation of a new efficient and ecological cement by using the petrous endocarp of macadamia nut. The normal compressive stress required to produce a fracture of two families of experimental blocks was compared against that of conventional Portland cement blocks. Likewise, since the petrous endocarp of macadamia nut is a strong but light material, the relative weights of the blocks were compared. The data obtained were used to create contour diagrams that allowed the analysis of normal compressive stress as a response variable to the volumetric portion and granulometry of endocarp aggregates.

2. Methodology
The present investigation was carried out within the laboratories of applied research and innovation and mechatronics of the Technological Institute of Colima, México. All the blocks were prepared from the following base materials:

- Powder cement: used as a binder in mixtures of constructive materials, like sand or gravel, for preparing constructive elements that require mechanical resistance [13]. The powder cement used in this work was obtained from a local hardware store.

- River sand: obtained from a local hardware shop. All kinds of contaminants, either organic or inorganic, were removed by washing with purified water. A sieve was used to ensure that the sand granules were smaller than 5 millimeters [14].

- Petrous nut endocarp: the most external layer of macadamia nut. It is characterized by its hardness and woody texture. The material was obtained from local producers. The nut pulp residues were removed and dried. The waste was crushed in a manual mill, resulting in grains whose size does not exceed 5 millimeters, to emulate the maximum grain size of sand.

A total of 52 prototype blocks were prepared to evaluate if there was an enhanced mechanical resistance in cement with aggregates of crushed petrous endocarp of macadamia nut. These blocks were arranged in fourteen groups, representing variations of two specific mixtures of cement and sand: 1 serving of cement and 4 of sand (labeled as “1:4”) and 1 serving of cement and 6 of sand (labeled as “1:6”).

On each of these mixtures, there were two control subgroups (prepared from mixtures of cement and sand only) and five experimental groups, with a small amount of sand (either 5% or 20%) replaced by an equal amount of crushed petrous endocarp. Each experimental group of blocks had three variations defined by the average diameter of the endocarp granules: (a) fine grains, smaller than 1.5 mm, (b) Thick grans, at the range within 1.5 mm and 5 mm and (c) an heterogeneous mix of fine and thick grains. The ratio of percentage of substitution of stone endocarp by river sand and granulometry is detailed in Table 1.

Each one of the mixtures shown in Table 1 were prepared by dry mixing all materials within a plastic container and adding slowly pouring water until and homogeneous paste was obtained. A series of polystyrene cubes, with edges of 5 cm, served as molds for the blocks. Given its relative fragility, polystyrene was an optimal choice to avoid damaging the blocks during their unmolding.
The size of the block was chosen so that these would, simultaneously, comply with the Mexican standard in [14] and fit within the hydraulic universal testing machine at our disposal. The paste from each mixture, was poured into the cubic molds, until it reached their upper border. A wooden square plunge was used to slowly press the paste, ensuring the elimination of bubbles. This process was repeated multiple times until until each mold was completely full. Small amounts of water were poured during the curing time to avoid the fracturing of the blocks.

After the curing process was finished, all the blocks were submitted to direct exposure to sunlight and to the air stream produced by a household ventilator. Most of the moisture within the blocks was removed after 72 hours of exposition. Figure 1 shows the blocks made at the end of the drying time. The compressive stress tests were performed by submitting the block to the pressure generated by the plunger of a Shimadzu hydraulic universal testing machine, model UH-500 Kni [15].

The blocks were randomly selected and put under the plunge of the testing machine, taking care that the lower edge of the block was resting on the smooth surface of the machine to avoid failure due to torsional fatigue. The machine was activated and the plunge exerted a growing compressive stress at the upper edge of the block until a fracture was recorded by the pressure sensor on the machine. Then, the results of the test were used to construct a factorial design which would allow to analyze the effect of the proportion of petrous endocarp and its granulometry on the necessary compressive stress to produce a fracture on the blocks.

Table 1. Dosages for each of the mixtures used from two families (in percentage).

| Family | Mixture | Control (5%) | Mixed Fine (5%) | Thick (5%) | Mixed (20%) | Fine (20%) | Thick (20%) |
|--------|---------|--------------|-----------------|------------|-------------|------------|-------------|
| 1:4    | Sand    | 80.0         | 76.0            | 76.0       | 64.0        | 64.0       | 64.0        |
| 1:4    | Endocarp| 0.0          | 4.0             | 4.0        | 16.0        | 16.0       | 16.0        |
| 1:6    | Sand    | 86.0         | 81.7            | 81.7       | 68.8        | 68.8       | 68.8        |
| 1:6    | Endocarp| 0.0          | 4.3             | 4.3        | 17.2        | 17.2       | 17.2        |

Figure 1. Prototypes arranged according to their proportion and granulometry.

3. Results
Once the ratio of substitution of sand for grains of petrous endocarp was established, the blocks were elaborated following the relation indicated in Table 1. As a first stage, the weight of each block was measured to determine the existence of a potential weight-mechanical resistance relation; the results of families 1:4 and 1:6 are shown in Table 2 and Table 3.

Table 2 shows the recorded weights of each block after their direct exposition to direct sunlight and artificial airflow, following the curation process; except for the blocks on the 1:6 family (with five percent of their sand content substitute by petrous endocarp), all of the blocks from the
The experimental group are lighter, to different degrees, than their analog on the control groups. Within the group in which the cement to sand ratio is 1:4, the blocks with 5% of petrous endocarp aggregates reported a reduction in weight of about 5%, while those with 20% of their sand content substituted by petrous endocarp aggregates had an average weight reduction around 12%.

A similar result is found when comparing the weight of the blocks from the 1:6 group, in which the lightest blocks belonged to the group with 20% of the sand content replaced by endocarp granules (an average weight reduction around 12%).

| Mixture | Control | Mixed (5%) | Fine (5%) | Thick (5%) | Mixed (20%) | Fine (20%) | Thick (20%) |
|---------|---------|------------|-----------|------------|-------------|------------|-------------|
| 1       | 236.60  | 250.80     | 225.10    | 212.80     | 209.30      | 206.60     | 227.90      |
| 2       | 247.50  | 242.10     | 237.20    | 233.10     | 218.50      | 220.50     | 219.30      |
| 3       | 243.50  | 233.90     | 227.80    | 239.50     | 225.50      | 212.30     | 210.80      |
| **Average** | 242.30  | 242.26     | 230.03    | 228.46     | 217.76      | 213.13     | 219.33      |

| Mixture | Control | Mixed (5%) | Fine (5%) | Thick (5%) | Mixed (20%) | Fine (20%) | Thick (20%) |
|---------|---------|------------|-----------|------------|-------------|------------|-------------|
| 1       | 243.6   | 214.70     | 233.50    | 240.00     | 211.40      | 201.10     | 225.70      |
| 2       | 227.1   | 213.40     | 236.30    | 230.00     | 201.00      | 191.80     | 215.70      |
| 3       | 225.4   | 230.80     | 226.90    | 231.30     | 186.50      | 198.50     | 195.40      |
| **Average** | 229.0   | 219.63     | 232.20    | 233.76     | 199.63      | 197.13     | 212.26      |

Figure 2 shows the average stress to compressing stress reported in block from each group before fracture appeared. Each type of block is coded by the group number 1 to 7. The group “1” corresponds to the control group. The remaining six groups are divided into triads, in accordance to the “mixed, “fine” or “thick” granulometry. Groups “2” and “3” correspond to blocks with 5% of their sand content replaced by petrous endocarp. Groups “5”, “6” and “7”, corresponds to the blocks with 20% of the sand volume replaced by petrous endocarp.

Figure 2(a) corresponds to the 1:4 family. For this family, there was a clear difference in the necessary compressive stress between those from the 5% and 20% subgroups. Thus, blocks from the 5% group surpass the resistance of their analogs from the control group: the smallest average value was obtained from the “thick” granulometry (which required an increment on stress around 38%), while the largest required stress was obtained for the blocks in the “mixed” group (almost 50%). This changed for the blocks which had 20% of their sand content substituted by endocarp granules, as all of them were shown to be more fragile than their control group (although the groups showing the smallest and largest stress were the same).

Most of the blocks from the 1:6 family (Figure 2(b)) required to apply a smaller compressing stress to produce fractures than those on the 1:4 family (Figure 2(a)), with the exception of those from the “thick” groups (showing similar average resistances than those from the 1:4+5% group). In the 1:6 family (Figure 2(b)), there is no marked difference on the average resistance for blocks with either 5% or 20%.
Figure 2. Average compressive stress required to produce a fracture in the blocks described in this study. (a) corresponds to the 1:4 family and (b) to the 1:6 family. Each type of block is coded by the group number 1 to 7; the group “1” corresponds to the control group. The remaining six groups are divided into triads, in accordance to the “mixed, “fine” or “thick” granulometry; groups “2” and “3” correspond to blocks with 5% of their sand content replaced by petrous endocarp. Groups “5”, “6”, and “7”, corresponds to the blocks with 20% of the sand volume replaced by petrous endocarp.

We used the Minitab [16] software package to obtain, through factorial design, the contour diagrams shown in Figure 3. Contour diagrams represent the dependence of a multivariate function within a two-dimensional plot, using color bands to represent specific magnitude ranges for the function. In the present case, the compressing force (in Newtons) required to produce a fracture in the blocks is depicted as a function of either the volume percentage occupied by the endocarp fragments and cement, in Figure 3(a), Figure 3(b), and Figure 3(c).

In all instances, the blocks with 5% of the sand volume replaced by endocarp fragments had the highest resistance. The blocks from the “mixed” granulometry showed the highest resistance to compression, while, respectively, the blocks made from the “fine” and “thick” granulometry had progressively smaller resistances.

In Figure 3(a), the blocks from the 1:4+5% family required more than 17500 Newtons to be applied to produce a fracture. The blocks from the 1:6 family obtained the smallest resistance (between 5000 and 7000 Newtons, almost independently of their endocarp content). This diagram makes it evident that there is an inverse correlation between the endocarp percentage, as increasing it up to 20% lowers the mechanical resistance to the range between 10000 to 12500 Newton.

Figure 3(b) represents the resistance under compression for blocks within the “fine” granulometry group. The behavior is similar to that of the “mixed” group, with only two differences: first, although qualitatively, each group of blocks gives analog results to those on the “mixed” group, the magnitude of the threshold resistances is lower, as the maximum resistance does not surpass the 17500 Newton threshold and the minimum resistance falls below 5000 Newton. Secondly, it appears that the dependence of mechanical resistance to the endocarp content is weaker than that of the “mixed” group, as the slope of each interval is less pronounced.

Figure 3(c) shows the results for the “thick” group, which shows a similar maximum threshold to that of the “fine group, while its lower threshold is never below 5000 Newtons. Also, this group shows the strongest dependence between mechanical resistance and the endocarp content, as it can be seen in the, almost vertical, borders of each region that show a pronounced decrease in resistance when the endocarp content increases from 5% to 20%.
Figure 3(d) shows mechanical resistance as a function of the volume percentage occupied by the endocarp fragments and their granulometry. The “fine”, “mixed” and “thick” groups are labeled as “1”, “2” or “3”, on the horizontal axis. This diagram confirms that the “mixed” granulometry group has the largest mechanical resistance and that the “thick” group has the strongest dependence on the endocarp content (as can be seen from the change in each region’s slope).

Figure 3. Contour diagrams that depict the compressing stress (in Newtons) required to produce a fracture in the blocks described in this study. (a), (b), and (c), show results for the blocks made from the “mixed”, “fine” and “thick” mixtures. The horizontal axis corresponds to the percentage of the volume occupied by the endocarp fragments, while the vertical axis corresponds to cement; in contrast, (d) shows the dependence of the predicted compressing force as a function of granulometry and the percentage of the volume occupied by endocarp fragments.

4. Conclusions
This work analyzed the effect of substituting sand for macadamia nut endocarp and its relationship under different granulometric sizes. In addition to this, it contributes to the physics of materials the potential of the use of organic residues capable of increasing the resistance under compression at the same time as reducing the weight of reducing the weight and rate of heat transfer of building structures built with cement.

Through a factorial design and contour diagrams, an inverse correlation was determined between the compression resistance of the prepared blocks and the percentage of sand substituted by petrous endocarp fragments, with the resistance of the blocks with 5% of their sand content
substituted by endocarp fragments being larger than that of the blocks in which 20% of the sand was substituted.

One of the key points of the study was to determine if whether employing an specific granulometric size would improve the resistance to compression of the blocks. We found that the blocks from the "mixed" granulometry shown the highest resistance to compression, requiring more than 17500 Newtons to be applied to produce a fracture. Regarding the granulometry effect, it was observed that the blocks in which only endocarp fragments larger than 1.5 mm were aggregated, showed to have a higher resistance to compression, although their resistance showed a stronger dependence on the exact percentage of aggregated endocarp.

When evaluating the synergistic effect of the sand-endocarp relationship and granulometry, it was observed that the proportion of cement to sand corresponds to 1:4 and that have 5% of their sand content replaced by endocarp fragments are capable of increasing the resistance under compressing stress of constructive elements.

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