Parameterization of Oil Palm Shell Concrete on Numerical Damage Model Based on Laboratory Experiment using Digital Image Correlation

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Abstract. As a country that contributes to 85% of the world’s crude palm oil, Indonesia produces enormous amounts of waste-by-products (ex: oil palm shells, fiber, etc.) with its potential to be processed into other useful products, including construction material substituent. Previous studies have shown that the use of oil palm shell as a concrete aggregate substituent can produce lightweight concrete that achieved the structural concrete strength requirements. Nevertheless, a further robust computational model on OPS concrete towards regular concrete using concrete damage model is to be characterized using finite element code CAST3M. OPS concrete’s parameterization is conducted based on concrete cube compression tests using digital image correlation (DIC). The average modulus of elasticity obtained is similar to lightweight concrete. The compression strength obtained is 20.33 ± 1.19 MPa, and the split-tensile strength is 1.23 ± 0.19 MPa.

1. Introduction
Indonesia is the world’s largest crude palm oil producer, and Malaysia, Indonesia has produced around 85% of the world’s crude palm oil. Over the past decades, oil palm shells’ explorations of coarse aggregates in lightweight concrete have significantly increased. It has become one of the substantial steps in reduction on the exploitation of natural aggregates.

Different materials produce different mechanical responses and comply with varying laws of behavior. Previous studies, which focused more on the mechanical behavior of oil palm shell, show that oil palm shell concrete tends to have lower compressive strength than regular concrete. In this paper, the experimental works focused more on observing oil palm shell concrete’s behavior law towards standard lightweight concrete within relatively smaller samples; of 15×15×15cm cube and D15×30cm cylinder. In order to obtain better characterization on the behavior law, both displacement and strain experienced by the models are to be observed using a strain gauge.

A 2-dimensional digital image correlation (DIC) method is introduced with speckles to produce displacement and strain within the sample. Compared with traditional methods, the DIC method is contactless. It provides extra insight into the strain distribution before crack propagation and the crack propagation path. The results obtained from the previously mentioned methods are compared to the numerical results from an open-source, finite element
software, CAST3M using the damage behavior law proposed by Mazars. Mazars [8] proposed the damage model in a computationally efficient combination for both local plasticity and non-local damage for regularization of localized deformation. The mechanical properties and the behavior law of oil palm shell concrete based on experimental works can be further evaluated compared to the normal concrete.

Table 1. Mechanical Properties of OPS and Natural Sand

|                        | Tenera Oil Palm Shell (OPS) | Natural Fine Aggregate (Pasir Bangka) |
|------------------------|-----------------------------|--------------------------------------|
| Max. Size (mm)         | 19.05                       | 2.38                                 |
| Specific Gravity       | 1.37                        | 2.95                                 |
| Bulk Density           | 1.21                        | 2.85                                 |
| Water Absorption       | 22.37 %                     | 1.21 %                               |
| Fineness Modulus       | 6.32                        | 2.24                                 |
| Abrasion               | 4.00 %                      | -                                    |
| Mud Content            | -                           | 5.40 %                               |

2. Material Characterization
This paper’s oil palm shell is the commonly grown palm trees in Indonesia, the tenera species from the Province of Bengkulu, which contain approximately 10-50% of the palm fruits. Typically, some oil coating is naturally present on the surface of OPS, and therefore, the removal of this oil coating is required. The pre-treatment was done by soaking the OPS with hot water, under the previous study by Sung Taek Lee. This paper used a fine natural aggregate of white beach sand (pasir Bangka). Both mechanical properties of OPS and natural sand are presented in Table 1, and the mix design used in this paper is based on the previous research, as shown in Table 2.

Table 2. Mix Design Proportion for 1m³[10]

| Portland Composite Concrete (PCC) | 500 kg |
|-----------------------------------|--------|
| Natural Fine Aggregate (Pasir Bangka) | 860 kg |
| Tenera Oil Palm Shell (OPS)         | 273 kg |
| Water                              | 234 kg |

3. Experimental and Modeling Method
3.1. Experimental Testing
Based on American Society for Testing and Materials (ASTM), both compression and split-tensile test is conducted on a cylinder sample of D15×30 cm. This paper used ASTM C39-20 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens as the guideline for compression test. On the other hand, for split-tensile strength, ASTM C496/C496M-17 Standard Method for Splitting Tensile Strength of Cylindrical Concrete Specimens is used. For DIC, the samples used are cube 15×15×15 cm with random speckles to be observed. The observed surface is flat with a cube shape and provides an unbiased 2-dimensional image to be interpreted by the software. In order to have better image quality, the concrete is to be painted with white non-reflective paint, and the use of spotlight is introduced, so-called speckle. The random speckle will form some pattern, then the DIC system will detect the movement of the pattern. Other than that, any external vibrations or sudden movement
should be minimized. Throughout the experiment, three frames per second/fps are captured, and therefore, every small activity from the sample can be analyzed.

3.2. Numerical Modelling
The computational calculation/modeling is done with the finite element code CAST3M, in which the behavior of concrete is described using a constitutive model proposed by Mazars. The modeling will be given a force until the model is damaged, and the element used in this method is the CUB8 element. CUB8 part is a three-dimensional solid model with eight Gauss integrated points. The damage and the elasticity surface are given with the expression of D, an internal variable of the damage, which is defined as the combination between the two damaging modes of traction $D_t$ and compression $D_c$. For non-cracked or healthy material is 0, and 1 is for broken material, and the value of D varies continuously between those two limits. The laws of evolution of the damage can be expressed using the equivalent deformation as follows:

$$D_t = 1 - \frac{(1 - A_t)\varepsilon_{d0}}{\varepsilon_{eq}} - A_t \exp \left( -B_t \left[ \varepsilon_{eq} - \varepsilon_{d0} \right] \right)$$

$$D_c = 1 - \frac{(1 - A_c)\varepsilon_{d0}}{\varepsilon_{eq}} - A_c \exp \left( -B_c \left[ \varepsilon_{eq} - \varepsilon_{d0} \right] \right)$$

Whereas $A_t$, $A_c$, $B_t$, and $B_c$ are the parameters to be identified. $A_c$ and $A_t$ affect primarily on steepness or slope of force vs. displacement graph. On the other hand, $B_c$ and $B_t$ affect more on the power vs. displacement graph’s skewness. Despite that, both parameters are simultaneously affecting the model’s damage evolution, which is expected the same as an experimental result. Through these parameters, it is possible to modulate the shape of the curved post-peak in which they can be obtained using tensile and compression tests. This modeling was done to compare and to analyze the characteristic of oil palm shell concrete towards regular concrete using Mazars model.

**Table 3. Mechanical Properties of OPS Concrete**

| Mechanical Properties         | Value                  |
|-------------------------------|------------------------|
| Compression Strength, $f_{c'}$| 20.33±1.19 MPa         |
| Split-Tensile Strength, $f_t$ | 1.23±0.19 MPa          |
| Density, $\rho$              | 1957.96 kg/m$^3$       |
| Poisson Ratio, $\nu$         | 0.19                   |
| Young Modulus, $E$           | 16666.67 MPa           |

*Each value obtained from the average value of 9 samples*
4. Results and Discussion

4.1. Experimental Results

The results of oil palm shell concrete mechanical properties obtained from both concrete compression and concrete split-tensile strength are presented in Table 3. The young modulus of oil palm shell concrete got shows a similar value with normal lightweight concrete as it was obtained through Equation 3, with the young modulus of 16798.61 MPa. According to ACI 318-14 for normal concrete, theoretically, the split-tensile strength can be obtained from the compressive strength using Equation 4. The calculated splitting tensile strength is 2.51 MPa. However, based on the experiment results, the split-tensile power obtained is 1.06 MPa - 1.48 MPa, which is relatively 50% less than the theory. This result is following the previous study on OPS concrete conducted by Lee.

\[ E = \rho^{1.5} 0.043\sqrt{f'_c} \]  \hspace{1cm} (3)

\[ f'_{ct} = 0.55 \sqrt{f'_c} \]  \hspace{1cm} (4)

Typically, a compressive strength uses a cylindrical sample as the standard. However, for this DIC tests, the models used are cube instead of a cylinder. Due to this difference in geometry, a modification factor of cylinder/cube strength ratio is introduced based on BS EN 206-1. The cylinder/cube strength ratio to be used is 0.8 for C16/20 and C20/25. The DIC compression tests were conducted on three 36-days old concrete, in which a distributed load was applied on the top of the cube as described in Figure 1. The maximum compressive strength obtained from the tests is between 18.18 to 21.43 MPa. Both samples show a similar trend; right before the maximum compressive stress, the displacement was small, less than 0.5 mm. However, as the load is still continuously applied, the pressure of the samples is starting to decrease along with the formation of crack.

![Figure 2. Stress vs. Displacement from DIC Compression Test](image)

4.2. Numerical Modelling

In this section, we aim to simulate and predict OPS lightweight concrete’s numerical properties that have been found experimentally. With finite element code CAST3M, the modeling was carried out on an element of increasing size to determine the model parameter in a cube model. The material parameter was obtained from the experimental tests, as was summarized in Table 3.

The parameterization was done on an element of 0.1\(\times\)0.1\(\times\)0.1 m, given a distributed load on top of it. Based on that, the damage model parameter for OPS concrete was characterized as in table 4. The implementation of the parameters for the real sample of 0.15\(\times\)0.15\(\times\)0.15
Table 4. Damage Model Parameters of OPS Concrete

| Parameter                | Value (1 element) | Adjusted Value (64-1000 elements) |
|--------------------------|-------------------|-----------------------------------|
| Deformation Threshold, KTR | $7.38 \times 10^{-5}$ | $7.38 \times 10^{-5}$            |
| $A_c$                    | 1.22              | 2.0                               |
| $B_c$                    | 3550              | 2150                              |
| $A_t$                    | 0.8               | 0.3                               |
| $B_t$                    | 13000             | 9000                              |
| Shear Correction, $\beta$ | 1.06              | 1.06                              |

m with bigger element number shows some inconsistency and the finite element results in a dependence relationship with mesh density and size dimension. Therefore, some adjustments to the parameters obtained in table 4 (value for one element) are required and tested on a more significant number of pieces. From both the compression and split-tensile test model, further parameterization of the OPS concrete on $0.15 \times 0.15 \times 0.15$ m with a bigger number of elements is shown in Figure 3. The number of features used in the characterization is 64 to 1000 elements, in which the stress vs. strain graph obtained for each model shows a similar response.

Figure 3. Stress vs. Strain of OPS Concrete from CAST3M with its Damage

4.3. Comparison between Experimental Tests and Numerical Modelling

Figure 4 compares stress vs. strain from CAST3M numerical modeling, digital image correlation, and strain gauge can be observed. For the numerical modeling, the number of elements used is 512, considering that the model response towards stress and strain is more stable with 512 components, as it is shown in Figure 3, along with its damage response visualization. Both graphs have similar trends, although compared to the strain gauge and DIC results, the numerical model still has a difference in Young’s modulus that makes the beginning of graphics different. Yet, it has already reached the same peak. The DIC result is more consistent with the strain gauge results, but due to its sensitivity, the DIC shows some inconsistency from external factors.

5. Conclusion

Based on the laboratory experiment conducted in this study, the Poisson’s ratio obtained is 0.19, the Young Modulus of Elasticity of 16666.67 MPa, and 20.33±1.19 MPa, and the split tensile strength of 1.23±0.19 MPa. The oil palm shell concrete has a characteristic that belongs to regular lightweight concrete. Using the Mazars damage model for the numerical modelling in CAST3M, the concrete parameter of oil palm shell can be characterized and results in a similar
Figure 4. Comparison of Compression Stress vs. Strain Graph from DIC, Numerical and Strain Gauge

Figure 5. Comparison of Tensile Stress vs. Strain Graph from DIC, Numerical and Strain Gauge

response from the modeling and the experiment. However, further research and adjustment in the parameters are still required to apply more prominent geometry and several elements. From this study, the effect of the element’s size on the damage is feasible. For future works, oil palm shell concrete’s parameterization is used in the more extensive structural feature, such as beams.

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