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Cracking Behavior of Reinforced Lightweight Concrete Beam Using Hot Water Pre-treated Oil Palm Shell Coarse Aggregate

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Abstract. As one of the largest palm oil producers in the world, by-products of this commodity are also produced in Indonesia. One of the solid by-products that are obtained from palm oil production is called Oil Palm Shell (OPS). These days, this material is interesting to be studied as it has a lightweight but sufficiently tough and rough outer surface. In previous studies done in laboratory, OPS was used as alternative coarse aggregate in concrete mix proportion. The designed compressive strength of OPS concrete is in the range of 20-23 MPa. In this research, the authors are interested in studying the crack behaviour of reinforced lightweight concrete beams using OPS replacing natural coarse aggregates. First, pre-treatment of OPS is performed by using hot water at 50°C as based on previous studies. Second, two samples of identical beam with 15 × 25 × 300 cm³ of dimension were cast and tested under four-point loading using force control hydraulic actuator. Third, crack opening evolution due to flexural test that occurs in OPS lightweight concrete beam is measured, to be precise, on the pure bending area. The crack opening is compared to service limit cracks from building code to find the corresponding loading application.

1. Introduction

Reinforced concrete (RC) has been one of the most commonly used building materials in the world since its development in the 20th century [1, 2]. In most cases, the durability of RC structures becomes the main concern since it is necessary to ensure the operation of the facility. Durability is often related to crack opening of structures. In certain circumstances, cracks can lead to degradation of concrete and further damage the function of an RC building. Therefore, the behaviour of cracking on RC structure is a critical issue. In SNI 2847: 2013 [3], the effect of crack on RC elements, e.g. beam, is interpreted as stiffness reduction. Seventy per cent of the moment of inertia may be taken when beam has passed its first cracks phase. In the calculation of beam’s deflection, this cracked moment of inertia is also considered.

Moreover, Eurocode 2 has a design crack opening formulation in addition to crack spacing for RC Element. The maximum crack opening criteria are regulated based on the utilisation of buildings as service limit criterion. It limits the crack opening at 300 μm [4].

On the other hand, the development of new material is escalating along with the increasing demand for housing needs. Some potential substitution materials have been recently studied. One of the materials is called Oil Palm Shell (OPS). These solid shell-formed by-products are obtained from palm oil production [5]. As one of the largest producers of palm oil, OPS from this industry are produced massively in Indonesia. Ineffectiveness of this solid side product waste processing has led some researchers to study the potential OPS waste in the civil engineering domain [6-8]. According to Yew et al. [8], OPS can be used as coarse aggregate material (Biosource material).
Research in OPS concrete conducted in 2016 in Laboratory of Structural and Material, Civil Engineering Department, Universitas Indonesia resulted in the most effective and possible concrete mix design with compressive strength reaching 20-23 MPa [7]. Regarding this condition, the authors decided to study the performance of OPS RC structures.

In this paper, crack behaviour of lightweight RC beam using OPS substituting natural coarse aggregates is studied with concrete mix design following the previous works [7]. Steps were begun by pre-treatment of OPS using hot water at 50-°C based on [9]. In the second step, two samples of the identical beam with 15 × 25 × 300 cm³ of dimension were cast at the same time as the cylindrical samples for characterisation tests. The size of the beam represents the typical dimension of the beam in one to two storey houses in Indonesia. In the third step, the cylindrical samples were tested to find the concrete compressive, flexural and tensile strength. Then, finally, beams were tested under four-point loading using force control hydraulic actuator. Study on the crack evolution and opening in OPS concrete beam is emphasised on the pure bending area. The crack opening on concrete is related to its tensile strength as this material is weak in tension. The results from the split test and flexural test are compared to see whether or not the OPS concrete has the same trend compared to normal concrete with natural coarse aggregates.

2. Material Characterization

OPS concrete has 1792-kg/m³ of concrete density. Therefore, it fulfils the requirement of lightweight concrete as stated in the National Standard [10]. In this part, characteristic tests were performed to obtain the properties of concrete and steel bar. OPS concrete mix design is presented in Table 1 based on the previous research [7] with 7/20 water-cement ratio.

| Table 1. The proportion of OPS Concrete [7]. |
|-----------------------------------------------|
| Natural Fine Aggregates 0-5 mm (860 kg/m³)    |
| OPS coarse Aggregates 4.75-12.5 mm (273 kg/m³) |
| Cement PCC Portland Composite Cement (500 kg/m³) |

2.1. OPS Concrete Characteristics

| Table 2. Mechanical properties of concrete materials. |
|-----------------------------------------------|
| Concrete compressive strength [11]° f’c = 22.33 ± 0.42 MPa |
| Concrete flexural strength [12]° f’c = 2.15 ± 0.20 MPa |
| Concrete tensile strength [13]° f’t = 12.58 ± 1.89 MPa |

°Average ± standard deviation of experimental results from five samples at 28 days after casting.

Concrete for material characteristic tests and beams were cast at the same time. After demolding the samples, cylindrical samples were cured in a pond with room temperature water. Meanwhile for RC beam, after casting, it was let harden inside a room with usual treatment to prevent early shrinkage. The test was done to know concrete’s compressive, flexural and tensile strength based on standard [11-13]. Each test was performed on five cylindrical samples (15 cm of diameter and 30 cm in height).

2.2. Steel bar reinforcement

The nominal bar diameter is 13-mm for the ribbed bar (longitudinal reinforcement), and it corresponds to the cross-section of 132.73-mm². Tensile tests were performed according to SNI [14]. The yield strength of the bar is obtained at fy = 419.28 ± 17.74-MPa, and its ultimate strength reached fu = 568.60 ± 16.29-MPa (the average ± standard deviation of the tensile test results from four samples).

3. Experimental Campaign

3.1. Detail of experiment
Detail and configuration of OPS RC beam dimensions and steel bar reinforcement are presented in figure 1 and 2. Four-point loading tests were conducted on the beams after 44 and 48 days consecutively. The dimension of the beam is $15 \times 25 \times 300$-cm$^3$, which leads to 2.7-m of support in regard to support distance. The beams were designed as under-reinforced beams according to the standard [3].

By using a hydraulic actuator, loading charge was distributed into two points of loading within 0.9 metres leading to four-point flexure test with 200 kg of loading step application. For measurement, LVDT extensometer was employed to measure the displacement in the vertical direction at point C (see figure 1). Moreover, two strain gauges were attached to the tension bar, as shown in figure 2.

### 4. Experimental Results

#### 4.1. Global Behavior: Force-Vertical Displacement

Global behaviour results of the OPS RC beam present the force application and deflection at the mid-span of the beam. Figure 3 below shows force-deflection curves for beam 1 (purple) and beam 2 (pink). The blue line in the curve presents the limit of allowable beam’s deflection at the service limit condition ($l/240$) according to the standard [3]. At approximately 4.5 ton of loading application, OPS RC beam attains its service limit condition.

#### 4.2. Crack Evolution and Crack Opening

By nature, concrete is weak in tension, so the first cracks occur when tensile strength is passed. In the material characterisation test, tensile strength test was performed by split test following standard [13]. The cylindrical specimen is charged from its lateral side. Meanwhile, flexural strength test was performed by a four-point flexural test following standard [14]. During this test, the bottom fibre of beam is under tension and failure of the beam happens due to the first crack, which starts from its bottom edge. Both tests normally give more or less the same results [2]. In the material characterisation part, a significant difference of flexural strength and split test occurred; the split test had six times the value of the flexural test. Some standards mention that tensile strength is approximately one tenth of its compressive strength [8]. In other words, a split test to obtain tensile strength may not give the first crack stress in OPS concrete. According to these results, OPS concrete does not have the same trend as normal concrete with natural coarse aggregates. Further investigations for split and flexural test on OPS concrete are needed.

For crack observation, our interest is to measure the crack opening and to observe the cracking pattern on the surface of the beam for each loading step application. Figure 4 presents the crack
opening evolution curve for both samples. The presented crack width is the largest crack opening observed on the beam for each loading step, which is not necessarily measured from the same crack. Then, on the left part of figure 5, crack width measured by concrete crack measuring microscope is presented.

**Figure 3.** Force-Displacement Curve at Mid-span.  
**Figure 4.** Crack Opening Evolution.

In figure 4 above, 300-μm of crack opening occurs when the loading application attains approximately 4.33 tons. According to [4], Eurocode 2 limits the crack opening at 300-μm for some utilisation of buildings. It means that, from both crack opening (figure 4) and maximum deflection at mid-span (figure 3), service limit states occur at approximately 4.33 tons of load (the smallest one is chosen). The crack opening for sample 1 and 2 at the maximum load is 2500-μm and 1350-μm, respectively (see left part of figure 5). Beam 2 has a larger crack opening since the beginning was ultimately due to larger shrinkage in the initial condition. Nevertheless, in the end, the largest cracks in beam 1 were more widely opened than the ones of beam 2 (figure 4 and 5).

**Figure 5.** Crack opening and crack pattern for both beams at the end of the test.

Cracking pattern of the two beams at the end of the tests is presented in figure 5. Based on visual observation, beam 2 has cracks that are scattered along the beam. During the experiment, after the first loading step, horizontal, vertical and leaning cracks spread on the front and back vertical surfaces. This condition may signify these cracks were induced by early shrinkage. Further loading application showed flexural cracks initiated from the bottom edge of the beam and occurred more or less at the same time for both beams. The horizontal cracks that occurred at the beginning did not increase their opening. Nevertheless, the force-displacement mechanical response evolution for the two beams presented in figure 3 shows a same tendency.
5. Conclusion
Tensile tests using split and flexural strength experiments have significantly different results. It means that OPS concrete does not have the same trend as normal concrete with natural coarse aggregates. It is recommended to be mechanically investigated as future research work. Experimental results on OPS concrete is better tested using the flexural test to find the stress of the first cracks.

Crack opening from OPS RC beam was observed at each loading step. The two beams have the same tendencies in force-displacement at mid-span although the crack pattern on the beam is very different, as beam 2 is influenced by the shrinkage based on experimental observation. Moreover, at 4.33 ton of loading application, crack width 300-μm occurred. Compared to the theoretical calculation for normal concrete with natural coarse aggregates based on standard [3], 4.33 ton is 74% of the ultimate load. Shrinkage of OPS concrete should be studied further in future research.

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