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A comparison study of the mechanical properties and drying shrinkage of oil palm shell and expanded clay lightweight aggregate concretes

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ABSTRACT

For making artificial lightweight aggregate, selected raw materials are fed into a rotary kiln at high temperature. Providing such a high temperature is costly and generally, the process of making artificial lightweight aggregate is not environmentally friendly. The use of natural lightweight aggregate for making lightweight concrete can lead to low-cost construction. The use of a solid waste lightweight aggregate namely oil palm shell (OPS) as coarse aggregate, is not only environmentally friendly but leads to a low-cost material. This study is a comparison between some engineering properties of OPS lightweight concrete and an artificial lightweight (expanded clay) concrete with low water to cement ratio, along with having good workability and without any segregation. The test results show that OPS concrete has better mechanical properties and a higher efficiency factor than expanded clay lightweight concrete. The ceiling strength of expanded clay lightweight concrete occurs at an early age; while it happens in OPS concrete at a later age. The crack pattern of the tested specimens shows that OPS is much stronger than expanded clay. On the other hand, the compressive strength of OPS lightweight concrete is more sensitive to lack of curing. Although OPS lightweight concrete shows twice the amount of drying shrinkage than expanded clay lightweight concrete in the short term, this difference reduces significantly at later ages.

1. Introduction

When normal weight concrete is compared with steel, one of the main disadvantages of concrete is its low strength-weight ratio. Such a disadvantage of concrete can be resolved proportionally when lightweight concrete is made, particularly a high strength lightweight concrete. Structural lightweight concrete is categorized as a special type of concrete [1]. In most cases, structural lightweight concrete is made with a lightweight aggregate as coarse aggregate and normal weight sand as the fine aggregate. There are many different types of natural and artificial lightweight aggregates with different characteristics. Such a disparity in properties means that the lightweight concrete made of each type of lightweight aggregate has special engineering properties. Not all of the available aggregates are equally suitable for a particular application [2]. For example, among all the lightweight aggregates only a few can be used as aggregate for producing high strength lightweight concrete [3]. Therefore, for each type of lightweight aggregate the engineering properties should be investigated extensively before any application in the construction industry.

In countries located in tropical regimes such as Malaysia, Indonesia and Nigeria, there is a type of lightweight aggregate from the agricultural industry; namely, oil palm shell (OPS). OPS is a solid waste from the palm oil industry. Research over two decades has shown that lightweight concrete incorporating OPS has good mechanical properties [4] and durable performance [5]. It has been shown that reinforced concrete beams made of OPS lightweight concrete with normal strength have satisfactory shear and flexural performance [6,7]. The experimental bond strength of OPS lightweight concrete has been shown to be significantly higher than the design bond strength [8]. In addition, recent studies have demonstrated that OPS can be used as lightweight aggregate for producing high strength lightweight concrete [9].

In most cases, artificial lightweight aggregates are manufactured by a sintering process of raw materials from natural resources. The sintering process is an expensive method of manufacturing due to the large energy consumption [10]. For example, for manufacturing lightweight aggregates, such as expanded clay, shale and slate, selected raw materials are fed into a rotary kiln with a temperature of about 1200 °C. In the case of expanded perlite lightweight aggregate, a temperature of about 1800 °C is needed. However, with a new technique the temperature needed for rotary kiln is reduced to about 860 °C. Providing such a high temperature is very

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expensive. Priyadharshini et al. [10] suggest that for producing greener artificial lightweight aggregate, industrial by-products such as heavy metal sludge, mining residue, steel slag, bottom ash and fly ash, should be used instead of natural raw materials. In addition, Hossain et al. [11] suggest using natural lightweight aggregate such as pumice, instead of processed artificial lightweight aggregates. They demonstrate that natural lightweight aggregate concrete as a construction material can lead to low-cost construction. Inasmuch as OPS is a waste material that does not need any heating process, the use of this lightweight aggregate for manufacturing lightweight concrete not only leads to low-cost construction but also causes this type of concrete to be a more environmentally friendly material. Struble and Godfrey [12] stated that environment, economy and society are three components of sustainability, which the environment is the most important component nowadays and the economy component is given less attention in developed countries. Therefore, it is clear that OPS lightweight concrete can meet the requirements of sustainability.

The main aim of this study is to make a comparison between some of the engineering properties of OPS lightweight concrete as an environmentally friendly and low-cost material with that of an artificial lightweight aggregate concrete made of lightweight expanded clay aggregate. These two types of concrete are made with low water to cement ratio but with good workability and without any segregation. Various properties are compared such as compressive strength in different curing conditions, splitting tensile and flexural strengths, water absorption and drying shrinkage.

2. Experimental work

2.1. Materials used

The binder used was ordinary Portland cement (OPC), which was obtained from a local cement company with a specific gravity, Blaine surface area, initial and final setting times of 3.14 g/cm^3, 3510 cm^2/g, 65 min and 140 min, respectively. A superplasticizer (SP) based on polycarboxylic ether (PCE) was used in all mixes.

Local mining sand with a maximum nominal size of 4.75 mm, specific gravity of 2.65 and fineness modulus of 2.70 was used as fine aggregate. Crushed old OPS and expanded clay with a maximum nominal size of 8 mm as well as crushed granite with a maximum nominal size of 12.5 mm were used as coarse aggregate in the concrete mixtures. The specific gravity and 24-h water absorption of OPS were 1.2% and 20%, respectively, while for expanded clay they were 0.66% and 28%, respectively.

2.2. Mix proportions

The mix proportion of lightweight concrete containing OPS (mix P) was selected based on the method reported by Shafigh et al. [9]. This mix had a water to cement ratio of 0.29% and 1% SP (by mass of cement). The slump value of mix P was 145 mm. Mix L was made of expanded clay lightweight aggregate. In this mix the volume content of lightweight aggregate was the same as OPS. Therefore, the main difference between the two mixes is the type of lightweight aggregate used. However, it should be noted that mix L had a slightly lower SP dosage and water content. This is because unlike OPS aggregates expanded clay aggregates are round. This shape helps to improve workability. In addition, the density of expanded clay is significantly lighter than the OPS (approximately 45%). Therefore, if the SP and water used in mix L were similar to mix P then the expanded clay aggregate would float upwards. Therefore, mix L was made with a low water to cement ratio of 0.26 and SP dosage of 0.5% with a slump value of 120 mm. The mix proportions of the two mixes are shown in Table 1.

2.3. Test methods

The concrete specimens were cast in 100-mm cubes, cylinders of 100-mm diameter and 200-mm height, prisms of $100 \times 100 \times 500$ mm^3 and prisms of $100 \times 100 \times 300$ mm^3 steel moulds for measuring compressive strength, splitting tensile strength, flexural strength and drying shrinkage, respectively. All specimens were compacted using a vibrating table. The specimens were demoulded 24 h after casting. At least three specimens were prepared for obtaining the average value for mechanical properties and two specimens were used for the drying shrinkage test. The compressive strength of specimens was determined on the 1st, 3rd, 7th, 28th, 56th, and 90th day in accordance to BS 1881: Part 116 using a compression testing machine of 3000 kN capacity with a rate of loading controller. The drying shrinkage test, under laboratory environment condition, was conducted immediately after demoulding. The shrinkage value for each age is the average of six readings.

2.4. Curing regimes

For determining the effect of the curing regimes on the 28-day compressive strength of concretes, the specimens were cured in five curing conditions, as follows:

(a) Continuous moist curing (FW): specimens were immersed in water at a temperature of 23 ± 3 °C.
(b) Air drying (AC): specimens were kept in the laboratory environment with RH of 67–82% and temperature of 29 ± 3 °C after demoulding.
(c) 3 days (3 W), 5 days (5 W) and 7 days (7 W) partial early curing: curing in water for 2, 4 and 6 days, respectively, after demoulding and then air drying in a laboratory environment until the age of testing.

3. Results and discussion

3.1. Development of compressive strength

The compressive strength development of P and L mixes under continuous moist curing up to 90 days is shown in Fig. 1. Both of the mixes have a sharp compressive strength gain until the early age of 7 days. At this age, P and L mixes have about 95% and 97%, respectively, of the 28-day compressive strength. It is clear from Fig. 1 that the strength gain continues in mix P until the age of 90 days and after 7-day age. However, such a trend is not observed in mix L. In mix P, the 7 days to 56 and 90 days compressive strength is 91% and 87%, respectively, and 96% and 96%, respectively, for mix L. These results show that mix L reaches its ceiling strength at the age of 7 days. However, such a ceiling strength was not observed in mix P. The ceiling strength of concrete depends upon the type of aggregate [13]. In lightweight aggregate concrete, when the strength reaches the ceiling strength, further addition of cementitious materials will not significantly raise the maximum attainable strength [14]. Although mix L had a stronger mortar due to the lower water to cement ratio than mix P, its ceiling strength occurs at an early age of 7 days. This shows that OPS is stronger and stiffer than the expanded clay. Okpala [15] reports that the OPS has 37% porosity, is fibrous in nature, and has a compressive crushing strength of about 12.1 MPa. The Los Angeles abrasion value of the shell is approximately 76–91% less than granite aggregate [4,15].

Neville and Brooks [16] reported that generally, concrete made with expanded shale or clay aggregate has a higher strength than