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Lightweight Concrete Using Oil Palm Boiler Clinker (OPBC) – A Review

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Abstract. Lightweight concrete can be effectively produced by replacing normal aggregates (60% to 75% of concrete volume) with a lighter alternative. With depleting natural resources, utilising waste materials, such as oil palm boiler clinker (OPBC), in concrete for structural use is one way to mitigate environmental concerns raised by the construction industry. This paper presents a review of the mechanical properties, structural behaviour and performance of OPBC concrete. Lightweight concrete using OPBC can be designed to achieve different compressive strengths with different mixes. The different OPBC concrete mixes result in different densities and workability. The degree of content and the type of OPBC substitutes used affect the flexural strength and 28-day splitting tensile strength of OPBC concrete. A different effect was observed in the modulus of elasticity as the drying shrinkage and water absorption of OPBC concrete are also impacted. This review study also compares the structural performance of OPBC concrete to that of conventional concrete.

1 Introduction

The need to meet the demand for concrete from the construction sector raises environmental concerns. The resulting carbon dioxide emission is making concrete industry to be not sustainable [1], and construction activities to be labelled as not "green" [2]. Concrete manufacturing also consumes high amount of natural aggregates, accounting for 70% - 80% of total concrete volume [3]. The concrete industry has been known to be the largest contributor to the depletion of limited natural resources i.e. sand, water, rock, and gravel [4].

Because concrete is essentially a blend, the constituents can therefore be selected to enable the maximisation and optimisation of concrete's performance [5]. To curb the issue on environmental concerns, artificial aggregates e.g. fly ash, ground granulated blast furnace slag, and expanded clay, can be used as substitutes to produce an environmentally friendly lightweight concrete [6]. By using lightweight aggregates in concrete, lightweight concrete can be produced.

Concrete is considered as lightweight when its density ranges between 1440 kg/m^3 to 1840 kg/m^3. The density of conventional concrete lies between 2240 kg/m^3 to 2400 kg/m^3. Despite the lower densities, lightweight concrete is still expected to have a compressive strength of at least 17.0 MPa for use on structures [7].

The weight of lightweight concrete is about 25% to 35% less than conventional concrete [8]. With the use of lightweight concrete, the reduction in dead load is approximated to be 20%, which can be

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translated to about 10% of construction cost saving [9]. The reduction of dead weight consequently allows the reduction in size of load bearing elements as well as the use of steel reinforcement. Lightweight concrete also possesses a low coefficient of thermal expansion and a better fire-resistant as compared to normal weight concrete. It is therefore possible to construct a thinner fire rating slab which leads to a lighter building and lower construction cost [10].

By using low-cost lightweight aggregate, the production cost of lightweight concrete is also reduced. This has been shown possible with the successful substitution of aggregates with agricultural wastes for lightweight concrete production [11]. One of the agricultural wastes is OPBC [12]. OPBC usually has no economic value and are plentifully available [13]. Full aggregate substitution with OPBC has been shown to reduce 30% of manufacturing cost and 22.62% reduction in carbon dioxide emission, with comparable structural efficiency (strength-to-weight ratio) to conventional mix concrete [14].

2 Lightweight Concrete using Agricultural Waste as Aggregates

Lightweight concrete that is made with lightweight aggregate can be categorised into two categories based on its formation: (1) mechanical treatment and (2) thermal treatment. Lightweight concrete that uses agricultural waste as aggregates is grouped in the latter category, where aggregate is produced using combustion of natural or waste material. These aggregates can be made of coconut shell, rice husk, corn cob, tobacco waste, oil palm shell and OPBC as examples [11].

There is always a challenge in attaining high strength in lightweight concrete, i.e. compressive strength of above 55.0 MPa, due to its porosity that tends to restrain the development of mechanical properties of the concrete [15-18]. Despite that, lightweight concrete produced using agricultural wastes as coarse aggregate has been shown to be able to achieve high compressive strength. The 28 days compressive strength of lightweight concrete using crushed oil palm shell in saturated surface dry (SSD) condition was found to be 53.0 MPa [19]. This was achieved by having water-cement ratio of 0.45. When a lower water-cement ratio was used, i.e. 0.35, the 28 days compressive strength was found to be 42.5 MPa [20].

2.1 Lightweight concrete using OPBC as aggregates

OPBC stones are obtained from the combustion of palm oil fibre and palm oil shell. They are irregular in shape and thorny. The OPBC stones are usually grey in colour and are porous. Figure 1 shows the form of OPBC stones in coarse and fine sizes. OPBC particles that pass 4.75 mm sieve are used for fine aggregate replacement whereas the particles that has nominal size of 20 mm (above 4.75 mm) are used for coarse aggregate replacement [12]. Besides coarse and fine aggregates, OPBC can be ground into finer sizes, to be used as binder replacement [14].

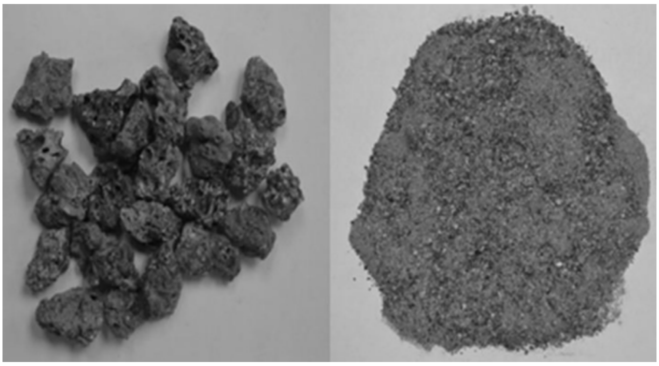

Figure 1. Coarse and fine OPBC [14].

2.2 Mix design

In the mix design, normal weight aggregate is usually substituted with OPBC by volume because OPBC is much lighter than normal weight aggregate. Like other lightweight aggregates, OPBC is porous, making it to be sensitive to water content. The use of OPBC in place of coarse and fine aggregates in lightweight concrete has been shown to achieve a 28-day compressive strength of 44.4 MPa in pre-stressed beams. This mix had a water-cement ratio of 0.44 [21]. With a higher water-cement ratio of 0.55, and the use of 10% fly ash, the strength was found to be 42 MPa [12].

At higher water-cement ratios, when OPBC concrete is mixed in accordance to ACI 211.2-98, the expected 28-day compressive strength was in the range of 17.00 to 33.17 MPa [22]. When mixed according to conventional mix design (ACI method), even if OPBC is used only as fine aggregates, it yielded lower compressive strength and workability [23].

In more recent studies, the highest 28-day strength was found in a mix that has even lower water-cement ratio of 0.38, which is 42.56 MPa [24]. For a mix that uses OPBC only as coarse aggregates and water-cement ratio of 0.331, the 28-day compressive strength was found to be about 5% higher at 44.89 MPa [25]. The latter, however, uses plasticizer to improve the workability of the mix.

When designed to be self-compacting concrete mix, OPBC concrete was found to be able to achieve 28-day compressive strength in the range of 50.0 – 60.0 MPa. This mix was designed with water-cement ratios of 0.43 to 0.54, and included a stage in the process where OPBC was immersed for 24 hours for absorption of water [26]. Then, it was shown that it is also possible for self-compacting OPBC concrete to be produced with 28-day compressive strength of between 60.0 to 70.0 MPa [14].

3 Physical and Mechanical Performance

3.1 Slump

For concrete that uses OPBC as coarse and fine aggregates, slump values of 85 to 125 mm could be achieved with 10% inclusion of fly ash as binder material [12]. With the addition of superplasticizer, a high workability mix (slump of 102 mm to 127 mm) was yielded for up to 37.5% of fine OPBC in the mix [25]. However, a reduced slump value of 50 mm to 80 mm was found in concrete incorporating up to 37.5% of OPBC aggregate (SSD condition) [13].

3.2 Density

Weight of concrete was observed to have reduced from 16% - 23% when different mixes of OPBC concrete were tested. The greatest reduction was found in the mix that uses OPBC as coarse and fine aggregates [12].

The use of OPBC in concrete reduces the density of concrete due to it being lighter than any of constituents of a concrete mix. For instance, the weight of OPBC sand is 22% lower than normal sand, that when used, was found to reduce the density of concrete up to 27% [13]. Similar range of densities was also found when OPBC concrete was mixed with oil palm shell as the replacement for the conventional coarse aggregate: 1889 kg/m3 to 1948 kg/m3 [25].

The reduction in density of concrete is directly proportional to the ratio of OPBC being used as replacement. A 100% replacement was found to reduce the density of concrete by 17% [14]. By comparing the effects caused by the use of OPBC in concrete, the use of OPBC as fine aggregate causes more reduction in concrete density. This may be attributed to the greater number of pores that exists in OPBC in the form of fine aggregates.

3.3 Compressive strength

The use of OPBC as fine aggregate was found to increase the compressive strength of concrete even at only 5% of OPBC [27]. However, this was only observed for OPBC concrete mixes under various partial early curing conditions due to the ability of internal curing of OPBC aggregates. When these mixes undergo continuous moist curing, only the mix with 25% of OPBC was able to achieve compressive strength of 37.4 MPa, almost equivalent to that without OPBC, which was 37.8 MPa.

The rest have shown a reduction in compressive strength [13].

When used as coarse aggregate, a high compressive strength was attained, i.e. 44.89 MPa [25]. The difference in effects when OPBC is used as coarse compared to as fine aggregates is due to the greater number of pores in fine OPBC [12].

A different phenomenon was observed when OPBC is used as partial and whole replacement of coarse aggregate, fine aggregate and binder material in self-compacting concrete. The compressive strength was found to be in the range of 60.0 MPa to 70.0 MPa. These values of compressive strength can still be achieved despite the 100% substitution of OPBC as fine and coarse aggregate [14].

3.4 Flexural strength

A similar trend to that of compressive strength is found in the effects that OPBC has in concrete on its flexural strength. It was found that there was an increase of 28% in flexural strength when OPBC is used as 5% of fine aggregates, and an increase of 33% when used as 10% [27]. The opposite effect was found when more than 10% of fine aggregates were replaced with OPBC. The flexural strength of OPBC concrete decreases as the content of OPBC in the concrete increases [13].

The negative effect was also observed when OPBC is used as both coarse and fine aggregates. When used only as coarse aggregates, the reduction in flexural strength was found to be 20.2%. The effect is greater when OPBC is used also as fine aggregates, causing a reduction of 32.3% in flexural strength. This can be attributed to the porous characteristic of OPBC [12].

3.5 Splitting tensile strength

The minimum 28-day splitting tensile strength of structural lightweight concrete is 2.0 MPa [28]. Although the using of OPBC in concrete is expected to reduce the splitting tensile strength of concrete due the weaker grain in OPBC aggregates [29], OPBC concrete is still found to be suitably used as structural lightweight concrete. For concrete that has OPBC as fine aggregates, the splitting tensile strength was only reduced by about 2.7%. This reduction increases as the content of OPBC increases up to 50% [13]. A higher reduction was observed when OPBC was used as both coarse and fine aggregates (up to 32.9%) as compared to when it was used only as coarse aggregates (from 23.5%) [12].

3.6 Modulus of elasticity

The typical modulus of elasticity of structural lightweight concrete is 10.0 GPa to 24.0 GPa [30]. OPBC concrete that uses OPBC as fine aggregates above 37.5% was found to have modulus of elasticity lower than the required values [13, 25]. OPBC concrete that uses OPBC as coarse aggregates, on the other hand, has high modulus of elasticity, 81.6% higher than that of OPBC as 25% of fine aggregate, at 22.95 GPa [25].

3.7 Shrinkage

A higher drying shrinkage in lightweight concrete is expected due to a lower elastic modulus of the aggregate used [31]. This was observed when OPBC is used as coarse and fine aggregates with 10%

of fly ash when compared to conventional concrete mix [32]. The use of OPBC as fine aggregate, on the other hand, was found to have no significant effect on the drying shrinkage of concrete [13].

3.8 Water absorption

The increased porosity in lightweight aggregate causes higher water absorption [33]. This was coherently found in OPBC concrete mix that uses OPBC as fine aggregate and water absorption increases proportionately with the amount of OPBC in concrete [13]. The 24 hours water absorption of fine and coarse OPBC aggregate was 3.60% [13] and 3.56 [34]. As most good performance concrete has water absorption value below 10% by mass [31], the recommended substitution of OPBC is therefore not to exceed 37.5% in oil palm shell concrete [13].

4 Structural Performances

4.1 Flexural behaviour

OPBC concrete beams when cast with the reinforcement ratio less than 0.5% and as pre-stressed were found to behave similarly to normal weight concrete beams. The failure of the beams was due to ductile failure, as expected in normal weight concrete beams [21, 24].

The experimental deflection values for OPBC concrete beams with reinforcement was found to be 10% to 45% less than what was expected according to BS8110. The resulting crack widths for these specimens were also found to be within the acceptable limit in accordance to BS8110 [24].

For OPBC pre-stressed concrete beams, greater deflection was found when compared to that caused in normal weight concrete, as expected. This difference in deflection is translated to only a drop of mere 6.4% in carrying capacity [21].

4.2 Shear behaviour

The shear failure mode in OPBC concrete beam was found to be similar to that of normal weight concrete beams and is in accordance to ASTM: C330 for structural use [24].

5 Summary

The use of OPBC in lightweight concrete has shown promising outcomes. The disadvantages of using OPBC in concrete due to its porosity can be lessened if OPBC is used in certain conditions, size, and percentage of volume. In spite of its sensitivity to water content, its weight brings more advantages to the concrete and construction industry. OPBC concrete, despite being lightweight, can be designed to achieve adequate compressive strength for structural application. The decrease in dead load means cost savings in the construction industry without compromising on structural integrity. The lowered flexural strength in OPBC concrete beams still qualifies itself for use as structural lightweight concrete.

By using OPBC as part of raw materials in concrete also makes the production of OPBC concrete to be more “green’ as it calls for less demand for non-renewable natural resources and on top of that, makes use of waste. The cost of OPBC being very low at RM 0.020 per kg [14], can significantly reduce the cost of concrete.

Lightweight concrete using OPBC can potentially be widely used in the construction industry when optimum ratios of OPBC in different forms can be found to achieve desirable outcomes. More studies could perhaps be conducted to look into the durability of OPBC concrete for these findings to be more conclusive.

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