Comparative study of mechanical properties for substitution of normal weight coarse aggregate with oil-palm-boiler clinker and lightweight expanded clay aggregate concretes

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Received: 26th December 2019 *Final version received: 30th December 2019*

This paper deals with a comparatively study of the engineering properties of the Oil-palm-boiler clinker (OPBC) OPBC and lightweight expanded clay aggregate (LECA) concretes. A grade 70 normal-weight concrete was designed as control mix. Normal weight coarse aggregate was substituted with OPBC and LECA up to 100% by volume, respectively. Their properties — workability, density, compressive strength, splitting tensile strength, flexural strength, modulus of elasticity, and water absorption — were studied. Results showed that at the same mix proportion, all mixes exhibited acceptable workability, except for concrete containing LECA up to 75% onwards, which required the reduction of superplastisizer dozen to 16%. Mixes with 75% onwards LECA content exhibited acceptable workability. The oven dry density of concrete containing 100% OPBC and 50% LECA onwards, respectively, in this study can be considered as lightweight concrete. The use of saturated OPBC and LECA in concrete improves the mechanical properties of concrete under air drying condition. The ceiling strength of LECA concrete is at the early age of 7 days, whereas it happens to normal weight concrete and OPBC concrete at a later age. The water absorption of all mixes is below 3%, which can be considered as good concrete.

Keywords: Oil-palm-boiler clinker (OPBC), lightweight expanded clay aggregate (LECA), mechanical properties, water absorption

1. INTRODUCTION

The building industry is currently facing a critical issue, that is, significant reduction of raw materials that are primarily used in the production of concrete (e.g., crushed rock, gravel, sand, and water) to cater to the needs of the industry (Mefteh et al. 2013). To address the extinction of resources, the utilization of recycled aggregate in concrete can be promoted (Ramezanianpour et al. 2009). Large amounts of not less than 10 billion tons of concrete are produced annually due to the rapid development of the construction industry (Meyer 2009). Thus, to cope with mass production, natural aggregates are needed to compensate for the approximately 8 to 12 billion tons depleted per year after 2010 (Tu et al. 2006). By 2050, the number of concrete needed will increase to 18 billion tons per year (Mehta and Monteiro 2006).

The primary ingredient of concrete is aggregates. Several studies have been conducted to achieve not only a lightweight but also sustainable concrete (Lee et al. 2017a; 2017b; Shafigh et al. 2018). Ground-granulated blast furnace slag, fly ash, and recycled concrete are classified as waste materials that have successfully transformed into aggregate supplant and have been utilized for decades (Federico and Chidiac 2009; Meyer 2009).

Malaysia contributes approximately 39% of world palm oil production and 44% of world export and disposes approximately 45,750 m3 of oil-palm-boiler clinker (OPBC) from the palm oil mill in Sabah annually. These statistics make

Malaysia as one of the major palm oil producers globally (Mannan and Neglo 2010). Malaysia, however, has been facing the problem of disposal recently. The OPBC is a type of waste from the palm oil industry, which is generated from further combustion of palm oil fiber and oil palm shell (OPS) in the rotary kiln to produce fuel for electricity. The OPBC is generally treated as a waste with low market value because it is usually discarded arbitrarily in landfill areas or used for filling up potholes on access roads (Kanadasan and Razak 2015). Reusing the OPBC for production of concrete would therefore be economical and environment friendly.

Nevertheless, the breaking of traditional philosophy of incorporating the OPBC in the manufacture of lightweight concrete has brought several advantages in different respects. By designing the OPBC as self-compacting concrete, its 28-day compressive strength can reach up to 60 to 75 MPa (Kanadasan and Razak 2015).

Through the substitution of coarse and fine aggregate with OPBC and adding of 10% fly ash, the 42 MPa comparable strength of lightweight concrete can be obtained (Ahmad and Mohd 2007). The slump value of this concrete is 125 mm, whereas its water–cement ratio is 0.55. This slump value demonstrates that the mixture is as relatively feasible as normal weight concrete.

The inclusion of OPBC as coarse aggregate can produce a mixture with 28-day compressive strength of 45 MPa (Ahmmad et al. 2014). This amount of strength is achieved by employing low water-cement ratio of approximately 0.331, as well as adding superplasticizer that can improve the workability. The slump value and density of 124 mm and 1,948 kg/m3 are achieved, respectively.

Lightweight expanded clay aggregate (LECA) is manufactured by burning clay at a temperature of approximately 1,150 °C in a rotary kiln. It is an artificial aggregate that can be used as an alternative material for concrete manufacturing. After heating fabrication, the volume of the material expanded to about four to five times. Sintering of raw material to produce the material is the main reason for the excessive amount of LECA. The LECA can be incorporated into concrete to improve the properties of concrete as LECA and possess good insulation characteristics (Netweber 2015; Priyadharshini et al. 2012). By substituting normal fine and coarse aggregates with LECA with low water–cement ratio, compressive strength of up to 47 MPa is successfully achieved with the density ranging from 1,435 to 1,753 kg/m3 (Bogas et al. 2014).

High-strength lightweight concrete with 28-day compressive strength of 45 to 50 MPa and densities of 1790 to 1825 kg/m3 can be produced by substitution of normal coarse aggregate with LECA (Moreno et al. 2014). Mousa et al. (2014) reported that adding LECA under saturated surface dry (SSD) condition is advantageous because it can be used as internal curing agent in the mixture. Therefore, lightweight aggregate concrete (LWAC) with 28-day compressive strength ranging from 41 to 45 MPa is successfully obtained. The inclusion of LECA leads to an appreciation of 10% to 17.5% of compressive strength compared with those without LECA. Mousa et al. (2014) also found that the use of LECA as self-curing agent increases compressive strength and substantially boosts tensile strength, flexural strength, and modulus of elasticity (MOE) by 3.7% to 7.4%, 1.6% to 7.2%, and 1.4% to 4.1%, respectively.

The addition of LECA with 20% silica fume as binder in the mix can produce 71 MPa compressive strength (Novokshchenov and Whitcomb 1990) and achieve a relatively low density value of approximately 1860 kg/m3 only. With the inclusion of LECA, silica fume, and fly ash in manufacturing lightweight concrete, 365-day compressive strength of up to 70 MPa is achieved (Malhotra 1990).

The substitution of coarse and fine aggregates with LECA produces lightweight concrete with 28-day compressive strength of 59 MPa and slump values ranging from 50 mm to 245 mm with the addition of superplasticizer (Bogas and Gomes 2013). These data confirm the success and proper workability of the concrete mix. The concrete products are also weighed significantly lower than conventional concrete, ranging from 1607 to 1996 kg/m3. According to all the presented data, the strength of lightweight concrete is concluded as it is primarily relies on its lightweight aggregate (Bogas and Gomes 2013).

This investigation primarily aims to explore a novel LWAC by comparing several engineering properties between the high-strength LWAC of OPBC, which is an environmentally friendly and low-cost local solid waste, with those of artificial LECA concrete, which is a costly material imported from Malaysia. High-strength normal weight concrete was substituted with coarse aggregate with OPBC and LECA in different percentages to evaluate various properties, such as workability, density, compressive strength with different curing regimes, splitting tensile strength, flexural strength, MOE, and water absorption.

2. EXPERIMENTAL PROGRAM

2.1. Materials and Properties

This experiment used ordinary Portland cement (OPC) with a specific gravity of 3.14 and Blaine surface area of 0.351 cm2/g. Sika Viscocrete-2199, a superplasticizer are used in all mixes.

Local mining sand was used as fine aggregate with a fineness modulus of 2.33, specific gravity of 2.63, and maximum nominal size of 2.36 mm. Crushed granite from Kajang, OPBC from Dengil, and imported LECA were used as coarse aggregate. Table 1 and Figure 1 show the physical properties and sieve analysis grading curve, respectively, of crushed granite, OPBC, and LECA. The OPBC and LECA were used as substitutes for crushed granite. All types of coarse aggregates were used under SSD condition. Figure 2 shows the coarse aggregates of (a) LECA, (b) crushed granite, and (c) OPBC.

Table.1 Physical properties of the crushed granite, OPBC, and LECA

Physical property	Crushed granite	OPBC	LECA
Specific gravity	2.67	1.90	0.66
Fineness	5.54	5.88	5.96
Bulk density (compacted)	1491 kg/m^3	1471 kg/m^3	810 kg/m^3
Water absorption (24 hours) %	0.62%	3.91%	26.5%

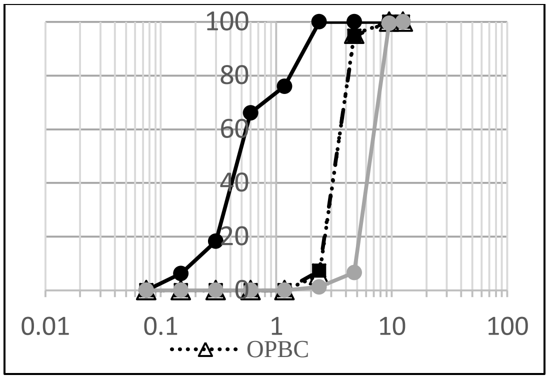

Fig. 1. Sieve analysis grading curve

Fig. 2. Coarse aggregate of (a) LECA, (b) crushed granite, and (c) OPBC.

2.2. Mix Proportions

For comparison, a normal weight concrete with crushed granite as control mix (mix CM) was designed for grade 70 with high workability to investigate the effect of the substitution of normal weight coarse aggregate between OPBC and LECA on their engineering properties. A total of nine concrete mixes were prepared for this study. In this mix CM, normal weight coarse aggregate (granite) was substituted with OPBC (mix group A) and LECA (mix group B) from 0% to 100% by volume in increments of 25%. The design of LWAC mixes is developed by trial (Shetty 2005). In this method, all of the mixes have the same mix proportions while containing different types of coarse aggregates. Given that LECA aggregate is round with the lowest weight compared with crushed granite and OPBC aggregate, high slump of LECA LWAC (B75 and B100) were found to easily cause floating of aggregate. Figure 1 shows the shapes of LECA, crushed granite, and OPBC. Superplastisizer, the dosage of which was reduced to approximately 16%, was used in these two mixes to overcome the high slump. Table 2 shows the mix proportions of the nine concrete mixes. Basri et al. (1999) and Okafor (1988) claimed that the workability of a mixture is also dependent on the surface texture of aggregate from waste materials.

Table 2 Mix proportions in one batch

Mix group	Mix code	Cement (Kg/m^3)	Water (Kg/m^3)	Super Plasticizer (Kg/m^3)	Fine aggregate	Coarse aggregate			Replacing percentage (%)
					Sand (Kg/m^3)	Granite (Kg/m^3)	OPBC (Kg/m^3)	Leca (Kg/m^3)	
Control mix	CM	63.30	20.30	0.63	112.3	112.3	0	0	0
Group A	A25	63.30	20.30	0.63	112.3	84.3	20	0	25
	A50	63.30	20.30	0.63	112.3	56.2	40	0	50
	A75	63.30	20.30	0.63	112.3	28.1	60	0	75
	A100	63.30	20.30	0.63	112.3	0	80	0	100
Group B	B25	63.30	20.30	0.63	112.3	84.2	0	7	25
	B50	63.30	20.30	0.63	112.3	56.2	0	14	50
	B75	63.30	20.30	0.53	112.3	28.1	0	20.9	75
	B100	63.30	20.30	0.53	112.3	0	0	28.1	100

2.3. Mixing Procedure and Concrete Casting

The mixing procedures are as bellow's steps:

Step 1: Place aggregates into a rotary drum-type mixer and mix for 2 minutes.
Step 2: Add cement and mix for 3 minutes.
Step 3: Add 70% of mixing water into the mixer and mix for another 3 minutes.
Step 4: Add balance to the mixing water with superplasticizer into the mixer and mix for 5 minutes.
Step 5: Perform consistency test.

The consistency test confirmed that the workability of concrete reached a satisfactory level. The concrete specimens were cast in steel molds of 100 mm cubes for compressive strength, cylinders of 100 mm diameter and 200 mm height for splitting tensile strength, prisms of 100 mm × 100 mm × 500 mm for flexural strength, and cylinders of 150 mm diameter and 200 mm height for MOE. All specimens were compacted using a vibrating table. The results correspond to the mean values of at least three specimens for mechanical properties.

2.4. Curing Regimes

The following tests have been conducted under five curing conditions after 24 hours of casting to investigate the impacts of different curing regimes on the 28-day compressive strength.

(1) Continuous water curing (FW): Specimen was soaked in water with temperature of 23 ± 3 °C for 27 days after 1 day of demolding.

(2) Air drying (AC): Specimen was placed under laboratory condition with RH% of 73 ± 5 and temperature of 29 ± 3 °C after 1 day of demolding.

(3) 3 days (3W), 5 days (5W), and 7 days (7W) of partial early curing: Specimen was soaked in water for 2, 4, and 6 days after 1 day of demolding and then put in air under laboratory condition.

3. RESULTS AND DISCUSSION

3.1. Workability

Table 3 depicts the slump values and densities of all mixes. The slump values of the mixes of groups A and B decreased while increasing the OPBC and LECA aggregates, respectively. This result can be attributed to the condition in which the water absorption of OPBC and LECA aggregates are more significant than that of crushed granite by 6 times and 43 times, respectively. The surfaces of these lightweight aggregates are porous. Thus, part of cement paste, which is absorbed into the grain, reduced the workability. By increasing the amount of OPBC and LECA aggregates and reducing crushed granite in the concrete mixture, the slump value decreased. However, the reductions of the slump values for the mixes of groups A and B are insignificant with substitution of the amount of OPBC and LECA aggregates, respectively.

Table 3. The slump and density of concrete

Mix group	Mix code	Slump (mm)	Density (Kg/m^3)			
			Demould	Air dry at 28 days	Saturated at 28 days	Oven dry at 28 days
Control mix	CM	105	2356	2317	2370	2294
Group A	A25	95	2148	2126	2159	2232
	A50	80	2200	2191	2220	2178
	A75	70	2290	2261	2303	2106
	A100	55	2076	2057	2121	1905
Group B	B25	90	2147	2132	2169	2098
	B50	85	1937	1893	1960	1879
	B75	70	1736	1703	1774	1693
	B100	50	1550	1510	1603	1507

The CM and all LWACs (mixes of groups A and B) confirmed acceptable workability. Mehta and Monteiro (2006) revealed that in general site application, the slump value of LWAC in the range of 50 to 75 mm is equivalent to that of 100 to 125 mm of normal weight concrete. Previous studies showed that OPBC concrete with 28-day compressive strength in the range of 17 to 47 MPa has a slump value of 45 to 190 mm (Abdullahi et al. 2008; Mohammed et al. 2013, 2014), whereas compressive strength of 27 to 35.5 MPa has slump values of 40–100 mm (Hassan et al. 2008). However, LECA LWAC with the compressive strength of 37.46 MPa showed a slump value of 95 mm (Shafigh et al. 2012a), whereas compressive strength ranging from 34.7 to 63.9 MPa showed a slump value of 110 to 140 mm (Lo et al. 2008).

3.2. Density

Table 3 shows that the oven dry density decreased by 2.7% to 17% through increasing the substitution of OPBC in the mix CM from 25% to 100% in mix group A. However, for mix group B, the oven dry density decreased by 8.5% to 34.3% because the weight of OPBC aggregate is approximately 65% higher than that of LECA aggregate. The OPBC and the LECA are approximately 29% and 75% lighter than crushed granite, respectively. Therefore, the substitution of crushed granite with the OPBC and the LECA are expected to reduce the density of normal-weight concrete (mix CM). As a comparison between the LWAC-containing OPBC (mix group A) and the LECA (mix group B), the oven dry density of mix group A is considerably higher than that of mix group B

Figure 3 depicts a strong linear relationship between the oven dry density and percentage substitution of the OPBC (mix group A), the LECA (mix group B), and the OPS (Shafigh et al. 2012b). In the comparison among mix group A, mix group B, and OPS concrete, the oven dry density of OPS concrete is substantially lower than that of mix group A while higher than that of mix group B from the substitution of 25% onwards. This result is due to the fact that the weight of the OPS grain is nearly half of the OPBC grain while 44% higher than that of the LECA.

According to BS EN 206-1, the category of lightweight concrete is defined in the range of 800 and 2,000 kg/m3 (BSI 1992). Therefore, the oven ‘dry density of concrete containing 100% OPBC (mix A100) and 50% LECA onwards (mixes of B50, B75, and B100) in this study can be considered as lightweight concrete.

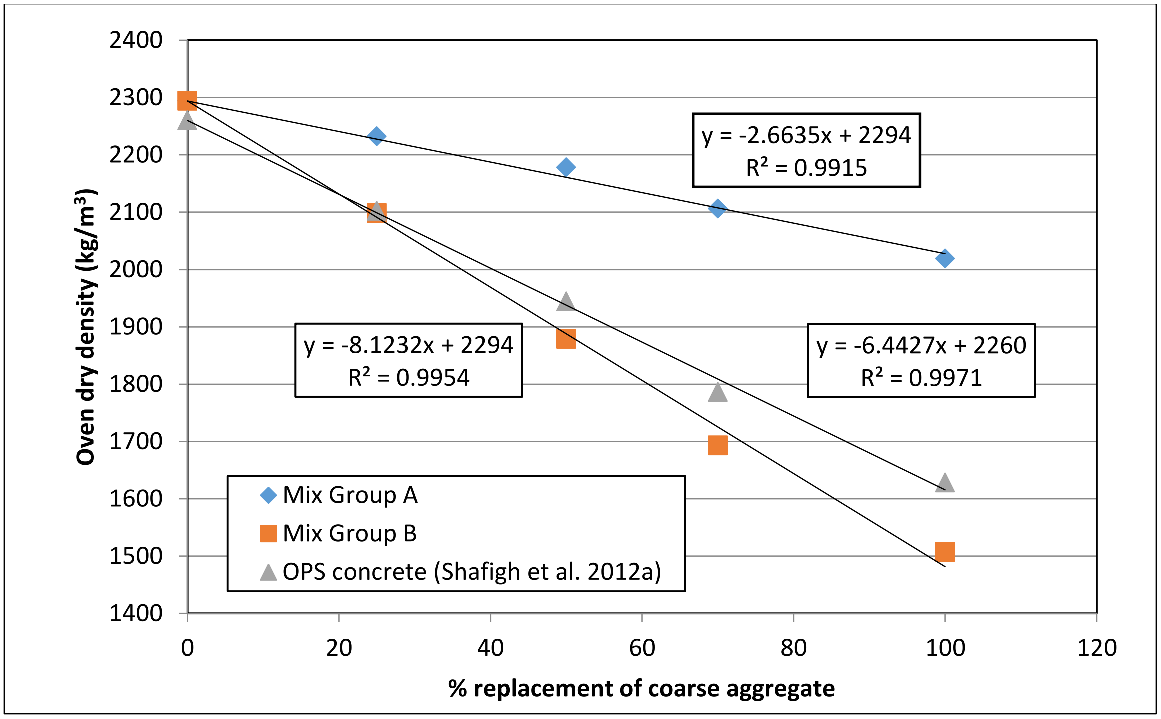

Fig.3. Relationship between density and percentage replacement of normal coarse aggregate by OPBC, LECA and OPS.

3.3. Compressive Strength

3.3.1. Under Continuous Water Curing

Table 4 shows the compressive strength of the full water-cured concrete of up to 56 days. The development of strength at 1st, 3rd, 7th, 28th, and 56th days of testing were almost the same patterns in all mixes. With the increasing age of concrete, the compressive strengths of all mixes increase. Mix CM exhibited the highest values of compressive strength compared with OPBC concrete (mix group A) and LECA concrete (mix group B). However, among the three mix groups, the LECA concrete (mix group B) showed the lowest compressive strength because LECA is the weakest aggregate whereas OPBC is weaker than crushed granite. The amount of improvement in compressive strength of mix group B (containing LECA) showed higher than that of mix group A (containing OPBC) in all ages. The compressive strengths at the age of 28 days of OPBC concrete (mix group A) and LECA concrete (mix group B) are approximately 5 to 22% and 42 to 79% lower than normal weight concrete (CM), respectively.

The use of 25% (mix A25) and 50% (mix A50) substitution percentage of OPBC in normal-weight concrete illustrated that the compressive strengths of both mixes were almost the same in all ages. In addition, the concrete containing 75% (mix A75) OPBC also confirmed that the compressive strength was similar to that of mix A100 mix in all ages. However, the rate of increasing the compressive strength of mix A75 mix onward was higher than that of mixes of A25 and A50 mixes in all ages. This result can be attributed to the fact that the OPBC aggregate is a more porous aggregate compared with crushed granite, as shown in Figure 1. As the cement mortar was absorbed into the porosity of the OPBC grain, the effective water-to-cement ratio decreased; therefore, the strength of the OPBC mixture increased.

The LECA-containing concrete containing up to 25% LECA of (mix B25) was substituted by normal-weight coarse aggregate. The compressive strengths at the ages of 3 days and 7 days were similar to the 28-day compressive strength. Furthermore, the inclusion of concrete with 25% and 100% LECA content in normal-weight concrete reached almost the same strength as 28-day compressive strength at the age of 7 days in this mix. Shafigh et al. (2014) and Mahmud et al. (2013) reported that the ceiling strength of LECA-containing concrete was at the early age of 7 days. The ceiling strength in the rest of the mixtures was not observed at this age. Ceiling strength point is largely determined by the grain of coarse aggregate and the quality of transition zone (Holm and Bremner 2000). Furthermore, the ceiling strength of concrete also depends on the type of aggregate used in the mixture (Clarke 1993). Lamond and Pielert (2006) reported that the strength of lightweight concrete would not be significantly improved by adding cementitious materials at the ceiling strength point of the mixture.

In addition, 7-day compressive strength of concrete containing the OPBC (mix group A) and the LECA (mix group B) is at approximately 81 to 88% and 90 to 99% that of 28-day compressive strength, respectively. Previous reports revealed that the 7-day compressive strength of the OPBC and the LECA, could reach up to 80 to 92% (Fujji et al. 1998; Omar and Mohamed, 2002) and 80 to 95% of 28-day compressive strength (CEB/FIP 1977), respectively.

Table 4 Compressive strength under full water curing

Mix group	Mix code	1day	3 days	7 days	28 days	56 days
Control mix	CM	30.15 (43%)	55.60 (78%)	55.98 (79%)	70.94	76.01 (107%)
Group A	A25	28.50 (42%)	50.51 (75%)	54.48 (81%)	67.52	71.89 (106%)
	A50	29.50 (45%)	49.93 (76%)	53.50 (81%)	65.70	70.30 (107%)
	A75	27.97 (50%)	44.49 (80%)	47.70 (86%)	55.46	58.79 (106%)
	A100	26.01 (47%)	44.84 (81%)	48.36 (88%)	55.00	57.68 (105%)
Group B	B25	30.10 (73%)	40.27 (97%)	41.16 (99%)	41.39	42.32 (102%)
	B50	18.15 (54%)	27.41 (82%)	30.09 (90%)	33.43	35.46 (106%)
	B75	14.32 (63%)	18.71 (82%)	20.99 (92%)	22.82	24.095 (105%)
	B100	11.43 (76%)	13.80 (92%)	15.02 (99%)	15.08	16.08 (107%)

3.3.2. Under AC and Partial Early Curing Conditions

Table 5 shows the compressive strength of all mixes under different curing conditions (AC, 3W, 5W, and 7W) at the age of 28 days. The compressive strength of the mixes of CM, group A, and group B under AC condition was reduced by approximately 7%, 3 to 10% and 7 to 12% as compared with those of specimens under FW condition, respectively. The reduction of the compressive strength in mix group B (LECA-containing concrete) is the lowest compared with those of mix CM and mix group A (concrete-containing OPBC). The reason could be that the use of saturated LECA provided internal curing for the mixture which improved the strength by allowing continuous hydration in concrete (Mather 2001; Bentz et al. 2005; Wang et al. 1994; Dhir et al. 1994). However, the saturated LECA depicted higher sensitivity to the lack of curing compared with crushed granite and OPBC. By contrast, the reduction of compressive strength in mix group A is lower than the mix CM. The use of saturated OPBC as partial or full replacement of crushed granite resulted in reduction of the sensitivity of normal-weight concrete under poor curing condition. As the OPBC aggregate is highly porous with absorbed part of water during mixing process, the effective water–cement ratio of concrete may decrease. The reduction in water–cement ratio in mix Group A can lead to an increase in the compressive strength of concrete. Therefore, the existing reserved water inside the OPBC aggregate provided internal curing to the concrete. Bentz et al. (2005) reported that the acceleration of hydration and increasing the strength of concrete can be achieved by using saturated lightweight aggregate to provide additional existing reserved water to the mixture. The compressive strength in LECA-containing concrete (mix group B) of this study is the lowest among all mixes under AC and partial early curing conditions because LECA is weakest and has the highest porosity compared with crushed granite and OPBC.

The 28-day compressive strength of all mixes under partial early curing regime is expected to be higher than those of the corresponding specimens under AC. This result may be due to the fact that FW promoted a high amount of hydration leading to high compressive strength in concrete under partial early curing while a low amount of hydration led to low compressive strength of concrete under AC condition. The rate of improvement of the 28-day compressive strength under 3W, 5W, and 7W was 1 to 4%, 10 to16%, and 12 to 25% for mix group A while 0 to 14%, 5 to 34%, and 5 to 42% for mix group B, respectively, compared with that of AC condition. The amount of compressive strength gained under 5W and 7W of the two types of mixtures was higher than that under 3W curing regime. The 28-day compressive strength of 5W was close to that of 7W regime condition for both mix groups. Furthermore, the amount of improvement in compressive strength under partial curing of mix Group B (LECA-containing concrete) was higher than that of mix group A (OPBC-containing concrete) because the porosity of LECA is higher than that of OPBC. Cusson et al. (2005), Bentz et al. (2004, 2005), and Jensen and Hansen (2001) reported that the water stored inside saturated LECA particles can provide continuous hydration by producing cement paste to fill up voids and create a strong bonding force between an aggregate and cement paste.

In the 28-day compressive strength under the partial early curing regimes of 3W, the compressive strength was almost the same or even higher than that of standard curing in all mixes, except of mixes of B75 and B100. For both 5W and 7W curing conditions, the compressive strengths of mixes of CM, Group A, B25, and B50 were slightly greater than that of standard curing, while it was slightly lower for mixes of B75 and B100. Haque (1990) recommended that a minimum of 7 days of moist curing shall be practiced in all concreting works.

Table 5. The compressive strength of concrete at the age of 28 days under different curing regimes

Mix group	The compressive strength at the age of 28 days (MPa)					
	Mix code	Standard curing condition (FW)	Partial early curing			
			AC	3W	5W	7W
Control mix	CM	70.94	65.70	67.79	77.64	78.56
Group A	A25	67.52	65.67	67.82	73.89	75.96
	A50	65.70	62.94	65.69	69.05	70.50
	A75	59.46	57.83	58.50	63.50	64.97
	A100	55.00	49.60	50.20	57.80	62.10
Group B	B25	41.39	36.26	41.50	48.51	51.42
	B50	33.43	29.42	33.01	35.13	35.17
	B75	22.82	20.12	21.01	21.40	21.46
	B100	15.08	14.05	14.07	14.75	14.73

3.4. Splitting Tensile Strength and Flexural Strength

Tables 6 and 7 show the splitting tensile strength and flexural strength for all mixes. As can be seen the concretes containing OPBC (mix group A) and LECA (mix group B) have lower splitting tensile strength and flexural strength than normal-weight concrete (mix CM). The mixes subjected to water curing showed higher splitting tensile strength and flexural strength compared with those under the AC condition at the age of 28 days. As expected, continuous hydration under FW could improve the strength of all mixes. In addition, the amounts of differences between AC and FW conditions for splitting tensile strength and flexural strength were 7 to 16% and 3 to 11% for mix group A whereas they were 5 to 25% and 5 to 19% for mix group B, respectively. Compared with compressive strength, the splitting tensile strength and flexural strength for mixes of groups A and B were found to be more sensitive to poor curing regimes.

The requirement of splitting tensile strength at the age of 28 days should be more than 2.0 MPa for structural lightweight concrete members (Kockal and Ozturan 2011; ASTM: C330 2005). The splitting tensile strength of the present study showed more than 2.0 MPa at 7- and 28-day ages. Therefore, all these mixtures at 7 days can be recommended for constructing structural concrete components.

The splitting tensile strength–compressive strength ratio at the ages of 28 days for normal-weight concrete is within the range of 8 to 14% (Kosmatka and Wilson 2011). This ratio for high-strength lightweight concrete under FW is in the range of 6 to 7% (Holm and Bremner 2000). The ratios of 28-day splitting tensile strength/compressive strength of this study for mixes of groups A and B were 6.9 to 7.5% and 8 to 14.9%, respectively.

The amounts of improvement of splitting tensile strength from 7 to 28 days for Groups A and B were 8 to 23% and 1 to 8%, respectively. However, the increases in compressive strength from 7 to 28 days were 12 to 19% and 1 to 10% for mixes of groups A and B, respectively. Therefore, the amount of rate increase in splitting tensile strength and compressive strength with time for mix group A is more critical than mix group B.

Figure 4 shows the 28-day splitting tensile strength under AC, 7W, and FW conditions of all mixes. The figure shows that the slope of mix group B was more than that for mix group A. This result confirmed that the reduction rate in mix group B was more than that of mix group A. The negative effect of the substitution of LECA was more affirmed than the substitution of OPBC in normal-weight concrete.

Shetty (2005) revealed that flexural strength–compressive strength ratio for concrete with a compressive strength of not less than 25 MPa exhibited between 8 to 10%. Domagała (2011) reported that flexural strength–compressive strength ratio for lightweight concrete is lower than that of normal weight concrete. Omar and Mohamed (2002) also revealed that flexural strength–compressive strength ratio for high-strength lightweight concrete is in the range of 9 to 11%. As shown in Table 7, the flexural strength–compressive strength ratio of mixes of groups A and B is in the range of 8.6 to 10.1% and 12.3 to 21.6%, respectively.

Generally, the flexural strength is 35% higher than splitting tensile strength (Zheng et al. 2001). However, the flexural strength in this study is 16 to 37% and 38 to 53% higher than the splitting tensile strength for mixes of groups A and B, respectively.

Figure 5 shows that incorporating OPBC and LECA in normal weight concrete reduces the flexural strength because the two mixtures are porous aggregates. OPBC and LECA are weaker than crushed granite. However, the results show that the rate of reduction in mix group B (LECA-containing concrete) is higher than that of mix group A (OPBC-containing concrete) because LECA is lighter and weaker than OPBC.

Table 6. Splitting tensile strength of concrete mixes (MPa).

Mix group	Mix code	Splitting tensile strength		28-day splitting tensile strength	
		Water curing		Partial early curing	
		7 days	28 days	Air curing	7W
Control mix	CM	3.73	5.19	4.72	4.89
Group A	A25	3.70	5.03	4.66	4.78
	A50	3.68	4.90	4.14	4.43
	A75	3.63	4.06	3.86	3.89
	A100	3.36	3.79	3.40	3.60
Group B	B25	3.16	3.33	3.15	3.28
	B50	3.05	3.19	2.39	3.16
	B75	2.43	2.53	2.14	2.42
	B100	2.15	2.24	1.86	2.15

Table 7. Flexural strength of concrete mixes (MPa)

Mix group	Mix code	(f_{cu})	$(f_{r,AC})$	(f_r)	$\left(\frac{f_r}{f_{cu}}\right)\%$	$\left(\frac{f_r}{f_t}\right)$
Control mix	CM	70.94	5.95	6.31	8.9	1.16
Group A	A25	67.52	5.59	5.83	8.6	1.16
	A50	65.70	5.56	5.77	8.8	1.18
	A75	55.46	5.11	5.58	10.1	1.37
	A100	55.00	4.70	5.31	9.7	1.37
Group B	B25	41.39	4.42	5.09	12.3	1.53
	B50	33.43	4.28	4.50	13.5	1.41
	B75	22.82	2.94	3.49	15.3	1.38
	B100	15.08	2.63	3.25	21.6	1.38

*f_cu, f_(r,AC) f_r and f_t are 28-day compressive, flexural under AC condition, flexural and splitting tensile strengths (MPa), respectively.

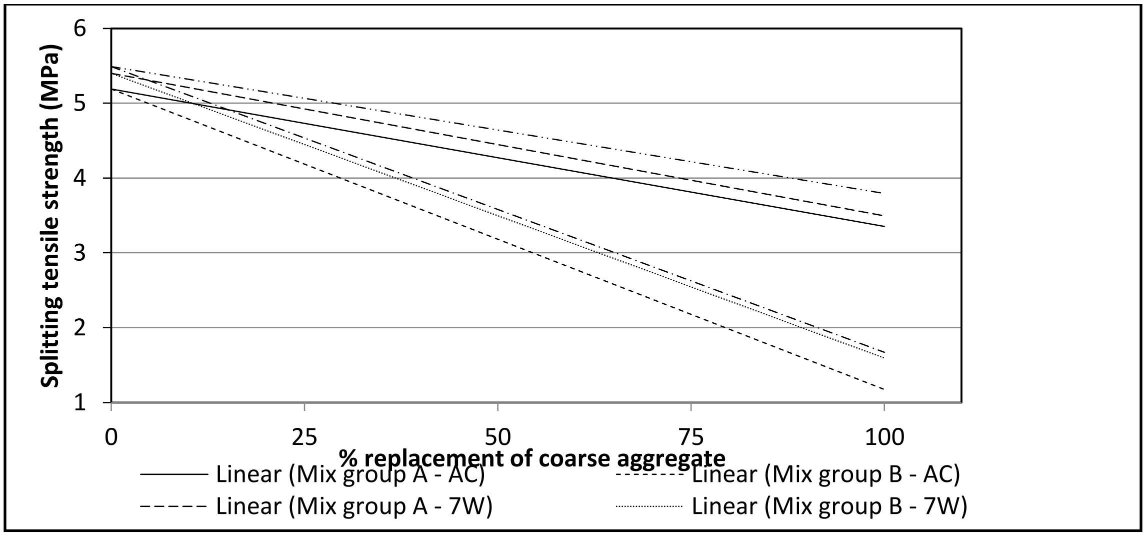

Fig.4 28-day splitting tensile strength under AC, 7W and FW condition

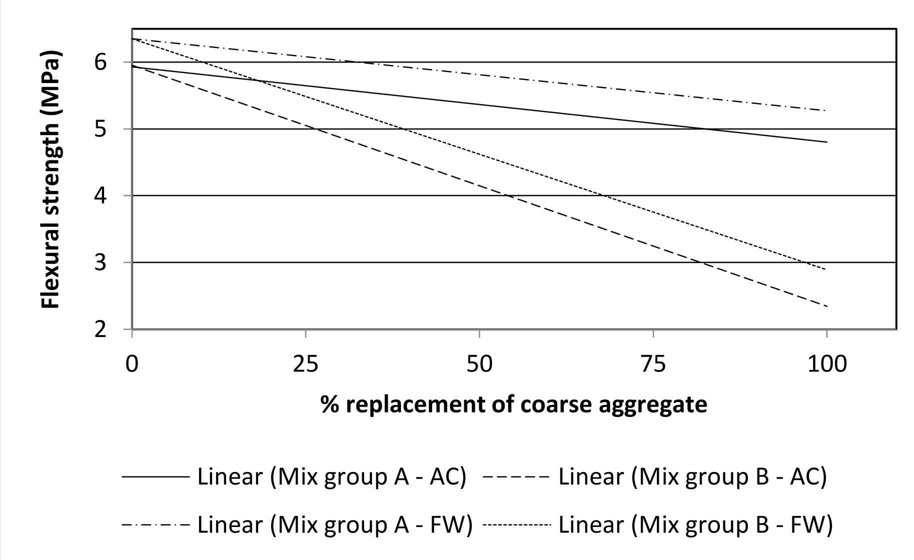

Fig.5. 28-day flexural strength under AC and FW condition

3.5. Modulus of Elasticity

The modulus of elasticity (MOE) of all mixes are ~~is~~ shown in Table 8. The substitution of crushed granite with the OPBC (mix group A) and the LECA (mix group B) in normal-weight concrete reduced the MOE. By increasing the amount of substitution from 25 to 100% in both mixtures, the MOE was gradually reduced. The amounts of reductions of up to 29% and 54% were respectively found for mixes of groups A and B under AC condition, whereas 42% and 63% were observed for mixes of groups A and B under FW condition, respectively. However, the rate of reduction of mixture containing the LECA (mix group B) was higher than that of mixture containing the OPBC (mix group B). Therefore, the use of saturated LECA and OPBC in concrete could help in the continuous hydration of cement paste leading to the reduction in the porosity of concrete. However, the MOE of a mixture is largely dependent on the quality and the MOE of coarse aggregate instead of that of mortar. Caldarone (2009) reported that the MOE is dependent on the quality of coarse aggregate in the mixture. Thus, the MOE plays an important role in the mechanical properties of concrete.

According to the test results, regression analysis shows the relationship between the MOE and the compressive strength at 28 days, as expressed in Eq. (1) for the case of OPBC-containing LWAC (mix group A) and in Eq. (2) for the case of LECA-containing LWAC (mix group B).

$$E = 0.067\, {f_{cu}}^{1.4958} \qquad (1)$$

$$E = 2.5528 {f_{cu}}^{0.6708} \qquad (2)$$

where, E is the MOE (GPa), and f_{cu} is the 28-day compressive strength for the cube (MPa). The degree of confidence is 0.95 in the case of OPBC-containing LWAC (mix group A) and 0.92 in the case of LECA-containing LWAC (mix group B), as shown in Figure 6.

Figure 7 shows the comparison of the MOE values of the mixes with those predicted by the different equations proposed by BS 8110 (1985) [Eq. (3)]; ACI 318 (1995) [Eq. (4)] for compressive strength of 21 to 35 MPa with density in the range of 1440 to 2480 kg/m^3; Pauw (1960) [(Eq. (5)] who proposed a common estimating equation; Tasnimi (2004) [Eq. (6)] who reported artificial LWAC with cylinder compressive strength of 15 to 55 MPa; and Slate et al. (1986) [(Eq. (7)] who presented a high-strength lightweight concrete. The equations are expressed as follows:

$$E=0.0017w^2 f_{cu}^{0.33} \qquad (3)$$

$$E=0.043w^{1.5} f^{0.5} \qquad (4)$$

$$E=0.04w^{1.5} f_{cu}^{0.5} \qquad (5)$$

$$E=2.1684 f^{0.535} \qquad (6)$$

$$E=(0.062+0.029 f^{0.5})w^{1.5} \qquad (7)$$

where, E is MOE (GPa), w is air-dry density (kg/m^3), f_{cu} is cube compressive strength (MPa), and f is the cylinder compressive strength (MPa).

Figure 7 shows that among all equations, Eqs. (3), (4), and (5) for compressive strength less than 65 MPa and Eq. (7) for less than 55 MPa of OPBC-containing LWAC provide accurate estimates of the MOE values. However, Eqs. (3), (4), (5), (6), and (7) for LECA-containing LWAC underestimate the MOE values.

Table 8. Measured modulus of elasticity (GPa).

Mix group	Mix code	28-day modulus of elasticity	
		Air curing	Water curing
Control mix	CM	36.13	45.53
Group A	A25	34.93	38.01
	A50	30.13	33.50
	A75	26.55	27.73
	A100	25.74	26.58
Group B	B25	29.04	34.02
	B50	24.21	24.91
	B75	19.24	19.26
	B100	16.75	16.76

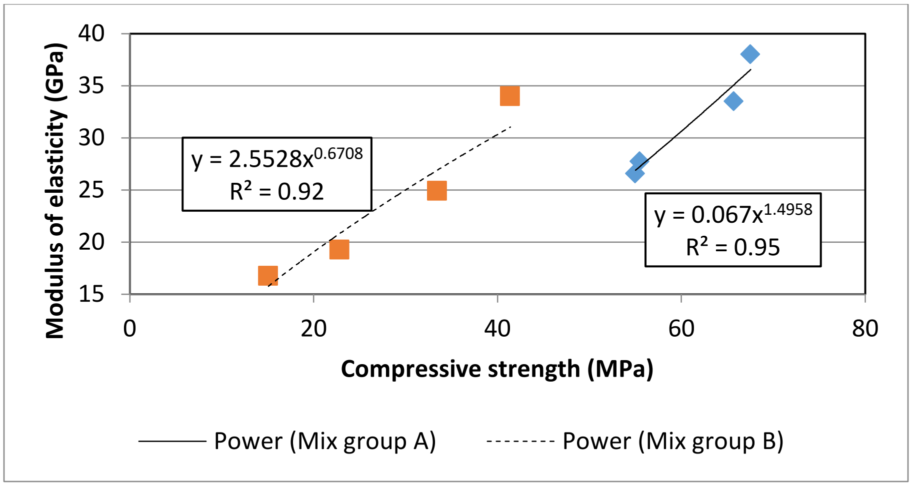

Fig.6. Compressive strength versus modulus of elasticity of mixes group A and B.

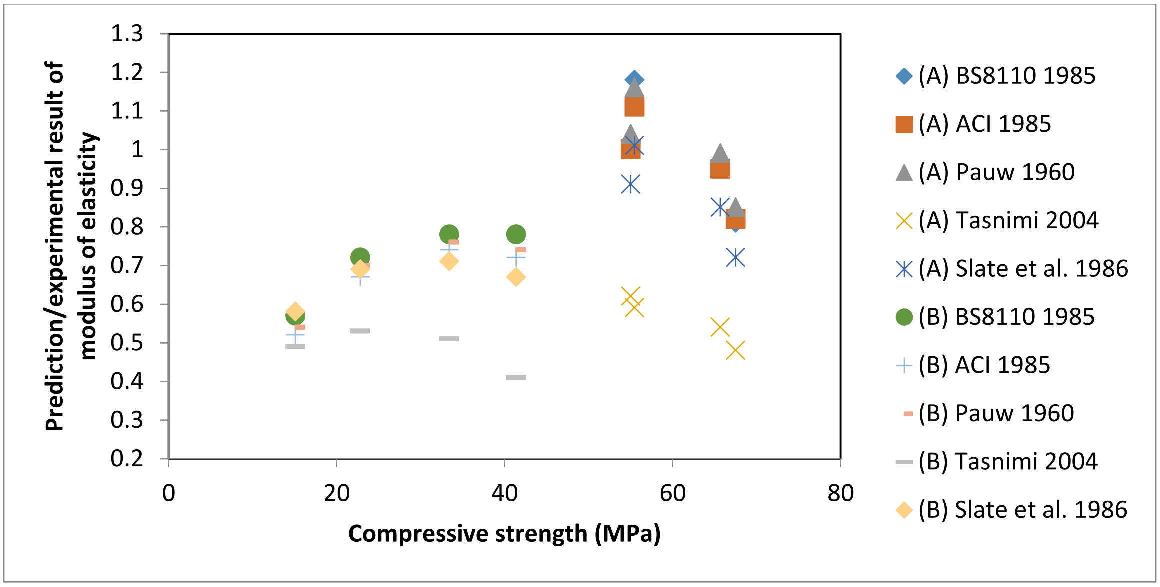

Fig. 7. Experimental and theoretical modulus of elasticity of mixtures

3.6. Water Absorption

The initial (30 minutes) water absorptions at the age of 28 days for all concrete mixes are shown in Figure 8. According to CEB-FIP (1989), categories for poor, average, and good for evaluation of the quality of concrete based on initial water absorption (water absorption in 30 minutes) are defined in the range of 5% and above, 3 to 5%, and 0 to 3%, respectively. Figure 8 shows that the initial absorptions of the three mixes are below 3%, which can be assumed to have good quality of concrete. Moreover, the water absorption rates of OPBC-containing concrete (mix group A) and LECA-containing concrete (mix group B) were 9 to 64% and 39 to 136% higher than that of CM, respectively. Highly porous OPBC aggregate has higher water absorption capacity than normal weight aggregate, as reported by Ahmad et al. (2007). However, the LECA containing concrete has the highest water absorption among all mixes because the LECA has the highest porosity. The inclusion of manufactured sand and slag in OPS concrete showed the initial water absorption within the range of 2.7 to 3.4% (Mo et al. 2016).

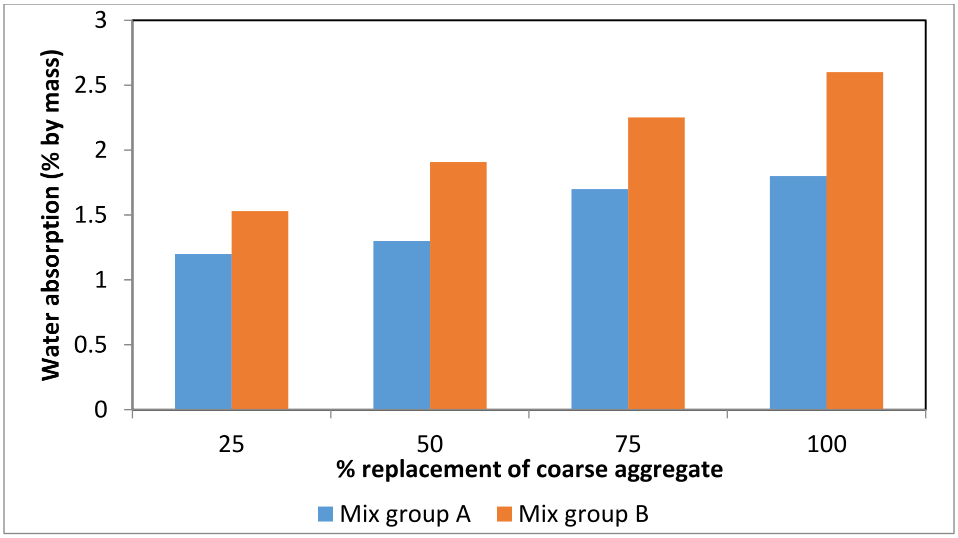

Fig. 8. Relationship between mix of concrete and water absorption.

4. CONCLUSION

A comparatively study has been proposed in this paper for the engineering properties of the Oil-palm-boiler clinker (OPBC) OPBC and lightweight expanded clay aggregate (LECA) concretes. According to the obtained results From the results obtained in this study, the following conclusions can be drawn:

1. The slump value decreases by increasing the OPBC and the LECA coarse aggregate in normal-weight concrete. Concrete containing the OPBC and the LECA exhibited acceptable workability.
2. Increasing the volume of OPBC and LECA in normal weight concrete leads to a reduction in density of the concrete. However, the oven-dry density of concrete containing 100% OPBC (mix A100) and 50% LECA onwards (mixes of B50, B75, and B100) in this study can be considered as lightweight concrete.
3. The 28-day compressive strength of OPBC concrete (mix group A) and LECA concrete (mix group B) is about 5 to 22% and 42 to 79% lower than that of normal weight concrete (mix CM).
4. The ceiling strength of LECA concrete is at the early age of 7 days. However, it occurred at a later age for normal weight concrete and OPBC concrete.
5. The use of saturated OPBC and LECA in concrete improves the mechanical properties of concrete under AC condition. However, the saturated LECA was more sensitive to the lack of curing compared with crushed granite and OPBC.
6. Two days of wet curing is almost the same or even higher for normal weight, OPBC-containing, and LECA-containing concretes to reach the compressive strength of standard curing at the age of 28 days.
7. Inclusion of OPBC and LECA in normal weight concrete reduces the splitting tensile strength and flexural strength. However, the rate of reduction on the splitting tensile strength and flexural strength in LECA containing concrete is higher than that of OPBC containing concrete.
8. The MOE is strongly correlated with compressive strength for concrete containing OPBC and LECA at different ages. A close agreement with the measured data can predict the MOE values by using Eq. (1) for OPBC-containing LWAC and Eq. (2) for LECA-containing LWAC.
9. The water absorption improves by increasing the substitution of OPBC and LECA. All mixes in this study can be considered as good concrete.

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