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EXPERIMENTAL STUDY ON LIGHTWEIGHT CONCRETE USING LIGHTWEIGHT EXPANDED CLAY AGGREGATE (LECA) AND EXPANDED PERLITE AGGREGATE (EPA)

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Abstract

In pursuit of reducing the dead-weight of precast concrete structures, one approach is by adopting lightweight concrete. EN 13369:2013 specifies a minimum cube compressive strength of at least 18 MPa for the lightweight concrete to be eligible for use in reinforced precast concrete products. This study conducts an experiment using LECA and EPA to produce lightweight concrete for structural use. Density, concrete quality, and strength of various mixes are observed by conducting cube compressive test and UPV test. Two phases of experiments were conducted, where the first phase variable is the percentage of LECA replacing the normal coarse aggregate, while the second phase variable is the percentage of EPA replacing the sand proportion. The optimum concrete mix is found to be the mix with 60% LECA and 50% EPA replacements, which achieved D1.8 lightweight density category that surpasses the specified minimum cube compressive strength and falls under the good quality concrete type according to the UPV rating. In summary, the inclusion of LECA and EPA into the concrete mix will decrease the cube compressive strength, lower the density, escalate the slump value and the travelling time of the ultrasonic pulse, but at the same time able to produce lightweight structural concrete.

Keywords: Cube compressive strength, Expanded perlite aggregate, Lightweight aggregate concrete; Lightweight expanded clay aggregate; Ultrasonic pulse velocity.

1. Introduction

Construction using precast concrete structures with heavy self-weight components is undesirable due to the inevitable reliance on heavier equipment that brings to difficulties in transportation and requirements for sturdier support elements, all of which, may escalate the overall construction cost [1]. One of the many ways of reducing the mass of dead weight of structures is by adopting lightweight concrete [2]. Lightweight concrete (LWC) is an oven-dry conditioned concrete with a density ranging from 800 kg/m^3 to 2000 kg/m^3 as compared to the densities of normal-weight concrete (NWC), which ranges between 2000 kg/m^3 to 2600 kg/m^3 and heavy-weight concrete (HWC), equals to or exceeds 2600 kg/m^3 [3]. The production of lightweight concrete involves the inclusion of air and void in the concrete. The most popular method to accomplish this is by substituting conventional mineral aggregates with lighter ones [4]. Even though lightweight aggregate concretes have inferior strength and durability due to the more porous attributes of the lightweight aggregates, admixtures such as silica fume (SF) can be introduced to strengthen the weakened compressive strength of the lightweight concrete. High reactivity and micro filler effect of SF will increase the strength of the concrete [5, 6].

The prevalent lightweight aggregate usually adopted in the production of lightweight concrete is the lightweight expanded clay aggregate (LECA) and expanded perlite aggregate (EPA). These two lightweight aggregates (LWA), categorised as type B LWA, are manufactured from natural source materials and possess a positive history of intended applications in concrete, mortar and grout, bituminous mixtures and surface treatments, and unbound and hydraulically bound mixes (other than concrete, mortar and grout) [7]. The production of LECA generally involves the heating of fine particle clays (or clay pallets) with low content of lime at 1100 to 1200 °C in rotary kilns. When exposed to the high temperature, the pallets will bloat and later retain its spherical shape upon cooling, producing a final product of lightweight expanded clay that has rigid outer ceramic shells yet porous in the inside. The circular motion of the rotating kilns causes the LECA to have spherical forms, as shown in Fig. 1(a).

Apart from its general term "LECA", this material also has other different patented names depending on the manufacturing countries, to name a few "Kermazite", "Aglite", and "Liapor". The manufactured aggregates vary in size, density and compressive strength, where smaller size aggregates have higher density and compressive size, and vice versa. Typical sizes of LECA products varies from 0-4 mm, 4-8 mm, 8-12 mm and 12-20 mm. Besides its advantageous characteristics such as having natural pH value of nearly 7, high acoustic resistance, good thermal insulation, non-biodegradable, non-combustible, and undamaged by water, LECA is known to be useful in various fields such as construction, water treatment, and agriculture [4, 8, 9]. Meanwhile, EPA as illustrated in Fig. 1(b) is created by crushing and heating natural volcanic glasses at high temperatures of 760 to 1100 °C so that it expands 4 to 20 times its original volume and forms a light cellular material with grain size products of less than 0.08 mm, 4.75 mm or 10 mm. The commercially attractive physical characteristics of EPA are high heat resistance, excellent acoustic resistance, low bulk density, high surface area, and chemical idleness. Similar to LECA, EPA is also proven to be versatile and had been used in the construction field as part of building material and horticulture field as hydroponic medium or filter media for pharmaceuticals and food products [4, 10, 11].

(a) Lightweight Expanded Clay Aggregate (LECA).

(b) Expanded Perlite Aggregate (EPA).

Fig. 1. Investigated lightweight aggregates.

The bulk density of natural mineral aggregates is between 1520 to 1680 kg/m^3, and that of expanded perlite is only 60 to 80 kg/m^3 [12]. Partially replacing the natural mineral aggregate proportions in concrete with expanded perlite will significantly reduce the density of the concrete. However, as the percentage of replacements increases, the compressive strength of the concrete produced will also be reduced [13]. Sengul et al. [14] reported that by replacing 20%, 40%, 60% 80% and 100% of the natural sand with EPA resulted in compressive strength reductions of 40%, 62%, 84%, 96%, and 99%. Oktay et al. [15] reported similar results where the EPA replacement percentages of 15%, 30%, 45%, 60% and 80% reduced the compressive strength of produced concrete by 38%, 65%, 71%, 86%, and 89%.

Meanwhile, Jedidi et al. [16] discovered even higher rates of compressive strength reductions where the EPA replacements percentages of 10%, 20%, 30%, 45% and 50%, caused the concrete compressive strength to reduce by 40%, 63%, 81%, 84% and 91%. LECA, on the other hand, has a lower rate of compressive strength reductions as reported by Rashad [8] and Anil Kumar and Prakash [17], where 10% to 100% of LECA content gave compressive strength reductions of between 0.44% to 56%, which is consistent with the report by Nawel et al. [18] that said concrete produced with 100% LECA replacement resulted in reduced compressive strength of only 39%. Moreover, Heiza et al. [19] concluded that LECA possesses excellent potential in producing low-density structural lightweight concrete. Both of these materials have been applied by researchers as aggregate replacements to produce concrete, mortar or bricks with reduced unit weight [8, 10]. Nevertheless, even though many publications discussed and experimented on the production of LWC made by replacing aggregate proportions with LECA alone or EPA alone, interestingly, through all the studies reviewed so far, no publication can be found on the production of lightweight concrete made of the combination of both the materials.

The combination of LECA and EPA as partial replacements for natural aggregates is expected to produce lightweight concrete that may attain better strength than the EPA-only concrete, and at the same time, possibly, acquire a lower density than the concrete made out of LECA alone. Therefore, this study aims at identifying the optimum lightweight concrete mix that satisfies the requirement for lightweight reinforced precast concrete products, made by replacing the natural coarse and fine aggregate with LECA and EPA.

2. Experimental Programme

This experimental programme is pursued by producing cubes of concrete mix with various proportions of aggregate from both LECA and EPA.

2.1. Materials

Information and characteristics of the materials used are given in this section.

2.1.1. Cement

The ordinary Portland cement CEM I 42.5 certified to MS EN 197-1 was adopted in this study as it contains an adequate amount of C_3S (Tricalcium Silicate) proportion, which was imperative to the contribution of strength in concrete [20]. The typical specific gravity value of cement is taken as 3.15 [21].

2.1.2. Aggregate

The maximum coarse aggregate size was limited to 10 mm crushed aggregate. Meanwhile, the percentage of fine aggregate passing 600 µm was determined by sieve analysis of 27.6%. LECA and EPA were used for the partial replacements of coarse and fine aggregates. The sizes of the lightweight aggregates were between 8 mm to 13 mm for LECA and in the range of 3 to 5 mm for EPA. The sieves analysis results of the two materials are as follows:

Sieve analysis of LECA (5-14 mm): Sieve size (37.5 mm), passing (100%); sieve size (20 mm), passing (100%); sieve size (14 mm), passing (91.44%); sieve size (10 mm), passing (26.45%) and sieve size (5 mm), passing (0%).

Sieve analysis of EPA (0.01-5 mm): Sieve size (5 mm), passing (98.81%); sieve size (2.36 mm), passing (74.06%); sieve size (1.18 mm), passing (10.69%); sieve size (0.6 mm), passing (10.5%); sieve size (0.3 mm), passing (10.3%); sieve size (0.15 mm), passing (9.90%); and sieve size (0.01 mm), passing (0%).

In accordance with ASTM C127-15, the water absorption and specific gravity of LECA were determined as 27% (for a soaking period of 24 hours) and 0.80 respectively while the water absorption and specific gravity of EPA were taken as 200% (for a soaking period of 24 hours) and 0.31 respectively [10, 22]. Whereas, the specific gravity of natural coarse aggregate and sand were both taken as 2.7 [4, 5].

2.1.3. Mineral admixtures

For a higher compressive strength effect, an optimum percentage of 10% (calculated from the cement proportion) by the absolute volume of as-produced silica fume was added into the mixtures as partial replacement of cement [5, 10]. More importantly, silica fume was included to help in dealing with the segregation issue due to the low weight of LECA, especially under the condition of a high slump [2]. Compared to ordinary Portland cement, silica fume is much finer and carries a bulk density value of about 200 to 300 kg/m^3. As a result of adding silica fume into the mixture, the produced concrete was expected to be darker than normal concrete [20]. In this study, the specific gravity of the silica fume was taken as 2.2 [2, 21, 23].

2.2. The mix design and experimental methods

As a starting point, the proportions of the concrete were designed according to the Building Research Establishment (BRE) mix design method for normal concrete before the proportions for coarse and fine aggregates were partially replaced with LECA and EPA. The initial strength of the control concrete mix was designed for compressive strength of 40 MPa [24]. High compressive strength was selected due to the reductions of strength expected to be caused by the introductions of lightweight aggregates in the mix. For the mix to be eligible for lightweight reinforced precast concrete products, it is required to achieve a minimum compressive strength of at least LC16/18 according to BS EN 13369:2013 [25, 26]. Pursuance to that, the mixes were prepared in two phases. In the first phase, only the percentage of LECA partial replacement was varied with values of 30%, 60%, 80% and 100%. The percentage of replacements was calculated by implementing the absolute volume method.

The primary purpose was to find a mix that has the lowest density and at the same time carries a 28-days cube compressive strength value of approximately 36 MPa, which is equal to twice the minimum strength needed for use in precast concrete products. The strength of 36 MPa was reserved in the event of further strength reduction that would take effect once EPA was introduced in the second phase. Consequently, the introduction of EPA will lead to more reduction of the mix densities. Once the best LECA replacement percentage was determined, it would then be combined with EPA as replacements for fine aggregate in the range of 5% to 75%. The aim was to find the best mix that holds the lowest density and at the same time carries a minimum 28-days cube compressive strength of at least 18 MPa. The ratios of the mixes are shown in Tables 1 and 2.

Table 1. Mix proportions of LECA concrete (kg/m^3) - first phase.

Concrete mix	Cement	Silica Fume	Water	*W*/*B* ratio	Coarse aggregate		Fine aggregate	
					Granite	LECA	Sand	EPA
NC + SF	488.7	37.92	250	0.47	592	0	965.00	0
*L*30[a]	488.7	37.92	250	0.47	414.40	52.62	965.00	0
*L*60[a]	488.7	37.92	250	0.47	236.80	105.25	965.00	0
*L*80[a]	488.7	37.92	250	0.47	118.40	140.33	965.00	0
*L*100[a]	488.7	37.92	250	0.47	0	175.41	965.00	0

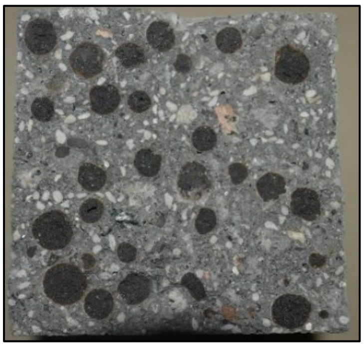
W = Water, *B* = Binder = Cement + Silica Fume, NC = Normal Concrete, SF = Silica Fume
a = Denotes the percentages of LECA partial replacement to the proportion of normal coarse aggregate

Table 2. Mix proportions of LECA-EPA concrete (kg/m^3) - second phase.

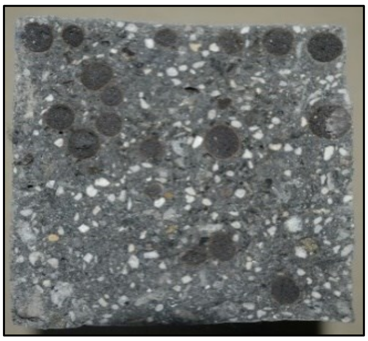
Concrete mix	Cement	Silica Fume	Water	*W*/*B* ratio	Coarse aggregate		Fine aggregate	
					Granite	LECA	Sand	EPA
*L*60[a]	488.7	37.92	250	0.47	236.80	105.25	965.00	0.00
*L*60EP5[b]	488.7	37.92	250	0.47	236.80	105.25	916.75	5.54
*L*60EP7.5[b]	488.7	37.92	250	0.47	236.80	105.25	892.63	8.31
*L*60EP10[b]	488.7	37.92	250	0.47	236.80	105.25	868.50	11.08
*L*60EP20[b]	488.7	37.92	250	0.47	236.80	105.25	772.00	22.16
*L*60EP25[b]	488.7	37.92	250	0.47	236.80	105.25	723.75	27.70
*L*60EP50[b]	488.7	37.92	250	0.47	236.80	105.25	482.50	55.40
*L*60EP75[b]	488.7	37.92	250	0.47	236.80	105.25	241.25	83.10

2.3. Preparation of concrete cube specimens and test procedure

Mixes of the concrete were prepared using a drum mixer, a method confirming with the BS1881-125:2013 [27]. Regarding the high-water absorptions of LECA and EPA, the LWAs were soaked in water to eliminate high water proportion and to gain similar effective water/cement ratio in all mixes. Both the LECA and EPA were pre-soaked for 24 hours and 30 minutes, respectively [5, 14, 28, 29]. Three 100mm cube specimens were prepared for the ages of seven days and 28 days curing period for each of the designated mixes. The compaction of cube specimen was done simultaneously using a steel rod and a vibrating table. This method of compaction was fixed to ensure that the LECA was evenly spread as shown in Fig. 2(a). The compaction using the rod alone produced unsmooth cube surface and honeycomb, whereas compaction solely using the vibrating table floated the LECA and segregated its upper section as illustrated in Fig. 2(b). After leaving the concrete mixes for 24 hours in the moulds, the samples were then removed and cured by immersing in water until testing at seven and 28 days. For all the 12 mix types, the fresh concrete slump value and hardened concrete density, UPV value and compressive strength were determined.



(a) LECA distributed evenly throughout the section.



(b) LECA floated and segregated to the top area of concrete section.

Fig. 2. The cross-section of LECA-EPA concrete.

Slump tests corresponding to the BS EN 12350-2:2009 were conducted during each mixing sessions to monitor the workability of the mixes [30]. The true slumps of the fresh concrete mixes were measured to the nearest 10mm and were expected to be in the range of 60 to 180 mm, as designed. All cubes were made in calibrated moulds conforming to the BS EN 12390-1:2012, and the densities of the cubes were calculated by procedures complying with the BS EN 12390-7:2000. The compression testing machines, conforming to the BS EN 12390-4, were used to load the hardened 100 mm cube specimens to failure at the rate of 0.6Mpa/s in accordance to the BS EN 12390-3:2009. The compressive strengths of the cubes were then calculated from the maximum load sustained readings [31]. The UPV test was conducted on each of the specimens before the compression test, by direct transmission method to assess the quality of the concrete produced. The time taken (Δt) by the pulse to travel from the transmitting transducer to the receiving transducer through the length of the specimen (L) was recorded to calculate the compressional wave pulse velocity (V). The concrete mixes were then categorised under the five categories of concrete qualities based on the UPV test [32].

3. Results and Discussions

The overall results were presented in Table 3, while the classification of concrete quality rating based on the UPV test is shown in Table 4.

Table 3. Slump, density, cube compressive strength, ultrasonic pulse velocity and concrete quality rating.

Concrete mix	Slump (mm)	Density (kg/m^3)			Cube compressive strength (N/mm^2)		Ultrasonic pulse velocity (km/s)			
		Before curing	7 days curing	28 days curing	7 days curing	28 days curing	7 days curing	Concrete quality rating	28 days curing	Concrete quality rating
NC+SF	100	2263	2315	2313	35.63	44.53	4.32	Good	4.29	Good
***L*30**	100	2159	2182	2208	27.24	39.13	4.05	Good	4.21	Good
***L*60**	110	2001	2028	2052	24.69	32.80	3.95	Good	3.99	Good
***L*80**	120	1962	1993	1997	23.04	31.54	3.87	Good	3.96	Good
***L*100**	150	1846	1860	1910	20.69	26.48	3.80	Good	3.84	Good
***L*60EPA5**	110	1991	2018	2038	25.81	29.07	3.90	Good	4.02	Good
***L*60EPA7.5**	120	1941	1973	2008	23.81	30.34	3.89	Good	4.07	Good
***L*60EPA10**	120	1939	1987	2005	23.06	27.70	3.86	Good	3.93	Good
***L*60EPA20**	140	1908	1947	1958	22.21	27.09	3.84	Good	3.88	Good
***L*60EPA25**	140	1858	1882	1915	21.78	25.75	3.79	Good	3.83	Good
***L*60EPA50**	170	1737	1788	1795	14.90	18.84	3.65	Good	3.60	Good
***L*60EPA75**	190	1676	1693	1735	14.41	17.70	3.39	Medium	3.58	Good

Table 4. Classification of concrete quality ratings based on UPV test BS 1881: Part 203 [32].

Pulse velocity (km/s)	Concrete quality (ratings)
⩾ 4.5	Excellent (E)
3.5 - 4.5	Good (G)
3.0 - 3.5	Medium (M)
2.0 - 3.0	Doubtful (D)
⩽ 2.0	Very weak (VW)

Workability and concrete quality

All mixes acquired slump values in the range of 100 mm to 190 mm as shown in Table 3. Since the LECA and EPA were pre-wetted before the mixing, the water absorbed and retained in the LWAs' particles may affect the consistencies of the concrete mixes. The slump test results of the mixes show that the higher the percentages of the LWAs in the concrete, the higher the slump values and the wetter the concrete would become. In general, the values of the slump observed show satisfactory concrete workability. According to BS 1881: Part 203, concrete quality ratings can be classified based on the pulse velocity value, as shown in Table 4. Figure 3 shows the qualities of the first phase concrete specimen where the UPV values declined with the increase of LECA content. The control mix of 0% LECA replacement shows the highest UPV reading of 4.32 km/s. Even though the UPV of the mixes continued to drop as the LECA replacement percentage increased, the ratings for concrete specimen still fall under the good quality concrete class. For the second phase specimen where EPA was introduced into the *L*60 mix, the UPV readings declined further with the increment of EPA content (Fig. 4). Despite the declining quality, the mixes still earn good quality ratings except for mix L60P75 at seven days. Apart from the concrete strength, the presence of voids in LECA and EPA also reduced the concrete density and hence increasing the travel path length of the ultrasonic pulse, which resulted in a lower UPV reading.

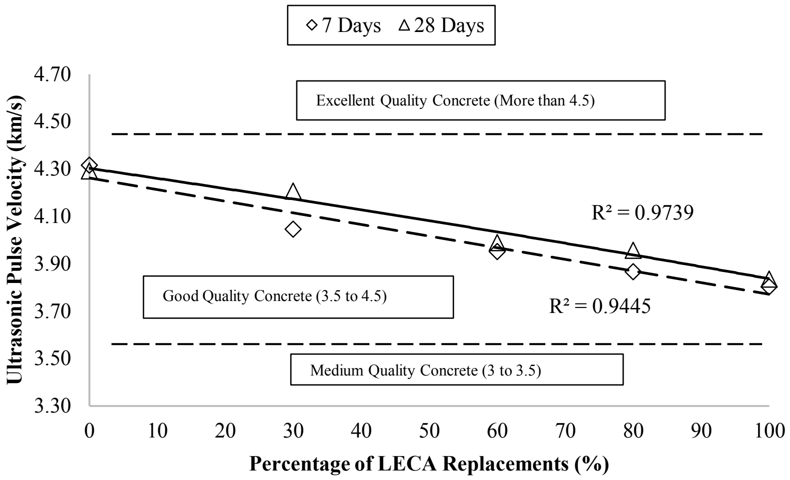


Fig. 3. Effect of LECA on the quality of concrete.

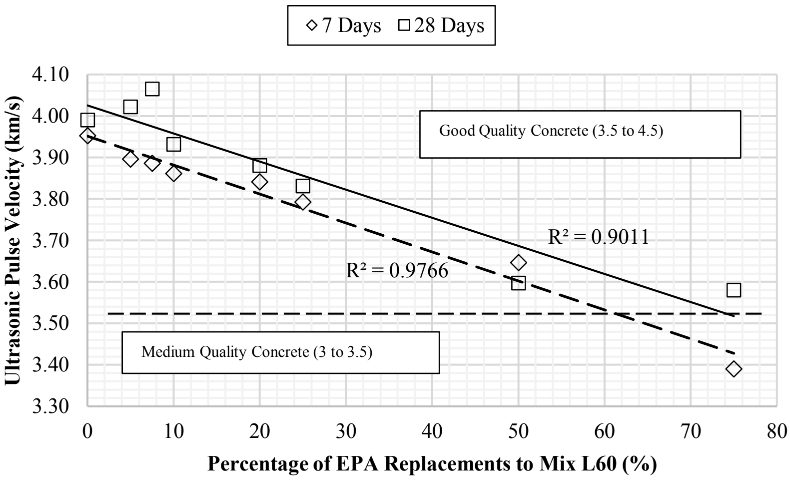


Fig. 4. Effect of varying EPA replacements and 60% LECA on the quality of concrete.

Density and compressive strength

Figure 5 shows the effect of LECA on the density of concrete. The BS EN 206: 2013+A1:2016 categorises the LWC into six different classes based on the density value. The LWC classification is shown in Table 5. The result reveals that there is a strong correlation ($R^2 = 0.99$) where the density of concrete decreased linearly with the increase of LECA content.

Mixes, where the LECA replacements were 30%, 60%, and 80% did not manage to lower the density of the concrete enough to enter the LWC category. Even though the densities of the *L*30, *L*60, and *L*80 were reduced, the values were still in the boundary of NWC region. The minimum density of the concrete was achieved at 100% LECA replacement, with 18% reduction before curing, 20% reduction after seven days water curing, and 17% reduction after 28 days water curing (Fig. 5). The *L*100 mix falls under the D2.0 LWC class. The rate of the density reduction was found to be quite low, most probably due to the low coarse aggregate proportion in the mix, which is only nearly half of the fine aggregate portion. However, the high proportion of fine aggregate and a low proportion of coarse aggregate was to be expected for a high strength mix design.

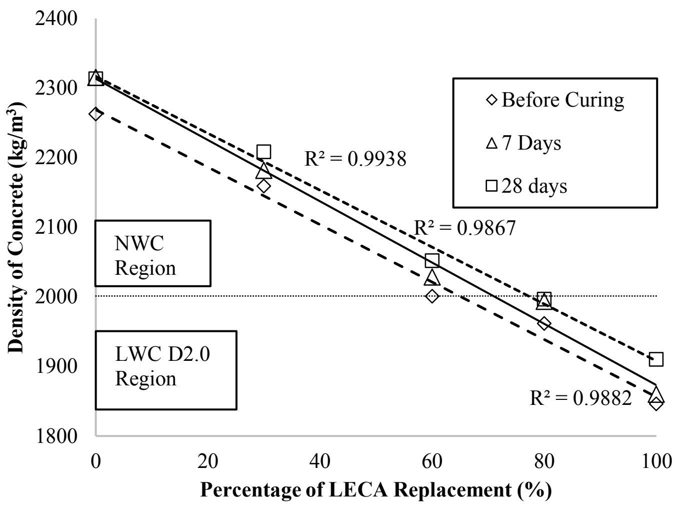


Fig. 5. Effect of LECA on the density of concrete.

Table 5. Density classes for lightweight concrete [3].

Density class	Range of density tested following the EN12390-7 (kg/m³)
***D*1.0**	⩾ 800 and ⩽ 1000
***D*1.2**	> 1000 and ⩽ 1200
***D*1.4**	> 1200 and ⩽ 1400
***D*1.6**	> 1400 and ⩽ 1600
***D*1.8**	> 1600 and ⩽ 1800
***D*2.0**	> 1800 and ⩽ 2000

The cube compressive strengths of the concrete mixes were assessed for curing periods of seven and 28 days. As displayed in Fig. 6, the strength of the mixes for seven days achieved an average of 75% of the 28 days compressive strength. The strong relationship (R^2 = 0.98) between compressive strength and percentage of LECA replacements shows that the rise of LECA content in the concrete mix reduced the compressive strength of the concrete. The correlation result was as expected.

The interconnected holes of different sizes inside the LECA particles made it more porous than the normal coarse aggregate. This means that by having more LECA percentage in the concrete, it will contain more porous material, and the concrete product itself as a whole will become more porous than normal concrete, resulting in the decrease of compressive strength while at the same time reducing the density. The result shows that for 100% LECA replacement of natural coarse aggregate, the compressive strength declined at the rate of 42% after seven days curing, and 41% after 28 days curing. Meanwhile, the seven-days compressive strengths of *L*30, *L*60, and *L*80 were decreased at the rate of 24%, 30%, and 35%. Similarly, for the 28-days compressive strengths, the rate of loss was 12%, 26%, and 29%.

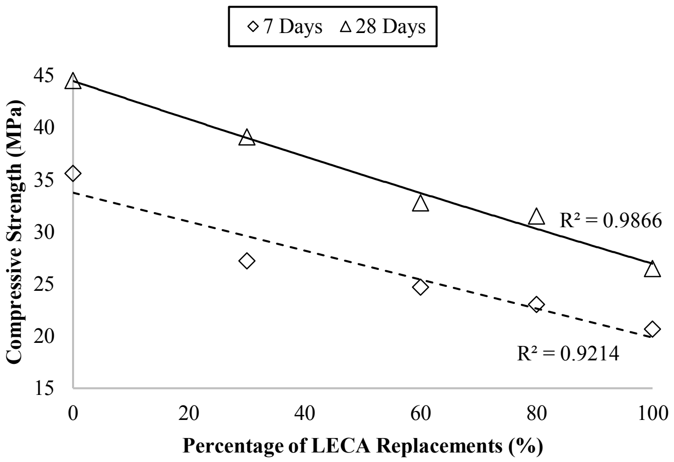


Fig. 6. Effect of LECA on the compressive strength of concrete.

The correlation between density and compressive strength of concrete by the effect of LECA was proven to be substantial and linear, as suggested by the regression values in Fig. 7. Among all the mixes, the control mix holds the maximum cube compressive strength of 44.53 MPa and the highest density value of 2315 kg/m^3. Conversely, mix *L*100 with seven days curing condition had the lowest cube compressive strength and lowest density values of 20.69 MPa and 1860 kg/m^3. In connection with the second phase of this study where EPA was introduced in the LECA mix to reduce the density of the concrete further, an optimum mix was chosen based on having approximately twice the strength of the minimum cube compressive strength required for lightweight reinforced precast concrete products while at the same time carried the lowest density value. In this case, the *L*60 mix was preferred as its 28-days cube compressive strength was 33 MPa. Even though the strength was a little below the required amount of 36 MPa, it can still be accepted considering its strength is very close to the target strength and furthermore, its density of 2052 kg/m^3 is at the borderline of LWC category, as illustrated in Fig. 7.

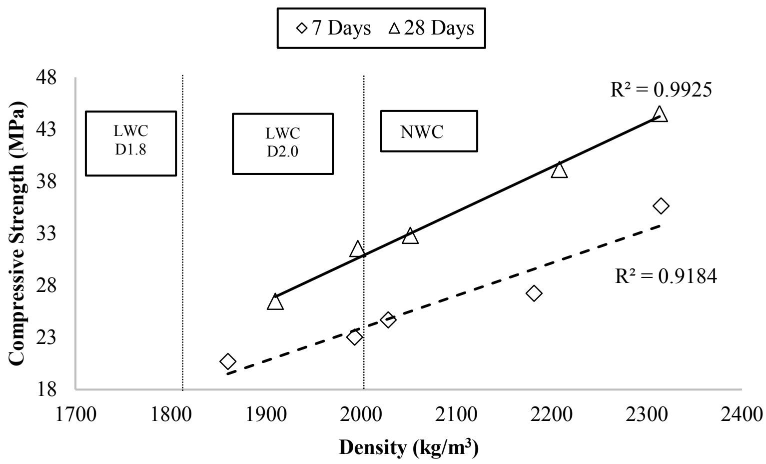


Fig. 7. Effect of LECA on the density and compressive strength of concrete.

In the second phase mixes, it was discovered that the behaviour of the density-EPA content relationship lines for the concrete mixes was slightly polynomial, as illustrated in Fig. 8. Three mixes (NC+SF, *L*30, and *L*60) fall under the NWC category, seven other mixes of *L*80, *L*100, *L*60EPA5, *L*60EPA7.5, *L*60EPA10, *L*60EPA20, and *L*60EPA25 are within the D2.0 LWC category, while the remaining *L*60EPA50 and *L*60EPA75 mixes managed to be in the range of D1.8 LWC category.

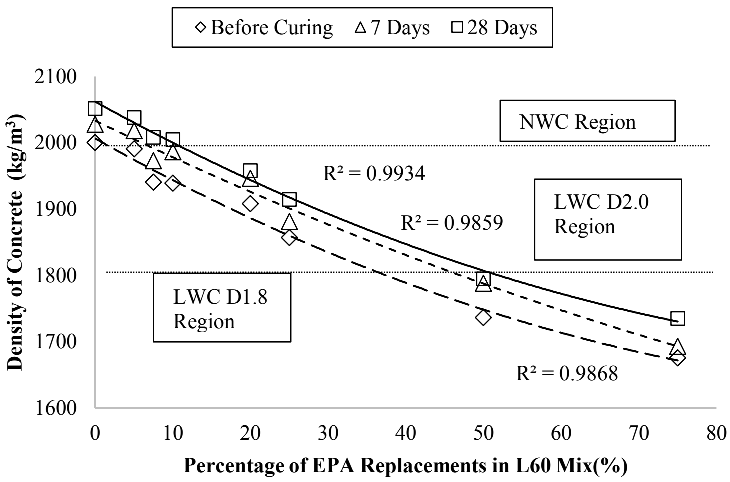


Fig. 8. Effect of varying EPA replacements and 60% LECA on the density of concrete.

Figure 9 shows the effect of varying EPA percentages replacing fine natural aggregates, and 60% of LECA replacing normal coarse aggregate. It was determined that the seven-days cube compressive strength of the EPA-LECA mixes achieved an average 83% of the 28-days cube compressive strength. This value was higher than that of the LECA mixes, which had an average of 75% for the same parameter. Therefore, in the context of the seven-days cube compressive strength, it was indicated that the EPA-LECA mixes had gained strength quicker than the LECA mixes. Considering the *L*60 mix as the control mix, the cube strength of L60 concrete mixes with EPA contents of 7.5%, 10%, 20%, 25%, 50%, and 75% was reduced by 4%, 7%, 10%, 12%, 40% and 42% respectively for seven days curing period, and 11%, 7%, 16%, 17%, 22%, 43%, and 46% for 28 days curing period. These outcomes pointed out that there were no significant drops of cube compressive strength for the mix with EPA replacements of 5% to 25% where the strength differences were only up to 12% for seven days curing period, and up to 22% for 28 days curing period. The decline in the strength, however, became quite high for EPA replacements of 50% and 75%, with the difference of 40% and 42% for seven days curing period, and 43% and 46% for 28 days curing period.

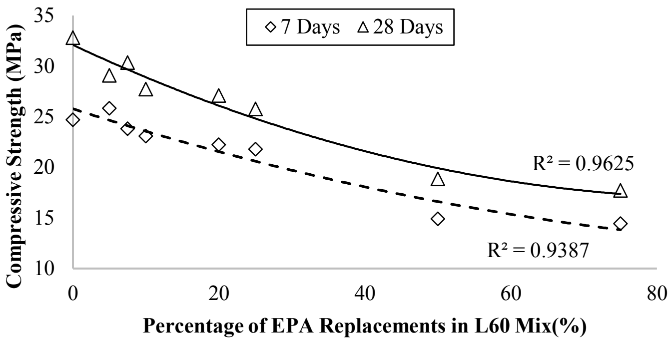


Fig. 9. Effect of varying EPA replacements and 60% LECA on the compressive strength of concrete.

Recapping the results from Figs. 5 and 6, the concrete mix produced with LECA replacement percentages of 30%, 60%, 80% and 100% resulted in compressive strength reductions of 12%, 26%, 29% and 41% and density reductions of 5%, 11%, 14% and 17%. Meanwhile, by considering mix NC+SF as the control mix and by referring to Figs. 8 and 9, the replacement of fine aggregate proportions of mix *L*60 with EPA percentages of 5%, 10%, 20%, 25%, 50% and 75% is found to achieve compressive strength reductions of 35%, 38%, 39%, 42% and 58%, and density reductions of 12%, 13%, 15%, 17%, 22% and 25%. This reduction shows that at 100% replacement, the concrete made of LECA can only achieve density reduction of 17%; meanwhile, concrete made of the combination of LECA and EPA managed to achieve maximum density reduction of 25%. The desired region for a structural LWC in a cube compressive strength - density relationships - are summarised in Fig. 10, where the target and aim would always be for the lowest density and highest strength (minimum strength of 18 MPa). In this respect, the optimum mix that fitted the criteria was the mix of L60EPA50 with the 28 days curing period, in which, it achieved a place under the LWC D1.8 category with a density of 1795 kg/m^3 while at the same time carried a cube compressive strength value of 18.84 MPa.

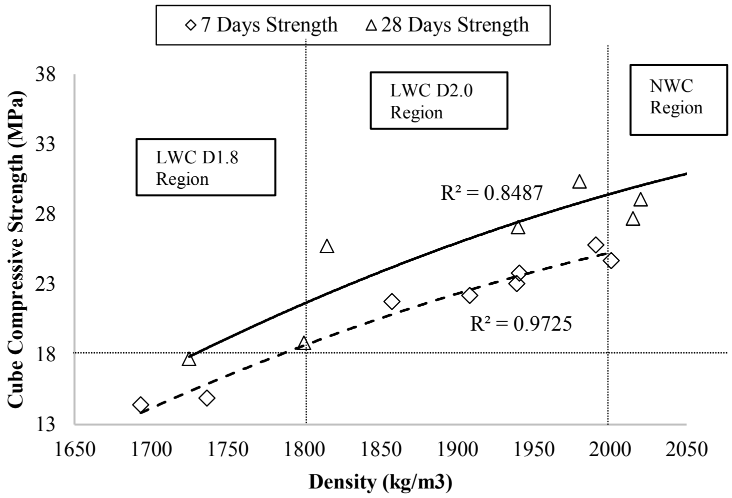


Fig. 10. Effect of varying EPA replacements and 60% LECA on the density and compressive strength of concrete.

4. Conclusions

This paper studied the effects of combining LECA and EPA as partial replacements in producing LWC. Based on the results, the following conclusions can be drawn:

- Increasing the percentages of pre-soaked LWAs as partial replacements of natural coarse aggregate and natural fine aggregate proportions in the mix causes an increase in the workability of the concrete.
- Escalating the partial substitution percentages of the LWAs to the proportions of natural aggregates in the concrete mix causes a longer travelling time for the ultrasonic pulse. In other words, increasing the contents of LECA and EPA in the concrete reduces the UPV value and hence, the concrete quality rating.
- In seven days, the LECA-EPA concrete had gained an average of 83% of its 28-days compressive strength, compared to an average of 75% for the LECA-only concrete, indicating that the LECA-EPA concrete achieved its intended strength faster than the LECA-only concrete.
- The concrete made by replacing 100% of coarse aggregate proportion with LECA can only achieve maximum density reduction of 17%. Meanwhile, concrete made from the combination of LECA and EPA managed to achieve maximum density reduction of 25%. However, in the scope of compressive strength reduction, the LECA-only concrete is considered to perform better by having a lower maximum compressive strength reduction of 41% compared to the LECA-EPA concrete's 58%. Consequently, the LECA-EPA concrete offers a lower density concrete than the LECA-only concrete, but at the cost of a slightly higher compressive strength reduction.
- The optimum mix that had achieved a balance of having the lowest density and passing the minimum strength requirement of BS EN 13369:2013 is the mix 60% LECA and 50% EPA replacement with a density of 1795kg/m^3, and cube compressive strength of 18.83 MPa.

Nomenclatures

ASTM	American Society for Testing and Materials
BS	British Standard
BS EN	British Standard European Norm
EPA	Expanded Perlite Aggregate
HWC	Heavy-Weight Concrete
LECA	Lightweight Expanded Clay Aggregate
LWA	Lightweight Aggregates
LWC	Lightweight Concrete
MS EN	Malaysian Standard European Norm
NWC	Normal-Weight Concrete
SF	Silica Fume
UPV	Ultrasonic Pulse Velocity

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References

1. Yardim, Y.; Waleed, A.M.T.; Jaafar, M.S.; and Laseima, S. (2013). AAC-concrete light weight precast composite floor slab. *Construction and Building Materials*, 40, 405-410.
2. Sajedi, F.; and Shafigh, P. (2012). High-strength lightweight concrete using leca, silica fume, and limestone. *Arabian Journal for Science and Engineering*, 37(7), 1885-1893.
3. British Standards Institution (BSI). (2013). Concrete - specification , performance, production and conformity. *European Standard, BS EN 206.*
4. Shetty, M.S. (2008). *Concrete technology: Theory and practice*. Ram Nagar, New Delhi, India: Vikas Publishing House.
5. Mahdy, M. (2016). Structural lightweight concrete using cured LECA. *International Journal of Engineering and Innovative Technology (IJEIT)*, 5(9), 25-31.
6. Demirbog, R. ; Orung, I.; and Gul, R. (2001). Effects of expanded perlite aggregate and mineral admixtures on the compressive strength of low-density concretes. *Cement and Concrete Research*, 31(11), 1627-1632.
7. British Standards Institution (BSI). (2016). *Lightweight aggregates*. *European Standard, BS EN 13055:2016*.
8. Rashad, A.M. (2018). Lightweight expanded clay aggregate as a building material - An overview. *Construction and Building Materials*, 170, 757-775.
9. Chandra, S.; and Berntsson, L. (2002). *Lightweight aggregate concrete : science, technology, and applications*. New York, USA.
10. Rashad, A.M. (2016). A synopsis about perlite as building material - A best practice guide for Civil Engineer. *Construction and Building Materials*, 121, 338-353.

11. Wang, L.; Liu, P.; Jing, Q.; Liu, Y.; Wang, W.; Zhang, Y.; and Li, Z. (2018). Strength properties and thermal conductivity of concrete with the addition of expanded perlite filled with aerogel. *Construction and Building Materials*, 188, 747-757.
12. Celik, A.G.; Kilic, A.M.; and Cakal, G.O. (2013). Expanded perlite aggregate characterization for use as a lightweight construction raw material. *Physicochemical Problems of Mineral Processing*, 49(2), 689-700.
13. Madadi, A.; Tasdighi, M.; and Eskandari-Naddaf, H. (2019). Structural response of ferrocement panels incorporating lightweight expanded clay and perlite aggregates: Experimental, theoretical and statistical analysis. *Engineering Structures*, 188, 382-393.
14. Sengul, O.; Azizi, S.; Karaosmanoglu, F.; and Tasdemir, M.A. (2011). Effect of expanded perlite on the mechanical properties and thermal conductivity of lightweight concrete. *Energy and Buildings*, 43(2-3), 671-676.
15. Oktay, H.; Yumrutaş, R.; and Akpolat, A. (2015). Mechanical and thermophysical properties of lightweight aggregate concretes. *Construction and Building Materials*, 96, 217-225.
16. Jedidi, M.; Benjeddou, O.; and Soussi, C. (2015). Effect of expanded perlite aggregate dosage on properties of lightweight concrete. *Jordan Journal of Civil Engineering*, 9(3), 278-291.
17. Anil Kumar, R.; and Prakash, P. (2015). Mechanical properties of structural light weight concrete by blending cinder & LECA. *International Advanced Research Journal in Science, Engineering and Technology*, 2(10), 64-67.
18. Nawel, S.; Mounir, L.; and Hedi, H. (2017). Characterisation of lightweight concrete of Tunisian expanded clay: mechanical and durability study. *European Journal of Environmental and Civil Engineering*, 21(6), 670-695.
19. Heiza, K.; Eid, F.; and Masoud, T. (2018). Lightweight self-compacting concrete with light expanded clay aggregate (LECA). *MATEC Web of Conference*, 162, 02031.
20. Nawy, E.G. (1997). *Concrete construction engineering handbook*. Boca Raton, Florida, United States of Americs: CRC Press.
21. Mortazavi, M.; and Majlessi, M. (2012). Evaluation of silica fume effect on compressive strength of structural lightweight concrete containing LECA as lightweight aggregate. *Advanced Materials Research*, 626, 344-349.
22. Perlite Institute, Inc. (2018). Perlite as an absorbent or carrier. Retrieved March 15, 2019, from https://www.perlite.org/wp-content/uploads/2018/03/perlite-absorbent-carrier.pdf.
23. Holland, T.C. (2005). Silica fume user's manual. *Report No. FHWA-IF-05-016*. Silica Fume Association, Federal Highway Administration, US Department of Transportation, Washington, D.C., United States of America.
24. Teychenne, D.C.; Franklin, R.E.; Erntroy, H.C.; Nicholls, J.C.; Hobbs, D.W.; and Marsh, D.W. (1997). *Design of normal concrete mixes (second edition)*. Building Research Establishment, Garston Watford, England.
25. British Standards Institution (BSI). (2018). *Common rules for precast concrete products*. *European Standard BS EN 13369:2018*.
26. Construction Research Institute of Malaysia (CREAM). (2016). *Specification for the design, manufacture & construction of precast concrete structures*. Kuala Lumpur, Malaysia: Construction Research Institute of Malaysia (CREAM).

27. British Standards Institution (BSI). (2013). Testing concrete. Methods for mixing and sampling fresh concrete in the laboratory. *European Standard, BS1881-125:2013.*
28. Bogas, J.A.; Gomes, M.G.; and Real, S. (2014). Bonding of steel reinforcement in structural expanded clay lightweight aggregate concrete: The influence of failure mechanism and concrete composition. *Construction and Building Materials*, 65, 350-359.
29. Wegian, F.M. (2012). Strength properties of lightweight concrete made with LECA grading. *Australian Journal of Civil Engineering*, 10(1), 11-22.
30. British Standards Institution (BSI). (2009). Testing fresh concrete. Slump-test. *European Standard, BS EN 12350-2:2009*.
31. British Standards Institution (BSI). (2009). Testing hardened concrete. Compressive strength of test specimens. *European Standard, BS EN 12390-3:2009.*
32. Hasbullah, M.A.; Yusof, R.; and Yusoff, M.N. (2017). Assessing the performance of concrete structure based on the width of the crack using UPV. *Journal of Engineering Science and Technology (JESTEC)*, Special Issue on ISSC'2016, 17-25.