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Compressive strength of lightweight foamed concrete with charcoal as a sand replacement

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Foamed concrete, a high performance concrete with lightweight properties and strength-enhancing additive have drawn the attention of researchers towards a sustainable life style. This paper presents a study of the compressive strength of various charcoal-filled lightweight foamed concrete (LFC), where waste materials, water-reducing agent and strength enhancement additives are introduced to the mix design in order to obtain further lightweight concrete. Five series of experimental tests were carried out, where Series 1 tested optimum ratio of silica fume and superplasticizer, Series 2 depicted the design mix of sand replacement with charcoal, Series 3 described the mix for additives, Series 4 illustrated effect of aggregate size for charcoal and different densities, as well as Series 5 was the conventional design mix ratio. The fresh and harden densities have been recorded while the shrinkage of LFC had also been observed during the casting and curing period. From the results, the mixture with silica fume replacing the cement was found to have a lower compressive strength as compared to mixtures with a full portion of cement. The strength reductions ranged between 62 to 80% for the mix with no superplasticizer and 29 to 82% for the mix with superplasticizer, which was obtained from the 20 to 50% of cement replacement with silica fume. Foamed concrete with superplasticizer achieved 66% of higher compressive strength. However, concrete expansion and spalling were discovered at the later concrete age of Series 5 which degraded the concrete strength. From this study, it was found that charcoal with low specific gravity is a suitable for full sand replacement in foamed concrete prior to the treatment that can lower its alkalinity.

Keywords: Compressive strength, Charcoal, Lightweight foamed concrete, Sand replacement, Silica fume, Superplasticizer

Cement production, transportation of constructional materials, concrete casting process, and energy consumption during construction are the sources of carbon footprint in construction industry. From an analysis by Hertwich *et al.*[1], construction industry in China and Vietnam contributed high carbon footprint, recorded with 35% and 20%, respectively in the year 2001. From the year 1970, economic dominance in Malaysia shifted from the agricultural sector to the industrial sector[2], which resulted in the growth of carbon footprint. In an effort to move towards sustainable construction, lightweight concrete provides an advantage of the carbon footprint reduction by reducing transportation frequency and replacing aggregate with solid waste to achieve low concrete density.

The reduction of concrete density allows an over 20% of weight saving. Thus, the reduction of permanent load by using lightweight concrete can reduce the size of columns, beams, girders, as well as, the foundation[3]. There are several types of lightweight concretes that are applied in the construction, e.g., lightweight aggregate concrete and cellular concrete. Foamed concrete, as one type of the cellular concretes, is light, made from environmentally-friendly materials, simple to use, able to be casted in large volume and able to achieve structural application[4], and has the possibility to improve current conventional concrete towards sustainable development.

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Research on lightweight foamed concrete (LFC) depicts a gradual growth from non-structural to structural application. Jones and McCarthy[4] studied the development of LFC utilising fly ash with the potential for use in structural applications. The physical and mechanical properties of LFC such as strength, porosity, permeability and heat of hydration have been investigated[5-7].

Nevertheless, the study of influence of filler type also has been carried out[8] and found that reduction of sand particle size can improve the strength of LFC. Furthermore, Lim, *et al*.[9-11] focused their research on the mechanical properties of lightweight foamed concrete with different sand grading[9,10], palm oil fuel ash as filler[11] and granulated blast-furnace slag as cement replacement[12]. Finer sand particles, palm oil fuel ash and blast-furnace slag can increase the strength of the LFC. LFC with pulverized fly ash (PFA) also has been investigated[13]. PFA can further lower the density of LFC, increase workability and drying shrinkage. The optimum cement replacement with PFA was between 20 to 30 % for higher short term compressive strength[13].

In Malaysia, industrial waste from the oil palm production line are usually re-processed and reused in construction; this reduces the generated wastes and increases environmental sustainability. Oil palm shells are used to replace the coarse aggregate as lightweight aggregate in normal weight concrete[14-16].

Moreover, sand replaced with other low values of specific gravity can become another alternative in further reducing the weight of LFC, for an example, charcoal. Charcoal can be obtained from the bio-waste and provides unique functional characteristics and properties, such as being lightweight[17] to the construction application. Hence, charcoal with low specific gravity can be used as a sand replacement for LFC.

In order to enhance strength and achieve further lightweight properties of LFC, this paper aims to discuss the performance and compressive strength of LFC by using additives and replacements through experimental tests in order to achieve ultra-lightweight properties. In this study, additives and low specific gravity materials from argo-industrial wastes have the potential to be applied into the LFC mix to enhance the strength and performance while reducing its harden density. Utilising low specific gravity materials from wastes in the research is also part of the efforts towards increasing sustainable construction by reducing the carbon footprint during the construction stage.

Experimental Procedure

Materials

Experimental works were carried out in order to investigate the compressive strength of various mixtures for LFC. The identified solid materials with low specific gravity are bagasse, charcoal, powdered carbon which contain a density between 80 to 200 kg/m^3. Charcoal can be obtained from agro-industrial solid wastes which may be suitably mixed into LFC to further reduce its concrete density. Therefore, charcoal is selected to be investigated prior to its availability from solid waste.

Various mixtures with a strength enhancement additive (e.g. silica fume), a water reducing agent (e.g. superplasticizer), and sand replacements with waste materials (e.g. oil palm shell and charcoal) have been introduced to foamed concrete in order to obtain further lightweight properties without sacrificing its compressive strength.

The materials that used in this study are:

Cement – Ordinary Portland Cement (OPC) was used to produce the LFC. The OPC used complies with Malaysian Standard MS 522[18] and BS EN 196-2[19].

Sand – The sand used was river sand and oven dried at 105°C for 24 h to mitigate the moisture content inside the sand. The dried sand was then sieved to 100% passing through the sieve size 0.60 mm.

Water – Used for the cement hydration process and provides workability of the cement paste. Normal tap water source from laboratory was used in this study.

Foam agent – It is a locally produced chemical to generate stable foam for the casting process. The ratio of synthetic foam agent to water is 1:30. The mixture is pressurised in a foam generator at a constant of 5 bars (equivalent to 0.5 MPa) to produce stable foams.

Silica fume (SF) – It is a product of Scancem Materials, also known as scanfume; it is a dry powder additive that enhances the strength and durability of concrete and mortars.

Superplasticizer (SP) – As a water reducing agent, superplasticizer has been applied in the industry to obtain an optimum amount of water in concrete while maintaining its workability. However, conventional superplasticizer could cause the foams bursting in lightweight foamed concrete. In this research, the applied superplasticizer was high grade polycarboxylic ether which is friendly with the generated foams.

Oil palm shell (OPS) – They were found in the oil palm plantation in Kulai, Johor, Malaysia. Oil palm shells are the by-product, or considered as agricultural solid waste, of the palm oil production.

Charcoal (Char) – It is a low density argo-industrial solid wastes that can be used for sand replacement in this study. Three types of charcoal were used, namely coarse charcoal (CChar), fine charcoal (FChar) and charcoal powder (PChar). CChar particles passed through a sieve size 3.26 mm and retained at 0.6 mm, whereas 100% of FChar particles passed through a 0.6 mm sieve size. The PChar was grinded for 24 h and 100% passed through 0.1 mm sieve.

PYE waterpruf (PYE) – It is an admixture added into the concrete mixture for the complete and permanent waterproofing, while also enhancing the strength of the concrete. PYE is a building chemical from a Malaysian company who claimed that the 10% reduction of water-cement ratio can be obtained without affecting the mixture's workability and achieves higher compressive strength concurrently.

Mix design

There were experimental studies on four different mix designs, Series 1 to Series 4, as shown in Table 1 with one conventional mix design, Series 5. Series 1 to 3 were the trial mix to determine the mix design for Series 4. Series 5 was the conventional mix for comparison with previous research.

Early strength of 3-day concrete age will be investigated for the trial mix of Series 1 to 3. Series 1 depicted the variables of silica fume and superplasticizer. Different percentages of cement replacements have been proposed at 20%, 30%, 40%, and 50%. The same silica fume cement replacements were carried out twice by adding superplasticizer into the foamed concrete. Series 2 showed the variables of sand replacement and PYE waterproof.

For Series 3, the variables are additives (SP and PYE) and aggregate replacements. Sand replacement was applied in equivalent volumes as the specific gravity of charcoal is much lower than sand. For 1000 cm^3 of volume, sand, charcoal and oil palm shell (OPS) exhibited a weight of 1.238 kg, 0.460 kg and 0.312 kg, respectively. Therefore, if 1.238 kg sand is needed in the mix, the replaced charcoal should be 0.460 kg in weight, as it is equivalent to the volume of 1.238 kg sand. The same concept is applied to OPS. As the specific gravity of charcoal and OPS are low, it is advised to use equivalent sand volume replacement to maximise the lightweight characteristic in the design mix.

Meanwhile, for Series 4, the charcoal powder was applied to the mix in order to determine the performance of the mix towards aggregate or charcoal size, from the physical condition of coarse to powder and different of densities where more foams were required for lower concrete density.

Furthermore, for Series 5, the conventional cement-sand ratio of 1:3 was applied to the mix with charcoal acting as sand replacement. The water-cement ratio was also controlled at 0.25. The additive, SP also has been applied to the mix.

Specimen preparation

Since the specification of cube size should be 4 times of nominal size of aggregate, cubic moulds with three sizes 50.0 × 50.0 × 50.0 mm; 70.7 × 70.7 × 70.7 mm; and 150 × 150 × 150 mm; were prepared to produce the strength test specimens throughout the series. The specimens of Series 1 to 4 were prepared in 70.7 mm size, which is normally for the mortar specimen. For Series 5, three sizes were prepared for characteristic strength at 28-day and other concrete age as the conventional cube test at site also involved bigger size of cube compressive test. These three sizes of cube compressive tests were used to understand the effect of stress area towards the compressive strength of LFC. The fresh foamed concrete was left to set for 24 h before de-moulding, and the cubes underwent a water curing process until its respective testing age.

Trial mixes were performed in Series 1 to 4. Series 1 consists of 30 specimens, Series 2 has 18 specimens, Series 3 and 4 had 24 specimens each. All demonstrated that values for densities and compressive strengths average out the three specimens of each mix. The condition of the mix was also been observed to minimise the possibility of preliminary bubbles bursting.

Meanwhile, the compressive strength of each specimen has been carried out according to BS EN 12390-3[20] with the loading rate of 0.1 kN/s with reference to BS4551[21]. Series 1, 2 and 3 were tested at the 3-day concrete age, whereas Series 4 was tested at 21-day concrete age due to a malfunction in the compression machine lasting a two week period from expected testing age of 7-day.

Table 1 — Mix design for Series 1, 2 and 3

No	Cementitious materials		Aggregate					W/C	*Additives, %		*Stable foam, %	Designed density, kg/m^3
	Cement	SF	Sand	OPS	CChar	FChar	PChar		PYE	SP		
1A	1	-	1	-	-	-	-	0.4	-	-	21.0	1000
1B	0.8	0.2	1	-	-	-	-	0.4	-	-	5.0	1000
1C	0.7	0.3	1	-	-	-	-	0.4	-	-	8.0	1000
1D	0.6	0.4	1	-	-	-	-	0.4	-	-	4.0	1000
1E	0.5	0.5	1	-	-	-	-	0.4	-	-	19.0	1000
1F	1	-	1	-	-	-	-	0.25	-	0.55	3.7	1000
1G	0.8	0.2	1	-	-	-	-	0.25	-	0.55	3.9	1000
1H	0.7	0.3	1	-	-	-	-	0.25	-	0.55	5.9	1000
1I	0.6	0.4	1	-	-	-	-	0.25	-	0.55	5.6	1000
1J	0.5	0.5	1	-	-	-	-	0.25	-	0.55	6.6	1000
2A	1	-	-	-	1	-	-	0.25	0.7	-	4.8	1000
2B	1	-	-	1	-	-	-	0.25	-	-	3.0	1000
2C	1	-	-	1	-	-	-	0.25	0.7	-	5.5	1000
2D	2	-	-	1	-	-	-	0.25	0.9	-	3.1	1000
2E	3	-	-	1	-	-	-	0.25	0.9	-	2.4	1000
2F	2	-	-	1	1	-	-	0.25	-	-	2.5	1000
3A	2	-	-	-	1	-	-	0.25	-	3.9	3.4	1000
3B	2	-	-	-	-	1	-	0.25	-	3.9	2.8	1000
3C	2	-	-	-	-	1	-	0.25	0.8	3.9	2.0	1000
3D	2	-	-	-	1	1	-	0.25	-	3.4	2.4	1000
3E	2	-	-	1	-	1	-	0.25	-	3.4	3.7	1000
3F	2	-	-	1	1	-	-	0.25	-	3.4	2.2	1000
3G	1	-	-	-	-	1	-	0.25	-	3.4	3.6	1000
3H	1	-	-	-	-	3	-	0.25	-	4.4	4.4	1000
4A	2	-	-	-	-	-	1	0.25	-	3.9	4.6	800
4B	2	-	-	-	-	-	1	0.25	-	3.9	3.1	900
4C	2	-	-	-	-	-	1	0.25	-	3.9	2.6	1000
4D	2	-	-	-	-	-	1	0.25	-	3.9	2.0	1100
4E	2	-	-	-	-	-	1	0.25	0.8	3.9	3.4	1000
4F	2	-	-	-	-	1	-	0.25	0.8	3.9	2.8	1000
4G	2	-	-	-	-	-	1	0.25	0.8	3.9	2.6	1000
4H	1	-	-	-	-	-	1	0.25	-	4.4	1.7	1000
5	1	-	-	-	-	-	3	0.25	-	0.5	8.5	1000

SF=Silica Fume
OPS=Oil palm shells
CChar = Sieved charcoal with 100% passing 3.26 mm and retained 0.60 mm sieve size
FChar= Sieved charcoal with 100% passing 0.60 mm sieve size
PChar= Sieved charcoal with 100% passing 0.10 mm sieve size
*Percentage of additives/foams was based on the total weight of solids.

For the conventional mix, Series 5, the mix is the conventional ratio of cement-sand, 1:3, and the performance of the compressive strength was recorded for further analysis. This mix will be used for the investigation of its mechanical properties, namely, compressive strength test, splitting tensile test and void test at testing age. The splitting tensile strength was determined in accordance to ASTM 496[22]. From these series tests, a better mix design can be achieved through the obtained experimental results. The compressive strength was determined at the concrete age of 7, 14, 20, 28, 34, and 68 days. The concrete age for testing was proposed and amended with equipment availability.

Results and Discussion

Casting observation

There were no significant changes in the casting process for Series 1 and Series 2. However, an interesting finding has been observed at Series 2, where a reaction occurred in the mortar when PYE and SP were added into the mixture. The reaction produced gases as bubbles could be found in the mixture before the foam was applied. This reaction reduced the stability of the foams in the mixture. In order to solve the problem, the mixture that contained PYE and SP was left for 15 min to stabilise the reaction, before applying the foam. This procedure was pursued for later casting for Series 2 and 3.

Test observation

Figure 1 shows the fresh state of casted concrete with SP and PYE. Bigger bubbles were found and continually released from the mortar in 5 min period. Therefore, it is suggested to stabilize it by 15 min mixing before adding preformed foams into it.

Furthermore, shrinkage of the casted lightweight foamed concrete was found during the casting process. Irregular particle size for cement, OPS and coarse charcoal may be one of the reasons for foam bursting, hence, affecting the stability of the fresh and hardened foamed concrete. It can be solved with finer particle size of aggregate where specimens with finer size using FChar and PChar were found free from shrinkage phenomena at harden concrete.

Figure 2 shows the typical failure of specimens after compressive test. In addition, Fig. 3 shows the matrix formed in harden LFC where voids can be easily identified.

Trial mix design (Series 1 to 3)

Table 2 shows the fresh state density, 1-day aged density, density at the age of compression test, consistency, and stability for trial mixes of Series 1 to 4 specimens. For Series 1, 2 and 3, the compressive strength of 3-day concrete was determined, while, specimens from Series 4 were tested at day 21.

All results are presented in the performance index where strength is represented in unit density that can be used to compare for various densities.. For series 1, the replacement percentage of silica fume increased, the compressive strength would decrease gradually, compared to 100% cement foamed concrete. This shows that the cementing component is the main contributor for the calcium-silicates-hydrate (C-S-H) gel. The extremely fine particles of silica fume are located in very close proximity of aggregate-cement particles. However, an excessive content of silica fume is inadequate for covering the entire aggregate-cement surface, providing no beneficiates from the marginal optimum replacement of silica fume. Also,

Fig. 1 — Bubbles found when SP and PYE were added to the mix

Fig. 2 — Typical fracture after compressive test

Fig. 3 — Voids formed in harden LFC

silica fume is contributing strength at 28-day and after where it is not beneficial to early strength[23], as this research was focusing. This, thus, reduces the cement content and affects the compressive strength of the foamed concrete.

In addition, foamed concrete with SP was recorded to have a higher compressive strength compared to specimens without SP. Since the base mix of the foamed concrete must remain fluid, SP is one of the alternatives to reducing the water-cement ratio

Table 2 — Densities, consistency and stability for Series 1, 2and 3

Specimen	Density, kg/m^3			Consistency	Stability		Strength, MPa	Performance Index, MPa
	Wet	1-day	Testing age*		1-day	Testing age*		
1A	1090	1091	1125	1.09	1.00	0.97	2.43	2.16
1B	770	804	863	0.77	0.96	0.89	0.37	0.43
1C	955	966	997	0.96	0.99	0.96	0.78	0.78
1D	920	959	983	0.92	0.96	0.94	0.91	0.93
1E	895	971	990	0.90	0.92	0.90	0.80	0.81
1F	1120	1133	1224	1.12	0.99	0.92	4.40	3.59
1G	1075	1087	1231	1.08	0.99	0.87	3.13	2.54
1H	1025	1022	1146	1.03	1.00	0.89	1.79	1.56
1I	815	815	863	0.82	1.00	0.94	0.63	0.73
1J	1000	945	1026	1.00	1.06	0.97	0.66	0.64
2A	785	847	929	0.79	0.93	0.84	0.56	0.60
2B	1200	1354	1394	1.20	0.89	0.86	5.19	3.72
2C	885	979	1033	0.89	0.90	0.86	1.26	1.22
2D	1205	1231	1292	1.21	0.98	0.93	3.60	2.79
2E	1380	1445	1489	1.38	0.96	0.93	6.73	4.52
2F	1195	1358	1387	1.20	0.88	0.86	7.08	5.10
3A	775	967	1080	0.78	0.80	0.72	4.63	4.29
3B	950	1321	1382	0.95	0.72	0.69	11.37	8.23
3C	1165	1575	1641	1.17	0.74	0.71	18.77	11.44
3D	1010	1283	1382	1.01	0.79	0.73	7.90	5.72
3E	1360	1679	1717	1.36	0.81	0.79	19.19	11.18
3F	1150	1547	1599	1.15	0.74	0.72	15.08	9.43
3G	965	1316	1401	0.97	0.73	0.69	8.90	6.35
3H	900	1165	1264	0.90	0.77	0.71	3.66	2.90
4A	825	1168	1168	1.03	0.71	0.71	3.83	3.28
4B	935	1364	1297	1.04	0.69	0.72	6.83	5.27
4C	1010	1345	1297	1.01	0.75	0.78	7.57	5.84
4D	1120	1548	1509	1.02	0.72	0.74	15.35	10.17
4E	855	1410	1377	0.86	0.61	0.62	9.31	6.76
4F	970	1425	1405	0.97	0.68	0.69	9.43	6.71
4G	1055	1415	1368	1.06	0.75	0.77	14.31	10.46
4H	945	1282	1207	0.94	0.74	0.78	9.25	7.66

consistency = proportion of measured fresh density to designed density (1000 kg/m^3)
stability = proportion of measured fresh density to measured hardened density (1-day or 3-day aged)
* 3-day for Series 1, 2 and 3 and 21-day for Series 4

without affecting its workability. Silica fume is not a suitable cement replacement for obtaining early strength. From Fig. 4, it was found that the performance index of LFC with SP kept dropping until it reached below 40%. The drop in performance index was marginally constant, and the strength behaviour was identical to specimens without SP. It is recommended to use silica fume as an additive rather than as cement replacement. From previous studies, silica fume contributed to later strength of foamed concrete and should be added to the mixture design[16,23].

For series 2 and 3, there were various performance indices for the mixture with OPS and Char, as shown in Table 2. All specimens were below the density of

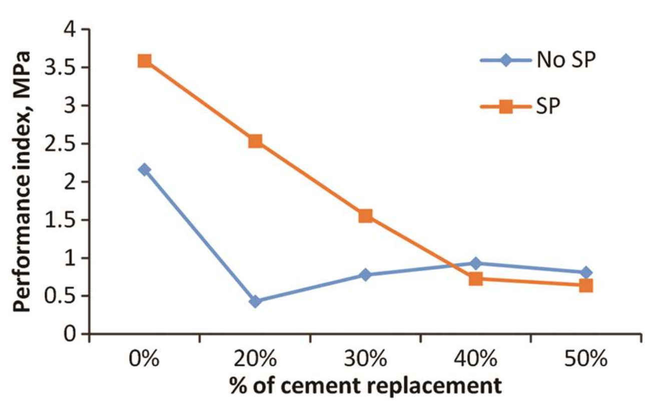

Fig. 4 — Performance index with different percentages of silica fume as cement replacement

1800 kg/m^3, which was considered lightweight compared to normal weight concrete with a density of 2000 to 2600 kg/m^3. Series 3 showed the lowest consistency and stability where was caused by coarse aggregates to burst the foams and thus increased the concrete density.

From the observation in Table 3 and Fig. 5, it can be seen that the specimens with a density range of over 1500 kg/m^3 demonstrate the highest performance index. Mixtures with higher cement content also exhibited higher strength. 3C, with the mixture combination of cement, fine charcoal, superplasticizer, and waterproof PYE achieved the highest performance index, which is 11.44 MPa. This is followed by the specimens 3E and 3F, which were about 2.27% and 17.6% respectively, lower than the performance index of 3C. All three specimens of 3C, 3E and 3F fall in the same density range. Throughout these values, mixture 3B was found suitable to be applied in structures with lightweight properties, as the density is about 15.8% lighter than 3C. The mixture was 2:1 cement-sand ratio, where sand was replaced by grinded charcoal with the equivalent volume of sand and added with SP and PYE, and it was applied to mix design of Series 4.

Table 3 — Performance index with the density ranges at the 3-day concrete age

Density range, kg/m^3	Specimen	Performance index, MPa
<1000	2A	0.60
1000-1099	2C	1.22
	3A	4.29
1200-1299	2D	2.79
	3H	2.90
1300-1399	2B	3.72
	2F	5.10
	3B	8.23
	3D	5.72
1400-1499	2E	4.52
	3G	6.35
>1500	3C	11.44
	3E	11.18
	3F	9.43

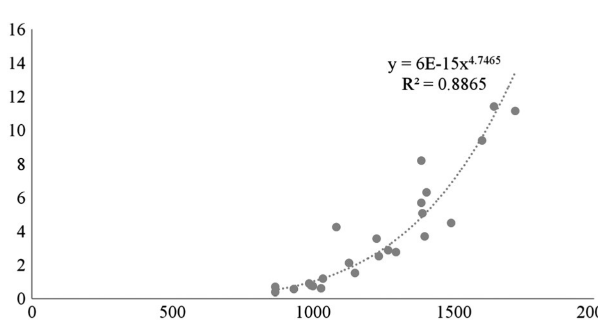

Fig. 5 — Correlation between performance index and concrete densities for Series 1, 2 and 3

Mix design of Series 4

The irregular aggregate size of Series 3 lead to low consistency and stability. Therefore, for Series 4, effects of aggregate size of charcoal and different concrete densities have been studied. The cement-sand ratio of 2:1 from trial mix investigation for Series 1 to 3 was applied. From previous research[9,10], sand grading of passing through 0.6 mm was greater than 2.36 mm in compressive strength. In this research, charcoal size that passing through 0.6 mm sieve was used and further fineness size of passing through 0.1 mm. With SP and PYE, particle size of passing through 0.1 mm sieve was found obtaining higher compressive strength by specimen 4G, compared to 4F with particle size passing through 0.6 mm.

Conventional mix design of Series 5

It is necessary to carry out a series of test with the conventional cement-sand ratio of 1:3. In Series 5, cement-sand ratio of 1:3 was used and the volume of sand had been fully replaced by the equivalent volume of charcoal powder. The targeted density was 900 kg/m^3.

Density

Table 4 shows the densities of the casted LFC with charcoal as sand replacement. From its fresh state until the 68-day, the density of the specimens increased, in a steady trend, by about 42%.

Compressive and splitting tensile tests

According to Table 5, as the concrete age increased, the compressive strength decreased, while the density increased. For Series 5, the highest compressive strength had been achieved at day 7. Cracks were observed before the compressive test. These cracks became significant as the concrete age increased, even in curing period. These cracks may contribute to lower strengths at later concrete age.

The reduction of strength occurred as the cube size increased; this is recognised as the reduction phenomenon, which is caused by the fracture mechanics-based derivation of size effect law[24]. Majeed[25] also performed the compressive strength test for different cube sizes and found that strength reduces as cube size increased.

Same with the compressive tests, the results obtained from the splitting tensile tests also exhibited

Table 4 — Density of the mix design of Series 5

Specimen	Size, mm	Density, kg/m^3							
		Wet	1-day	7-day	14-day	20-day	28-day	34-day*	68-day
Cube	50.0	945	1029	1080	1147	1132	1187	940	1345
	70.7	945	1045	1061	1099	-	1165	-	-
	150.0	945	993	1076	-	-	1104	-	1245
Cylinder	60	945	1067	-	-	-	1226	-	-
	100	945	1016	-	-	-	1171	-	-

Table 5 — Compressive strength of the mix design of Series 5

Specimen	Size, mm	Compressive strength, MPa					
		7-day	14-day	20-day	28-day	34-day*	68-day
Cube	50.0	5.0	4.49	4.19	3.82	2.75	2.66
	70.7	4.53	4.41	-	3.68	-	-
	150.0	3.91	-	-	2.59	-	2.75
Cylinder	60	-	-	-	3.39	-	-
	100	-	-	-	1.97	-	-

Table 6 — Results of the splitting tensile test of Series 5

Cylinder Diameter, mm	Density, kg/m^3			Split-tensile strength, MPa		
	7-day	14-day	28-day	7-day	14-day	28-day
60	1092	1149	1226	0.84	0.63	0.53
100	-	-	1139	-	-	0.35

reduction with increasing density and concrete age as shown in Table 6. Cracks were also found at the cylinder specimens before testing. Generally, the compressive strength and splitting tensile strength shared the same trend with increasing concrete age.

Void test

From Table 7, the recorded results from void tests indicated the average void percentage was 30.97%. There were 8 specimens for the void tests and the range was between 28.57 to 32.14%. Generally, with the charcoal fully replacing sand, approximately 30% of the void can be achieved for the 900 kg/m^3 as the targeted density.

The obtained results from Series 1 to 5 gave the mix performance with LFC. Corresponding to the designed densities, the consistency of the specimens of all series ranged from 0.77 to 1.38; whereas, the stability at testing age ranged from 0.62 to 0.97. The consistency and stability should achieve unity for a stable mix[26].

From previous research[27], charcoal was added as part of the Portland pozzolanic cement in the mix. The results indicated that the increment in charcoal content increased strength and thermal resistivity. The percentages of the charcoal additive ranged from 2.5 to 10%. The small amount of charcoal was introduced to control the alkalinity of the mix. In current research, charcoal acting as sand replacement increases the alkalinity of the mix and alkali-carbonate reaction[28] takes place. This reaction can cause concrete expansion (can be proved with increased of concrete density from Table 4), leading to spalling and loss of the concrete strength. It is essential to treat the aggregates. There are some proposed methods to prevent the alkali-carbonate reaction[29,30], namely, selective quarrying by identifying the rock groupings and stratification; blended aggregate with limit portion of reactive aggregate according to code or standard; applying the smallest practical nominal maximum size of aggregate to minimise detrimental expansion; application of low-alkali cement; use of pozzolans; and use of inhibiting compounds (lithium compounds).

For strength enhancement additives, PYE and silica fume were investigated. PYE reacted actively in the mix which may burst the bubbles, but also increased the density. If PYE should be applied, stable foams should add into the mix after the active reaction ends and the mix becomes stable. Silica fume was found to develop later strength[23], which may not be suitable for early strength development. The spalling and concrete expansion will initiate the cracks which will degrade the concrete strength and silica fume will not contribute much in this context. However, SP was found to increase the strength significantly by reducing the water-cement ratio.

Table 7 — Results of the void test

Specimen	Weight in water, W_s	Weight at atmosphere, W_u	Weight after oven, W_k	Compressive strength, MPa	Void percentage, %
V1	0.020	0.160	0.115	2.65	32.14
V2	0.020	0.160	0.115	2.86	32.14
V3	0.020	0.165	0.120	2.75	31.03
V4	0.020	0.160	0.120	2.43	28.57
V5	0.020	0.165	0.120	2.45	31.03
V6	0.020	0.160	0.115	2.85	32.14
V7	0.020	0.165	0.120	2.60	31.03
V8	0.020	0.155	0.115	2.79	29.63
Average	0.020	0.161	0.118	2.67	30.97

*Weight in kg

Table 8 — Comparison with previous LFC research

Reference	Investigation variable(s)		Density, kg/m^3		Strength, MPa	Performance index, MPa
			Fresh	Hardened		
Current study	Different charcoal proportion and particle size	Series 3*	775 - 1360	1080 – 1641	3.66 - 19.19	2.90 – 11.44
		Series 4**	825 – 1120	1168 – 1509	3.83 – 15.35	3.28 – 10.46
		Series 5***	945	1061 - 1080	3.91 – 5.00	3.63 – 4.63
Lim, *et al.*[9]	Sand grading with different water-cement ratio, 7-day strength	P1.18	-	1881 - 1928	24.2 – 42.0	8.80 – 12.76
		P0.90	-	1904 - 1931	17.0 – 21.7	8.80 – 11.27
		P0.60	-	1905 - 1931	17.0 – 22.6	8.80 – 11.86
Lim, *et al.*[10]	Sand grading with different water-cement ratio, 14-day strength	P2.36	1261 - 1352	1259 - 1350	2.98 – 4.06	2.30 – 3.01
		P1.18	1261 - 1352	1259 - 1349	2.97 – 3.98	2.31 – 2.95
		P0.90	1287 - 1399	1290 - 1345	3.19 – 4.39	2.47 – 3.36
		P0.60	1326 - 1352	1308 - 1352	4.27 – 4.52	3.19 – 3.43
Lim, *et al.*[11]	POFA as sand replacement, 28-day strength	No POFA	1248 – 1339	1200 – 1300	5.01 – 5.42	4.11 – 4.36
		10% POFA	1326 – 1365	1287 – 1338	4.39 – 6.72	3.28 – 5.22
		20% POFA	1326 – 1365	1288 – 1300	5.05 – 6.31	3.92 – 4.85
Zhao *et al.*[12]	Granulated blast-furnace slag as cement replacement, 28-day strength	100% cement	-	1167 – 1282	4.0 – 6.4	3.42 – 4.99
		50% cement, 50% slag	-	1192 – 1298	4.2 – 6.6	3.52 – 5.08
Koh *et al.*[13]	Pulverized fly ash (PFA) as cement replacement	0 to 60 % PFA	-	1300 – 1650	3.0 – 15.9	2.30 – 10.60

*at 3-day concrete age
**at 21-day concrete age
***at 7-day concrete age

In the terms of aggregate replacement, OPS and charcoal were introduced to the LFC. It was discovered that OPS did not contribute much to the strength as the particle size of OPS is bigger. Smaller particle sizes are advantageous in LFC[9]. Charcoal, with low specific gravity value, has the potential to be applied in the LFC mix to further reduce the weight of the casted concrete. The obtained results showed the performance index was achieved at the highest of 11.44 at day 3. The alkali-carbonate reaction of the mix with charcoal should be treated to minimise the possibility of strength reduction at later concrete age. The alkalinity of charcoal should be reduced if it is applied as sand replacement, whereas, the quantity should be controlled as pozzolans.

In term of its application, this LFC can be used in pontoon platform or walkway design. A preliminary test on a 0.5 × 0.5 × 0.1 m concrete pontoon is shown in Fig. 6. It was found that the pontoon can sustain a 12 kg weight before all concrete submerged into water with the mix design from Series 4 with 50% concrete filled pontoon. Structural LFC of 17 MPa[31] can be achieved with 1800 kg/m^3 from Fig. 5.

Comparison with previous LFC

Several LFC researches have been carried out for cementitious or aggregate replacement in order to maximise the compressive strength for structural usage in the construction industry. A comparison will also be performed to discuss the characteristic strength of the current mix of LFC. Table 8 shows

Fig. 6 — Research application of concrete pontoon

the comparison with previous LFC research. Form current research, it was found that the charcoal has the potential to be introduced in the LFC mix. This can improve the strength, without increasing the density of the hardened concrete while maintaining a conventional mix of cement-sand ratio of 1:3. Similar results were found in study conducted by Zhao *et al*.[12]

Conclusions

In an effort to reduce the carbon footprint from the construction industry, lightweight foamed concrete can be used as an alternatives, moving towards sustainable construction by lessening the frequency of transportation and heavy machineries usage. In this study, compressive strength was recorded for lightweight foamed concrete with various mixtures. Several conclusions can be drawn from this investigation;

(i) Silica fume can be used as an additive to enhance the strength of the foamed concrete rather than act as a cement replacement to develop early strength. Foamed concrete with superplasticizer achieved 66% of higher compressive strength.

(ii) Charcoal with low specific gravity value has the potential to be applied into LFC mix to enhance the strength and performance without increasing the density. Full sand replacement was suggested in this research. Cement-charcoal ratio of 2:1 was found relatively high in early compressive strength. Moreover, finer particle size of charcoal improved the compressive strength.

(iii) Alkaline-carbonate reactions should be considered to avoid concrete expansion and spalling which lead to concrete degradation which may occur in the mixture of full sand replacement with charcoal.

For further development of LFC research, charcoal can be treated by lowering the pH of the mix to avoid an alkaline-carbonate reaction, in order to obtain a better consistency of lightweight concrete without degrading the strength. These methods ensure the efficiency of the charcoal as the sand replacement for LFC. With this effort, LFC with treated charcoal as sand replacement can be widely used for a sustainable construction industry.

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