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MECHANICAL PROPERTIES AND FRACTURE PREDICTION OF CONCRETES CONTAINING OIL PALM SHELL AND EXPANDED CLAY FOR FULL REPLACEMENT OF CONVENTIONAL AGGREGATES

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Graphical abstract

Abstract

In order to reduce the continual depletion and exploitation of natural resources, this paper examines the mechanical properties and fracture prediction of sustainable lightweight aggregates concretes comprising agro-industrial waste or/and artificial aggregate, considering a full replacement of conventional coarse aggregate. The fresh and hardened properties are examined, from which three out of the five design mixes can achieve structural concrete specifications. It is observed that compression, tensile, and flexural strengths of the mixes exhibit a similar behaviour trend, as relatively higher values can be obtained from homogenous coarse aggregates compared to heterogeneous aggregates for different proportions of oil palm shell (OPS) and expanded clay replacement. The experimental results show compression strength of 13 to 32 MPa, splitting tensile strength of 1.32 to 2.97 MPa and flexural strength of 1.67 to 5.24 MPa for the investigated mixes at concrete age of 28-day. Most of the mixes are able to achieve structural use. Amongst the mixes, those containing expanded clay lower the corresponding sorptivity values. Although statistics prove that the prediction models of tensile and flexural strengths can represent existing experimental findings, further investigations are recommended for a better properties forecasting of lightweight aggregate concrete containing OPS and expanded clay.

Keywords: Lightweight aggregate concrete, expanded clay, oil palm shell, hardened property, fresh property, reinforced concrete design

Abstrak

Untuk mengurangkan penipisan dan eksploitasi sumber semula jadi secara berterusan, kajian ini bertujuan untuk memeriksa sifat mekanik dan ramalan kepatahan konkrit agregat ringan yang terdiri daripada sisa pertanian industri atau/dan agregat buatan, dengan

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mempertimbangkan penggantian penuh agregat kasar konvensional. Sifat konkrit segar dan keras telah diperiksa, di mana tiga dari lima bancuhan dapat mencapai spesifikasi struktur konkrit. Kajian juga memerhati yang kekuatan mampatan, tegangan, dan lenturan daripada bancuhan menunjukkan tren tingkah laku yang serupa, iaitu ditunjuk oleh peningkatan nilai yang diperolehi dari agregat kasar homogen berbanding dengan agregat heterogen yang berlainan nisbah penggantian bagi tempurung kelapa sawit (OPS) dan tanah liat diperkembangkan. Keputusan eskperimen menunjukkan bancuhan mempunyai daya mampatan dari 13 – 32 MPa, daya tegangan dari 1.32 – 2.97 MPa dan daya lenturan dari 1.67 to 5.24 MPa untuk 28 hari pengawetan konkrit. Kebanyakan bancuhan mampu mencapai kegunaan struktur. Selain itu, bancuhan yang mengandungi tanah liat diperkembangkan telah menurunkan nilai daya serapan. Walaupun statistik telah dibuktikan bahawa model ramalan kekuatan tegangan dan lenturan dapat mewakili hasil eksperimen yang ada, penyelidikan lanjut masih dicadangkan untuk mendapatkan ramalan sifat yang lebih baik bagi konkrit agregat ringan yang mengandungi OPS dan tanah liat diperkembangkan.

Kata kunci: Konkrit agregat ringan, tanah liat diperkembangkan, tempurung kelapa sawit, sifat keras, sifat segar, reka bentuk konkrit bertetulang

1.0 INTRODUCTION

Energy efficiency and resource conservation are two globally-relevant contemporary issues achievable via low energy consumption, a concern of which is highly applicable also to the construction industry [1]. The largest revolutions in construction energy proficiency occur mostly within buildings, specifically, in the innovated employment of materials. Lightweight concretes, which provide economic, technical, as well as environmentally-enhancing benefits [2–9], have recently reigned as the alternative materials in construction to reduce the colossal utilization of natural resources. In this regard, the minimisation of environmental impact and reduction of construction cost can be realised through the applications of lightweight concretes [10]. In the implementation, gravels or coarse aggregates with a high specific gravity in the concrete matrix may be replaced with bio-solid wastes or artificial aggregates as alternatives in achieving sustainability in building construction.

It is evident from existing research that lightweight concretes can fulfill structural requirements [11,12]. Therefore, they can be adopted as load-bearing members for the framing system of buildings. According to ASTM C330 [13], the minimum strength requirements for structural lightweight concrete are 17 MPa and 2 MPa, respectively, for compressive and tensile strength. In the past few years, numerous aggregate types have been explored and employed in concretes. Concrete comprising artificial aggregates of expanded clay exhibited 24.75 MPa and 3.06 MPa compressive and tensile strengths, respectively, with the fresh and dry densities of 1541 and 1526 kg/m3 [1]. Apart from aggregate replacement with expanded clay, the inclusion of steel fibres in concrete had shown a compressive strength of 25.6 MPa at the density of 1720 kg/m3 [14]. The incorporation of 15% fly ash and 40% expanded clay was determined as the optimal mix by Sonia et.al. [15], resulting in 28.56 MPa and 2.53 MPa compressive and tensile strengths, respectively. Replacement of coarse aggregate with biosolid waste, oil palm shell (OPS), was measured to demonstrate 45.1 MPa [16] and 35.7 MPa [17] compressive strengths at 28 days. The room temperature water curing was found as producing the highest compressive strength as compared to other curing conditions for OPS lightweight concrete [18]. Through OPS, the lightweight concrete beam displayed a higher toughness in the perspective of shock absorption [19]. Due to these excellent structural performances, numerous applications of OPS lightweight concrete, such as in footbridges and low-cost houses [19], are thus feasible.

Having highlighted the aforementioned attributes, it can be well recognised that the replacement of aggregates with either solely expanded clay or OPC can satisfy the structural concrete requirements. Therefore, it is asserted that the combination of artificial aggregate and agricultural waste may be structurally beneficial in replacing the conventional coarse aggregate in producing sustainable lightweight concretes. Since the database for the mechanical performance of such a concrete mix is currently absent from the literature, this paper aims to investigate the fresh and hardened properties of lightweight concretes with a full replacement of conventional coarse aggregate by expanded clay and OPS. The study package includes the fresh state properties of workability and density, with the hardened state properties of compressive, splitting tensile, and flexural strengths, as well as durability, all of which are determined at concrete ages of 7, 14, 21, and 28 days.

2.0 MATERIAL PROPERTIES

2.1 Raw Materials

Ordinary Portland cement (OPC) in compliance with Malaysian Standard MS EN 197-1 [20] and ASTM C150 [21] had been used in this investigation. In terms of the aggregates, the expanded clay was obtained from a local market with sizes of 10-25 mm and an average density of 451 kg/m^3. The properties of OPS can be found in [22], while its density was measured as 423 kg/m^3. Tables 1 and 2 show the physical and chemical properties of OPS and expanded clay. The particle sizes of OPS and expanded clay were determined with the sieve analysis and compared to the conventional aggregate grading, the outcome of which is displayed in Figure 1. Additionally, the adopted superplasticizer was MasterGlenium ACE 8589 polycarboxylic ether (PCE).

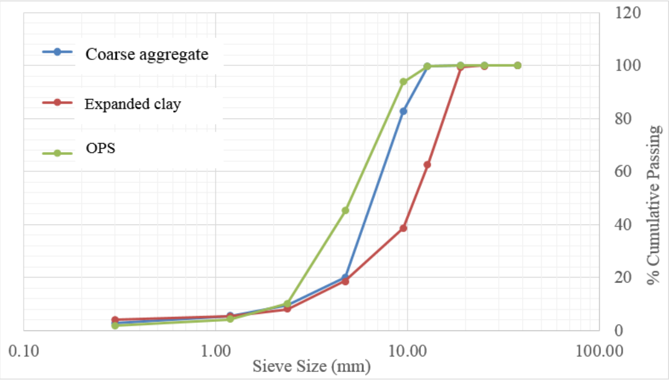

Figure 1 Sieve analysis of OPS, expanded clay, and conventional aggregates

Table 1 Physical properties of concrete aggregates

Properties	**Natural coarse aggregate** [23]	**River sand**	**OPS** [11]	**Expanded clay** [24]
Water absorption, %	0.68			
Specific gravity	2.86	2.45	1.17	
Maximum grain size (mm)		1.18	12.5	
Shell thickness (mm)			0.5 - 3.0	
Bulk unit weight (kg/m^3)		1500-1550	500-600	800-1480
Fineness modulus		1.40	6.08	
Los Angeles abrasion value (%)		-	4.90	
Aggregate impact value (%)		-	7.51	
Aggregate crushing value (%)		-	8.00	8.34 MPa
24-h water absorption (%)		3.89	33.0	2.65 (1 hour)

Table 2 Chemical properties of the concrete aggregates

Elements	**OPS, %** [11]	**Expanded clay, %** [25]
Ash	1.53	-
Nitrogen, N	0.41	-
Sulphur, S	0.000783	-
Calcium, CaO	0.0765	0.2
Magnesium, MgO	0.0352	0.4
Sodium, Na_2O	0.00156	0.3
Potassium. K_2O	0.00042	2.3
Aluminium, Al_2O_3	0.130	27.0
Iron, Fe_2O_3	0.0333	1.0
Silica, SiO_2	0.0146	58.0
Chloride, Cl^-	0.00072	-
Loss on ignition	98.5	-

Previous research showed the OPS [11] and expanded clay [1] were able to achieve structural use, as coarse aggregate replacement. However, there might be a gap to fully replace conventional natural aggregate.

2.2 Mix Design

A reference was made to a previous design mix from [1] by extending the mix design by the approach of replacement by volume to the current study. Five design mixes and one conventional concrete were examined. The design mix specimen codes were nominated according to the level of replacement by volume of expanded clay (EC) and OPS, which include 100% EC, 100%OPS, 75%EC+25%OPS, 50%EC+50%OPS, and 25%EC+75%OPS, for instance, EC75-OPS25 denotes a mix containing 75% of EC and 25% of OPS. Table 3 summarises the mix designs in kg.

Table 3 Investigated mix design

Mix	**OPC**	**Coarse Aggregate**		**Sand**	**Water**	**SP Dosage**
		EC	**OPS**			
CM	69.29	84.18		27.22	19.77	0.693
EC100-OPS0	69.29	25.36	0.00	27.22	19.77	0.346
EC75-OPS25	69.29	19.02	7.35	27.22	19.77	0.346
EC50-OPS50	69.29	12.68	14.71	27.22	19.77	0.693
EC25-OPS75	69.29	6.34	22.06	27.22	19.77	0.693
EC0-OPS100	69.29	0.00	29.41	27.22	19.77	0.693

*all units in kilogram (kg)

2.3 Test Procedure

The mixes were cast with 100 mm × 100 mm × 100 mm cubes for compressive strength and sorptivity tests; cylinders of 100 mm diameter × 200 mm height for splitting tensile tests; and prisms of 100 × 100 × 500 mm for flexural strength tests. Slump tests were conducted before the mould casting. The slump values and densities were recorded for the investigated mixes where the oven-dried densities were obtained at 28 days of concrete age. The fresh concrete were left in the mould for 24 hours in room temperature. Water curing was applied at room temperature (23 ± 2 °C) after demoulding.

Subsequently, the specimens were cured for 7, 14, 21, and 28 days for compressive, splitting tensile, flexural, and sorptivity tests.

Compressive strength tests were conducted for concrete age of 7, 14, 21 and 28 days which complied with ASTM C39 with 0.33 MPa/min loading rate using universal testing machine. Cylinder specimens were prepared for splitting tensile tests for four concrete ages, complied with ASTM C496 with loading rate between 0.7 to 1.4 MPa/min. According to ASTM C78, flexural strength tests were conducted with constant load rate of 0.017 MPa/min with concrete ages of 7 and 28 days. For sorptivity test, 100 mm concrete cube specimens were used to examine their rate of water absorption in concrete for 7 and 28 days concrete age based on ASTM C1585.

3.0 RESULTS AND OBSERVATION

3.1 Fresh State Properties

Table 4 lists the fresh state properties of the investigated mixes. The difference in the stability of the specimens ranged from 5 to 8% for the examined densities. According to Lim *et al.* [26], the stability should be controlled at ±5% to obtain mixed stability. To have a more stable mix, it is suggested to include pozzolan, such as palm oil fuel ash (POFA), silica fume, and fly ash [27]. It can be noticed in the table that the workability generally increased with a higher content of expanded clay due to its smooth contact surface with concrete pastes. More superplasticizer was applied with the increased content of OPS due to shape irregularity to increase workability without adding water to the mixture.

Table 4 Fresh state properties

Mix	Density, kg/m³		Stability	Slump, mm	
	Fresh	Oven-dried		Slump height	Slump diameter
CM	2356	-	-	58	-
EC100-OPS0	1540	1476	0.93	259	-
EC75-OPS25	1671	1523	0.95	208	-
EC50-OPS50	1736	1599	0.92	269	629
EC25-OPS75	1803	1612	0.93	252	571
EC0-OPS100	1840	1687	0.93	239	518

Stability = dry density / fresh density

CM = conventional concrete, EC = expanded clay, OPS = oil palm shell

As OPS is 15% heavier than expanded clay, it is expected to have a higher density following the increased replacement level of aggregate with OPS. The overall construction material cost may reduce in a direct manner with the self-weight of the building.

3.2 Compressive Strength

Figure 2 shows the concrete compressive strength at different curing ages for the studied mixtures. It can be seen that a full coarse aggregate replacement with OPS registered the highest compressive strength at concrete age of 28 days. All specimens except EC75-OPS25 reached the minimum requirement of compressive strength of 17 MPa for structural concretes. There was a structural crack incorporating some minor ones near the top loading surface of the specimen upon reaching the fracture load, as shown in Figure 3.

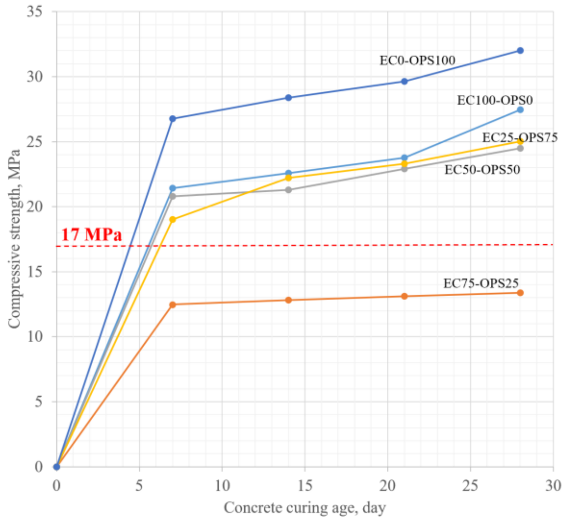

Figure 2 Compressive strength at various curing ages

Figure 3 Cube failure under compressive load

Shafigh *et al.* [28] discovered that OPS has stronger grains as compared to expanded clay, which enhances the compressive strength in the range of 9 to 23%. Also, the smooth surface of expanded clay inflicts weakness in bonding. From the currently obtained results, it can be witnessed that employing only one type of aggregate may benefit in the strength development rather than the use of heterogeneous coarse aggregates. A weaker bonding may form in the concrete matrix with both expanded clay and OPS due to the surface condition in the former constituent. Nevertheless, it can be well remarked that most of the mixtures achieved the compressive strength requirement of structural concrete.

3.3 Splitting Tensile Strength

The splitting tensile strengths were recorded at various concrete ages as summarised in Table 5. It is well recognised that 70% of characteristic strength was generally developed at the concrete age of 7 days. There are three mixes able to achieve the minimum requirement of 2 MPa of tensile strength, namely EC100-OPS0, EC0-OPS100, and EC25-OPS75. Furthermore, EC100-OPS0 attained almost 3 MPa of the tensile strength. In close inspection, the tensile strength also follows the trend of compressive strength, i.e., higher compressive strength promotes higher tensile strength. The typical corresponding failure mode of the splitting tensile test specimen is shown in Figure 4. There existed a straight vertical split without much off-axis shearing from the top to the bottom of the specimen.

Table 5 Recorded splitting tensile and flexural strengths at various concrete ages

Specimen	Splitting tensile strength, MPa				Flexural strength, MPa	
	7 days	14 days	21 days	28 days	7 days	28 days
EC100-OPS0	2.37	2.47	2.59	2.97	4.64	5.24
EC75-OPS25	1.07	1.17	1.25	1.32	1.20	1.67
EC50-OPS50	1.55	1.57	1.61	1.66	2.24	2.83
EC25-OPS75	1.82	2.10	2.15	2.18	2.13	2.96
EC0-OPS100	2.01	2.28	2.53	2.67	3.05	3.44

Figure 4 Failure mode of splitting tensile test specimen

3.4 Flexural Strength

EC100-OPS0 recorded the highest flexural strength, 5.24 MPa, at 28 days of concrete curing age. The ranking of flexural strength was similar to the tensile strength for other mixtures, as readily displayed in Table 5. Additionally, the typical failure state of the flexural specimen is illustrated in Figure 5. All specimens failed in aggregate fracture during the flexural tests. Therefore, it can be deduced that the bonding portion of the specimen, C-S-H product of the hydration process, possessed a higher strength than the aggregates (OPS and expanded clay), while normal concretes may commonly fail at the bonding zone. Such finding is imperative when manifesting analysis and design of beams fabricated with different concrete materials.

Figure 5 Flexural failure of the tested specimen

3.5 Sorptivity

The capability of water transmission through capillary suction in concrete can be reflected through a sorptivity test where the internal water in concrete may cause the corrosion of the reinforcement bars. Hence, this ability depicts the characteristics of concrete concerning the protection of its internal rebars. The sorptivity results are plotted and demonstrated in Figure 6. It is noticed that the specimen with 100% expanded clay (EC100-OPS0) has a higher sorptivity value than the concrete containing 100% OPS (EC0-OPS100) at both 7 and 28 days of curing ages. EC75-OPS25 recorded the highest sorptivity value at 28 days curing age as significant shrinkage cracks were found after its removal from the curing tank as shown in Figure 7.

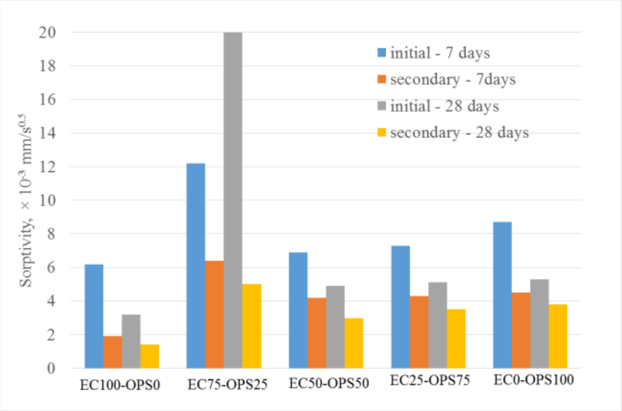

Figure 6 Sorptivity test results

Figure 7 Shrinkage cracks of EC75-OPS25 at 28 days of curing age

In addition, an increment in OPS resulted in higher water absorption as shown in Figure 6, an observation was also found in a previous investigation [29]. Porous network was found in OPS concrete due to high fibres that tend to absorb water, which in turn increased the sorptivity value [30]. To remedy, compaction of the mixture is suggested to reduce the voids in the concrete. Having stated this, the expanded clay concretes in this investigation also showed high sorptivity values, the phenomenon of which was assertively governed by the concrete shrinkage.

4.0 MATERIAL STRENGTH ANALYSIS AND DISCUSSION

The characteristic strengths of the investigated mixtures are tabulated in Table 6. Performance index is defined as the compressive strength corresponding to a unit density, which represents the correlation between compressive strength and its density. It is identified that EC100-OPS0, EC0-OPS100, and EC25-OPS75 were the three design mixes that achieved the structural concrete requirements. Although the highest compressive strength was offered by EC0-OPS100, the highest performance index was delivered by EC100-OPS0 due to the lower strength of the expanded clay.

Table 6 Characteristic strength at 28 days of curing

Mixture	Compressive strength, MPa	Performance index, MPa	Splitting tensile strength, MPa	Flexural strength, MPa
EC100*	24.75	16.22	3.06	-
EC100-OPS0	27.46	16.59	2.97	5.24
EC75-OPS25	13.37	7.6	1.32	1.67
EC50-OPS50	24.49	13.01	1.66	2.83
EC25-OPS75	25.01	12.94	2.18	2.96
EC0-OPS100	32.01	16.10	2.67	3.44

*referred mix from [1]

For an equivalent grade of concrete, lightweight concrete has a lower tensile strength than conventional normal concrete [31], hence, the observed characteristic strength pattern is well expected. Since fibres are generally favourable in solving the low tensile strength problem in concrete [3], it is recommended to include them as a constituent in structural lightweight concretes.

4.1 Effects of Replacement of Coarse Aggregate With Expanded Clay and OPS

From the observation of the compressive strength, it was found that the fracture of aggregate occurred at failure load causing the concrete debris to fall from the cube, as shown in Figure 3. Also, in the flexural test, the same failure mode was found in terms of aggregate fracture, as shown in Figure 8 for EC100-OPS0. The same pattern was discovered for both expanded clay- and OPS-contained concretes. The lower specific gravity of expanded clay and OPS as compared to gravel may result in lower crushing load and contribute to the early failure in terms of low mechanical strength for the lightweight concretes. It was reported from [32] that the convex and concave surfaces of OPS or the smooth surface of expanded clay are the direct link to the witnessed weak interlocking bond with cement paste. The overall mechanical properties were decreased due to this reason. Furthermore, the tensile and flexural strengths of EC100-OPS0 were higher than the highest compressive strength of EC0-OPS100. However, in terms of performance index, they were similar, i.e., high tensile strength followed by a high performance index. To overcome the surface issues, several researchers had proposed to use fly ash and silica fume that can penetrate to the pores of OPS [33] or expanded clay [34] in improving the interlocking bond.

Figure 8 Centre-fracture of flexural specimens with fracture in aggregate

4.2 Effects of Drying Shrinkage

Drying shrinkage of lightweight concretes was greater compared to conventional concretes [28]. Drying shrinkage increased with the OPS content [35]. The low stiffness of lightweight concrete is the major contributor to the drying shrinkage since materials and proportion both affect the stiffness of the final product. From Figure 7, it was found that the concrete showed premature cracks after taken out from the curing tank, which was particularly significant in EC75-OPS25. Therefore, its compressive, tensile, and flexural strengths were relatively low as compared to other mixtures. Moreover, its sorptivity value was high as the water can transmit in concrete through the cracks.

Under the SEM illustration, microcracks were found in lightweight aggregate concretes in [36]. In the current research, it was analogously found that most of the mechanical strength test specimens revealed the shear failure of expanded clay and/or OPS aggregates, as shown in Figure 9. Moreover, microcracks can be formed in the interfacial transition zone when expanded clay with low elastic modulus was substituted [37], and thereby produced concrete with lesser strength. To remedy, POFA, silica fume, or fly ash can be added to solve the drying shrinkage problem in lightweight concretes [27].

Figure 9 Shear failure of the OPS- and expanded clay-contained specimens

4.3 Effects of Prewetted Lightweight Aggregates

As hydrophilic or high water absorption of OPS and expanded clay may cause the drying shrinkage of lightweight concrete, the use of pre-wetted lightweight aggregate is suggested. In so doing, the water used for the hydration process would not be absorbed by lightweight aggregate. Although the concrete specimen is placed in a water tank for water curing, due to the high cement content and low water-cement ratio, the external water faces difficulty to penetrate the internal concrete matrix, and hence, increase the potential of internal cracking. Autogenous shrinkage was found in non-prewetted lightweight aggregate concrete [38]. Researches have proved that prewetted lightweight aggregate can reduce the potential of shrinkage in concrete [39]. Thus, a separate series of confirmation tests had been carried out in this investigation, with the finding that prewetting of OPS and expanded clay for 24 hours before casting produced higher compression strength than those without such treatment.

4.4 Correlation Between Compressive, Splitting Tensile, and Flexural Strengths

There exists a mathematical relationship that links the splitting tensile and flexural strengths of concrete to its compressive strength. For splitting tensile strength, Eq.1 was recommended by Oluokun [40] for concrete densities between 1400 kg/m3 to 1800 kg/m3; Eq.2 was suggested by the CEB model [41] and Amran et.al. [42] for lightweight aggregate concretes. In addition, for flexural strength, Eq. 3 was suggested by Lo *et al*. [43] for expanded clay concrete; Eq. 4 by Shetty [44] for Indian Standard; and Eq.5 by Zhang and Gjorv [45] for high content of expanded clay. Table 7 showcases the predicted strengths based on these equations.

$$f_t = 0.20 {f_{cu}}^{0.7} \tag{1}$$

$$f_t = 0.23 {f_{cu}}^{0.67} \tag{2}$$

$$f_f = 0.69 {f_{cu}}^{0.5} \tag{3}$$

$$f_f = 0.70 {f_{cu}}^{0.5} \tag{4}$$

$$f_f = 0.73 {f_{cu}}^{0.5} \tag{5}$$

Table 7 Concrete tensile and flexural strengths prediction, MPa

	Splitting tensile strength, MPa			Flexural strength, MPa			
Mixture	**Exp.**	**Eq.1**	**Eq.2**	**Exp.**	**Eq.3**	**Eq.4**	**Eq.5**
EC100-OPS0	2.97	2.03	2.21	5.24	3.62	3.67	3.83
EC75-OPS25	1.32	1.23	1.31	1.67	2.52	2.56	2.67
EC50-OPS50	1.66	1.88	1.96	2.83	3.41	3.46	3.61
EC25-OPS75	2.18	1.90	1.99	2.96	3.45	3.50	3.65
EC0-OPS100	2.67	2.26	2.35	3.44	3.90	3.96	4.13

Furthermore, Table 8 lists the statistical analysis performed for the experimentally and mathematically obtained outcomes. Upon checking, there are two pieces of evidence that the null hypothesis should not be rejected at the 99% confidence interval of the difference. Therefore, there is no statistically significant difference between experimental results and equation predictions. Even so, from strength values observation, it is advised to have a further investigation for obtaining a more accurate set of strength predictions so that a more reliable set of properties for building can be determined in terms of safety.

Table 8 Paired T-test at 99% of confidence level

	Paired Differences					*t*	*df*	Sig. (2-tailed)
	Mean	Std. Dev.	Std. Error Mean	99% Confidence Interval of the Difference				
				Lower	Upper			
Exp vs Eq.1	.30000	.42913	.19191	-.58358	1.18358	1.563	4	.193
Exp vs Eq.2	.19600	.39183	.17523	-.61078	1.00278	1.119	4	.326
Exp vs Eq.3	-.15200	1.00243	.44830	-2.21602	1.91202	-.339	4	.752
Exp vs Eq.4	-.20200	1.00148	.44788	-2.26407	1.86007	-.451	4	.675
Exp vs Eq.5	-.35000	.99199	.44363	-2.39253	1.69253	-.789	4	.474

5.0 FRACTURE PREDICTION

It is important to predict the failure of concretes not commonly employed in industrial applications since the relevant information is scarce. Therefore, the fracture of the lightweight aggregate concrete with agro-industrial wastes or artificial aggregate is discussed next to increase its reliability in future applications. For normal weight concrete, the weakest zone occurred at cement paste or interfacial transition zone, which may not be the same as lightweight aggregate concretes mode, i.e., in aggregates [46–48]. As concrete is not applied solely in structural members, the discussion is predominant on reinforced concretes with steel bars.

5.1 Flexural Member Application

The classical bending theory with the consideration of stress equilibrium, strain compatibility, and Hooke's law of materials has been widely applied in the derivation of both the linear and nonlinear behaviours of reinforced concretes. It was previously observed that OPS reinforced concrete beam failed at the crushing of beam top compression while the fibre-reinforced concrete beam with OPS failed with bar fracture [49]. By the introduction of fibres, strain localization can be achieved with confinement effects through the improvement of steel-concrete bonding [49–51]. A high volume of fibres induced bar fracture before full crack development as described in a previous experimental study [49]. Furthermore, expanded clay concrete reinforced by geogrid was found to have a higher flexural strength than normal weight reinforced concrete [52]. The 0.6 reduction factor was the modified factor of 0.75 of the maximum section bar should be limited in obtaining ductile beam behaviour [53].

The modulus of rupture as calculated from the flexural test has revealed that a better strength can be obtained from expanded clay concretes. It was noticed that all specimens failed at the locations within and outside the middle third span, in which the formed CSH bonding was greater than the aggregate strength and hence the failing of aggregate. This phenomenon is similar to that of high strength concretes but in contrast to that of normal concretes. Moreover, lower tensile and flexural strengths possessed by lightweight aggregate concretes may induce additional stress with large deformation and bigger cracks. As the steel reinforcement is the component taking the stresses in the beam tensile zone, the serviceability deflection check should be performed to achieve minimum non-structural cracks to prevent the water transportation to the corrodible steel bars.

According to Table 4, for the overdesign of the steel reinforcement bar, the lightweight concrete beam would fail at the top compression zone, such that expanded clay concretes with lower compression strength may easily fracture compared to OPS concretes. In the perspective of under-design, OPS concrete beams may fail at lower flexural strength.

Moreover, flexural rigidity should be considered in this analysis. OPS reinforced concrete beam was found more ductile than fibre-embedded concrete [49], which behaved inversely to its material behaviour. This can be explained through the failure mode; fibres improve the compression and tensile strengths of the concrete beams and shift the failure from the compressive zone (no fibres) to the tension zone (with fibres). In contrast, OPS reinforced beam was found more ductile than the normal weight reinforced concrete beam [54,55]. There is no sufficient data for the deformation of flexural specimens in the current study. Thus, it is suggested to perform an experimental investigation to obtain its flexural rigidity.

From the time-dependent study [56], it was shown that greater deformation was expected for OPS concrete beam and higher creep values should be applied for the theoretical prediction of the beam deflection as a function of time.

5.2 Other Structural Members

There is at present a limited reference on the column analysis using lightweight aggregate concrete. As concrete is predominant in compression, researchers are comparatively less interested in the research of concrete columns. There is, however, a possibility of concrete column failure due to creep or shrinkage. As reviewed by Amran *et al.* [4], air-entrained concretes like foamed concretes tend to have shrinkage or creep issues due to time effects. This behaviour creates additional stress to the structural member, also referred to as strength reduction.

Summarised from the current study, for axial loading without eccentricity, the highest compression strength is possessed by the OPS concrete. However, the durability of these lightweight aggregate concretes should be further evaluated in order to obtain their reliability and safety in numerous other applications.

5.3 Design Recommendations by Codes

There are some recommendations from the current codes of practice, BS8110 [57], Eurocode 2 [58], and ACI318 [59], as summarized in Table 9 for compression and flexural structural members with lightweight aggregate reinforced concrete. The modification factors have been applied in ACI318 to accommodate the specific behaviours exhibited by lightweight aggregate concretes. Hence, it is suggested to adopt a modification/reduction factor when employing lightweight aggregate concretes as compared to normal concrete design specifications.

To remark, existing models were not accurate in forecasting the tensile and flexural strengths of lightweight aggregate concretes containing OPS and expanded clay, thereby warranting a further investigation in improving the efficacy of the current models.

Table 9 Design specifications of BS, ACI, and Eurocode for lightweight aggregate concrete

	Requirements	Flexural	Compression
BS8110	Concrete classes LC20/22 and above	Not specified	Clauses 5.7 and 5.8; Eq. 34
Eurocode 2	Density <2000 kg/m3	Not specified	Not specified
ACI318	Minimum of 17 MPa for compressive strength	Table 19.2.4.2 RF: 0.75	Table 19.2.4.2 RF: 0.75

RF = reduction factor

6.0 CONCLUSIONS

Fresh and hardened properties of various concrete mixtures were studied with the consideration of OPS and expanded clay as the full replacement of coarse aggregate. Several conclusions can be drawn from the analysis.

i) The experimental results showed compression strength of 13 to 32 MPa, splitting tensile strength of 1.32 to 2.97 MPa and flexural strength of 1.67 to 5.24 MPa for the investigated mixes at concrete age of 28 day.

ii) 100% of expanded clay, 100% of OPS and 25% of expanded clay + 75% of OPS achieved the structural concrete requirements for compressive and tensile strengths.

iii) Tensile and flexural strengths have a similar trend in terms of performance index where higher strengths can be observed for concretes with a full replacement by OPS or expanded clay. However, a relatively low strength for a heterogeneous mix of coarse aggregates by OPS and expanded clay was found.

iv) Concretes mixed with expanded clay exhibited higher values of sorptivity, where cracks were found for most of the concretes with a high content of expanded clay. Significant cracks by shrinkage of EC75-OPS25 were discovered, which resulted in high water absorption and low strength.

v) Pozzolan like silica fume, fly ash, and POFA may improve the mechanical properties of lightweight aggregate concrete. Prewetted lightweight aggregate was also found to be useful in reducing the concrete shrinkage.

vi) Current prediction models were not accurate in forecasting the tensile and flexural strengths of lightweight aggregate concretes with OPS and expanded clay, thereby warranting a further investigation in improving the models' efficacy.

vii) Lightweight aggregate concrete with OPS or expanded clay exhibited higher strength values for reinforced concrete beam compared to normal weight concrete. From the current study, it can be concluded that OPS may benefit in the overdesign of reinforcement bars; while expanded clay may enhance the capacity of the under-design of section bars. Modification/reduction factor should be applied to lightweight aggregate concrete when referring to the current codes of practice.

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