Lightweight masonry block from oil palm kernel shell

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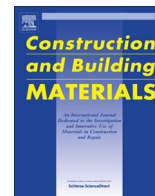**50** PUBLICATIONS **267** CITATIONS

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Lightweight masonry block from oil palm kernel shell

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HIGHLIGHTS

- We use oil palm kernel shell to make masonry block, called as shellcrete.
- The physical and mechanical properties and the optimum mixtures design is evaluated.
- The best mix design is 1 OPS:1 Sand:2 PKS.
- The shellcrete is acceptable for lightweight materials and masonry block.

ARTICLE INFO

ABSTRACT

A large amount of waste produced in the processing of palm oil is one of the main contributors to the environmental problem. This paper presents an experimental study on the development of the shellcrete masonry block that made of oil palm kernel. The study was focused on the physical, compressive strength and flexural strength of shellcrete. The eco-efficiency of the shellcrete was also evaluated by measuring the carbon footprint. The shellcrete was made by mixing the Portland cement (PC), sand, and oil palm kernel shell (PKS). A control specimen made of PC and sand mixture (sandcrete) was also prepared. The specimen size was 220 mm length, 110 mm width and 80 mm in thickness. The maximum strength obtained was 22 MPa by mixing proportion of 1 PC:1 Sand:1 PKS, but the recommended mix proportion of the shellcrete for building materials was 1 PC:1 Sand:2 PKS as an optimum mix design for eco-friendly shellcrete.

1. Introduction

The production of palm oil has increased almost threefold over the past three decades in the world. The total production of palm oil was estimated at 45.1 million tons for the year 2009–2010 in which Indonesia and Malaysia produced about 85% of the total production and each of them produced over 18 million tons of palm oil [1]. UN ESCAP [2] reported that Indonesia and Malaysia contributed to a large number of oil palm residues among the South East Asian countries. After processing and extraction of oil, solid residues and liquid wastes have been generated from the fresh fruit bunches, and resulted in varying by-product including empty fruit bunches fiber, shell, and effluent. As a result, air, river, sea and groundwater pollution have increased due to the large amount of waste produced which was one of the main contributors to the environmental pollution. Therefore, countermeasures should be taken to manage the agriculture by-products for sustainable development. As the "zero waste policy" in oil palm production to prevent the environmental pollution, the by-products have to be reused and recycled for other purposes e.g. the empty fruit fiber as fuel, and the ash as fertilizer. But, the oil palm kernel shell waste (PKS) has not well managed, and they were just dumped near the mills. It was found in the previous researches that the Los Angeles abrasion value of the PKS was about 4.8%. The aggregate impact value and aggregate crushing value of PKS aggregates were much lower compared to traditional crushed stone aggregate [3,4]. Hence, the PKS is a potential by-product for construction materials. The palm kernel shell has recently been used as a base material of the access road at the oil palm mill, but no report is yet written on its performance.

Several investigations have used PKS as aggregate in concrete [3–9]. These researches have brought immense changes in the development of building structures using lightweight concrete (LWC). The shell is hard and does not easily suffer deterioration. However, the water absorption capacity of the shell is high which ranges from 21% to 33% subjected to 24 h of submersion. This value implies that the PKS absorbs more water than the conventional gravel aggregates [3,4]. The PKS can be utilized to develop a normal strength concrete, which ranges from 20 to 30 MPa, if the material is mixed at proper mix design [4–9]. But, less or none of

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the study has been investigated on the application of PKS as masonry brick.

In many developing countries, the utilization of clay mud in housing construction is one of the oldest and most common methods used in the sustainable housing development. This type of housing is a common choice for the medium and low-income group of the society [10]. The housing development has become a huge challenge particularly because of the huge capital outlay required to do so. Furthermore, utilization of industrial waste in infrastructure development is proven economically viable when environmental factors are considered, and these materials meet appropriate performance specifications and standards [11]. Efforts are being made to find alternative applications of the by-products instead of allowing it to waste. Environmentally friendly material recycling and energy saving are very important research fields today. On the other hand, as a result of environmental regulations, the demand for construction of eco-materials is increasing. Continuous investigation is needed to study the possible use of the PKS to produce masonry block. The PKS can be used as a partial replacement of aggregate in sandcrete block. The research focuses on the compressive and flexural strength of the PKS masonry block (named as shellcrete). The objective of this study is to obtain mix proportion that produces a high compressive and flexural strength and to investigate the effect of PKS sizes and mix proportion of the physical and mechanical properties of the shellcrete. The expected outcome of this research is to produce low-cost and low-carbon building material.

2. Research methods

2.1. Materials used

2.1.1. Cement
The cement used to be a general type of Portland cement (PC), having a specific gravity of 3.14. Its Blaine specific surface area was 3510 m^2/g. The PC contains of 63% CaO, 20% SiO_2, 5.2% Al_2O_3, 3.3% Fe_2O_3, 2.4% SO_3, and 2.5% loss of ignition (LOI). The density of cement was about 2950 kg/m^3. The PC confirmed to Type I PC according to the ASTM C150 [12].

2.1.2. Sand
Local river sand with a fineness modulus of 1.32 was used as fine aggregate. The grain size distribution of sand is illustrated in Fig. 1. The sand is classified as fine sand. Its specific gravity and water absorption was 2.64% and 1.1% respectively. The density of sand was about 2300 kg/m^3.

2.1.3. Oil palm kernel shell
The PKS was collected from a local crude palm oil producing mill. They comprised old discarded waste in the oil palm mill area. The grain size distribution of PKS was shown in Fig. 1. The physical properties of the PKS are fineness modulus
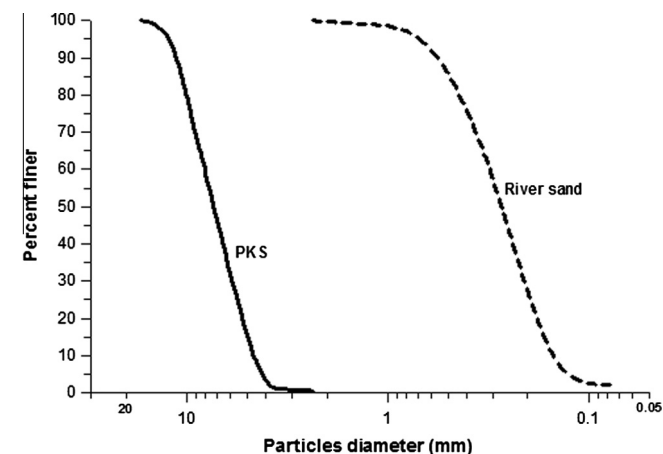

Fig. 1. The particles size distribution of the sand and PKS.

of 5.78, specific gravity of 1.19, and water absorption of 20%. The PKS have fibers up to 30% on the shell surface. Three PKS sizes were used to produce shellcrete (Fig. 2) that are PKS sizes (1) passed the 4.75 mm and retained on 2.36 mm sieve (Size A: small), (2) a size passed the 9.5 mm and retained on 4.75 mm sieve (Size B: medium), and (3) a size retained on 9.5 mm sieve (Size C: large). The smaller size of PKS behaves more fracture than, the larger size, since their skin thickness is smaller than the larger size as depicted in Fig. 2a and c. The compacted bulk density of PKS was 645 kg/m^3, 630 kg/m^3, and 605 kg/m^3 for size A, B and C respectively.

2.2. Specimen preparation and tests

In this research, the size of shellcrete was made of 200 mm × 100 mm × 80 mm. The ratio of cement, sand and PKS was designed as 1:1:1, 1:1:2, and 1:1:3 by the volume ratio (see Table 1). The sandcrete made from 1:4 of cement and sand ratio was prepared as control specimens. Three specimens were prepared for each mixture proportions. The cement and water ratio (w.c.r) was adjusted accordingly about 0.5 to obtain an acceptable workability. Before the PKS were used, they were soaked in water for about 1 h, and subsequently air-dried in the laboratory to get about a saturated surface dry condition. The specimens were prepared by three steps. First, the amount of sand and cement was mixed and stirred in the mechanical mixer to obtain a homogenous mixture. Second, the mixing was continued and followed by addition of water until all materials were homogeneously mixed. Duration of the mixing was about 10–15 min. The mixtures were placed in the mold and compacted on hydraulic pressed-machine (Fig. 3). The pressure was gradually applied from the hydraulic jack up to 5 MPa until the top plate touches the mold surface. The specimens were dismantled from the mold and then placed in a humidity control room and cured for 28 days (Fig. 4). After this curing period, the specimen was subjected to water absorption, compressive and flexural strength tests.

Water absorption test on the specimens was conducted after 28 days of curing. Before immersed, the weight and size of specimens were measured. The specimen was immersed in water for 24 h, and oven dried subsequent to immersion at 115 °C for not less than 24 h. The method was modified from ASTM standard C140 [13]. The amount of absorbed water was calculated by the following equation

$$w_{24} = \left(\frac{m_s - m_d}{m_d} \right) \times 100\%$$ (1)

where w_{24} is the absorbed water after 24 h of immersion (%); m_s the mass of specimen after immersion (g), and m_d is the mass of the oven dried specimen subsequent immersion (g).

The compressive strength test was performed in the dry and wet specimens. Three specimens were made for each testing condition. The dry specimens were treated as the air cured for 28 days. The wet specimens refer to immerse specimen for 24 h in the water after 27 days of curing, and then oven dried subsequently to immersion. The entire specimen was tested on the universal testing machine. Before the test, the surface of specimens was flattened by the sulfur capping. The test method referred to the standard test of ASTM C67 [14]. The loading rate was adjusted to 1 kN per minute. The vertical force was applied to the specimen gradually to reach failure. The maximum force was recorded to calculate the compressive strength by dividing the contact area as follows:

$$S_c = \frac{P}{A}$$ (2)

where S_c is the compressive strength of the specimen (MPa), P the maximum load (N) indicated by the testing machine, and A is the average of the gross areas of the upper and lower bearing surfaces of the specimen (mm^2).

The flexural strength test was performed for selected specimens as presented in Table 1. A center-point loading test was conducted on the same specimen size as used in compressive strength test. The test setting and method refer the ASTM C67 [14]. The specimen was placed in the flatwise on the supports of two solid steel rods. The load was placed on the upper surface of the specimen through a steel bearing plate and gradually applied at the midspan of specimen. The loading rate was controlled to 1 kN per minute. The modulus of rupture of each specimen was calculated by using the following formula:

$$\text{MR} = \frac{3PL}{2bd^2}$$ (3)

where MR is the modulus of rupture of the specimen at the plane of failure (MPa), P the breaking-load indicated by the testing machine (N), L the distance between the supports (mm), b the net width of the specimen at the plane of failure (mm), d is the depth of the specimen at the plane of failure (mm).

The load–deflection curves from the test were collected by computer-based data acquisition system. The flexural toughness as specified by the toughness indices which was calculated based on the area under the load–deflection up to specific deflection after the first crack. The first crack was defined as the point on the load–deflection curve at which the form of the curve first becomes nonlinear. The flexural toughness indices at I_5, I_{10} and I_{20} according to ASTM C1018 [15] were calculated using the load–deflection curve obtained from the test results.
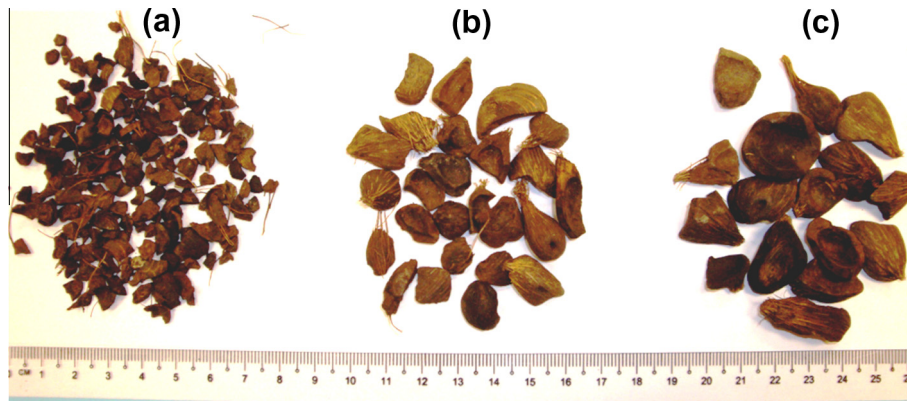
Fig. 2. The PKS used in this study (a) retained on 2.36 mm sieve (Size A), (b) retained on 4.75 sieve (Size B), and (c) retained on 9.5 mm sieve (Size C).

Table 1
Mixture proportion and testing design.

Mixture	Specimen	Test		
	Code	Compressive	Flexural	Absorption
1 OPC:4 Sand (sandcrete)	CTRL	Y	N	Y
PKS size A:				
1 OPC:1 Sand:1 PKS	S1A	Y	N	Y
1 OPC:1 Sand:2 PKS	S2A	Y	N	Y
1 OPC:1 Sand:3 PKS	S3A	Y	N	Y
PKS size B:				
1 OPC:1 Sand:1 PKS	S1B	Y	Y	Y
1 OPC:1 Sand:2 PKS	S2B	Y	Y	Y
1 OPC:1 Sand:3 PKS	S3B	Y	Y	Y
PKS size C:				
1 OPC:1 Sand:1 PKS	S1C	Y	N	Y
1 OPC:1 Sand:2 PKS	S2C	Y	N	Y
1 OPC:1 Sand:3 PKS	S3C	Y	N	Y

Note: Y = test performed, N = test not performed.

**Fig. 3.** The design of compressed-hydraulic machine.

3. Results and discussion

3.1. Bulk density

Density is the parameter to classify a lightweight construction material. The variation of the bulk density of each mixture is shown in Fig. 5. The figure shows the range bulk density for various mixture proportions of the shellcrete. The average density of the control specimen made from 1:4 was 1980 kg/m^3. The Fig. 5 shows

that replacing the sand fraction with PKS decreased the bulk density of the specimens. It was known that the PKS had the lowest density among the mixing materials. As a consequence, the increasing of the PKS in the mixture will decrease the density of shellcrete. The bulk density of the shellcrete decreased up to 31%, 27%, and 22% lower than the control specimen, respectively for size A, B, and C PKS. Other studies of a PKS concrete show that the 28-day air-dry densities were 19–24% lower than ordinary crushed stone concrete or normal weight concrete [6,7,16].

Fig. 4. The compacted specimens of control and shellcrete.
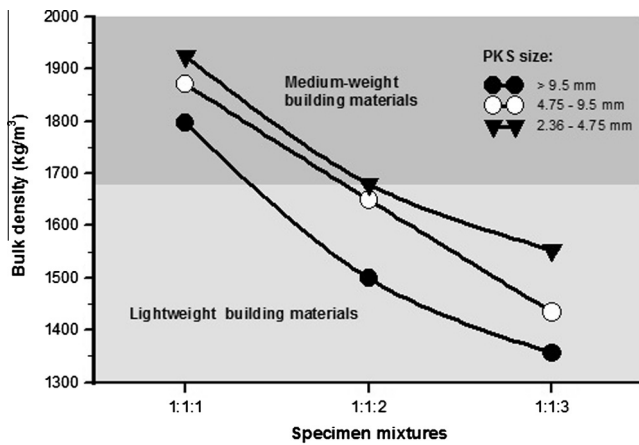
Fig. 5. The bulk density of the shellcrete with various mixtures.

Density is defined as the measure of how many particles of an element or material is squeezed into a given space. The more closely packed the particles, the higher the density of the material [17]. Fig. 5 clearly shows that the density of a size A of PKS is higher than the size B and C. The result indicated that a smaller PKS size forms a more packed void in the matrix, therefore, results in a denser and a higher density than larger PKS size. In contrast, a lager PKS size will produce a larger space in the specimen, and result in low the bulk density as shown in Fig. 5. The ASTM standard C55 [18] classified the lightweight concrete building brick if the dry density is lesser than 1680 kg/m^3, while medium weight is 1680–2000 kg/m^3, and normal weight is greater than 2000 kg/m^3. The densities of the PKS specimens were lesser than 2000 kg/m^3 which are a requirement for lightweight concrete. It was reported in Okafor [5]; Mannan and Ganapathy [7] that it was possible to produce a concrete with a density of approximately 1758–1850 kg/m^3 using the oil palm shell. Furthermore, this study found that the density of shellcrete can be designed as low as 1400 kg/m^3 by mixture proportion of 1:1:3. But, the mix proportion only produced an acceptable strength for non-structural section. For non-structural application of lightweight construction materials, a lightweight density is often more important than the strength.

3.2. Water absorption

The standard specification for concrete building brick or block limited the maximum water absorption. The ASTM C55 [18] stated
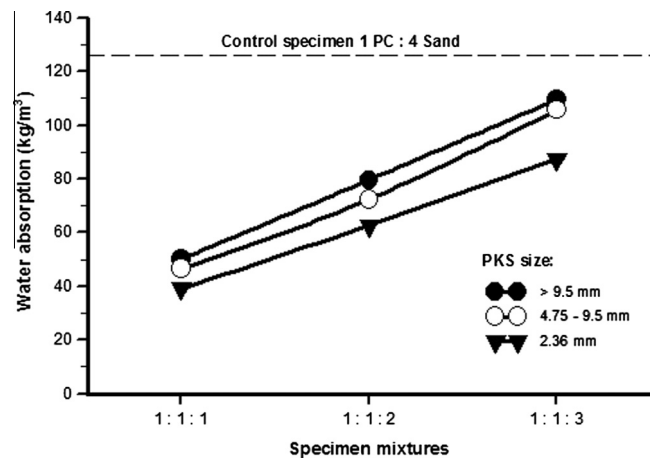
that the maximum water absorption required for lightweight concrete building block is 320 kg/m^3. Water absorption is defined as the transport of liquids in porous solids caused by surface tension acting to the capillaries. Fig. 6 shows the water absorption of the shellcrete with different mixture proportion. The mix proportion of 1:1:1 had the lowest water absorption. The water absorption of shellcrete increases with increasing of the PKS proportion. A larger PKS size also had higher water absorption than the smaller PKS size. The possible reason of the increasing of water absorption is the existence of microspores on the shell surface [19]. The porosity of a large size PKS was about 37%; hence, the use the size in a higher content will have a greater interparticle-void and existent of microspores. However, all shellcrete mixtures had water absorption than the control specimen. Inspection of the fracture specimens after compressive strength test, it was observed that the sandcrete specimen had more pores than the shelcrete specimen as illustrated in Fig. 7. The figure shows that it was possible for sandcrete to absorb water more than the shellcrete. The results indicate that all shellcrete specimens comply the specification for lightweight concrete building brick as required in ASTM C55 [18].

3.3. Compressive strength

The variation of compressive strength of the shellcrete and the control specimens are shown in Fig. 8. It is illustrated that the compressive strength is affected by the mix proportion, the PKS sizes, and water immersion. The highest compressive strength of the shellcrete was about 23 MPa that was obtained by mixing proportion of 1:1:1 at dry condition. Comparing the results with the other lightweight concrete, Okafor [5] reported that the highest compressive strength of concrete produced using PKS aggregate was about 25–30 MPa, while Mannan and Ganapathy [7] lead to produce compressive strength between 20 and 24 MPa for 28 days; that satisfies the strength requirement of structural lightweight concrete.

3.3.1. Effect of mixture proportion and water immersion treatment
In general, the compressive strength of shellcrete mixtures was higher than the control specimen excluded the S2A, S3A, S3B, and S3C specimens. The maximum strength was obtained by mixing proportion of 1:1:1 for both dry and wet treatment, while the lowest strength was obtained by mixing proportion of 1:1:3. Addition a large amount of PKS tends to decrease the compressive strength. A possible reason for the low compressive strength is reducing the ratio of cementitious matrix and PKS. Lack of

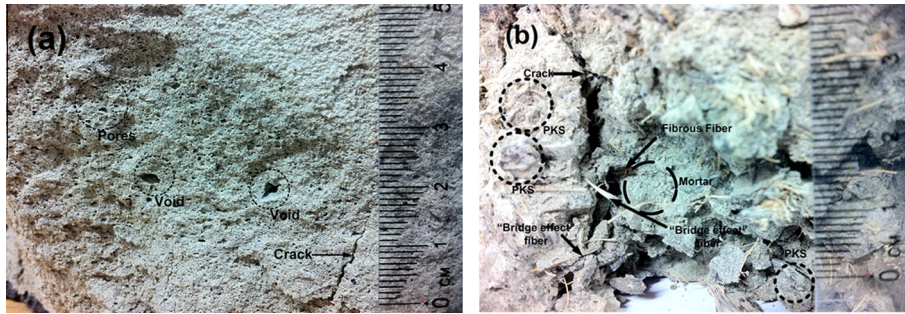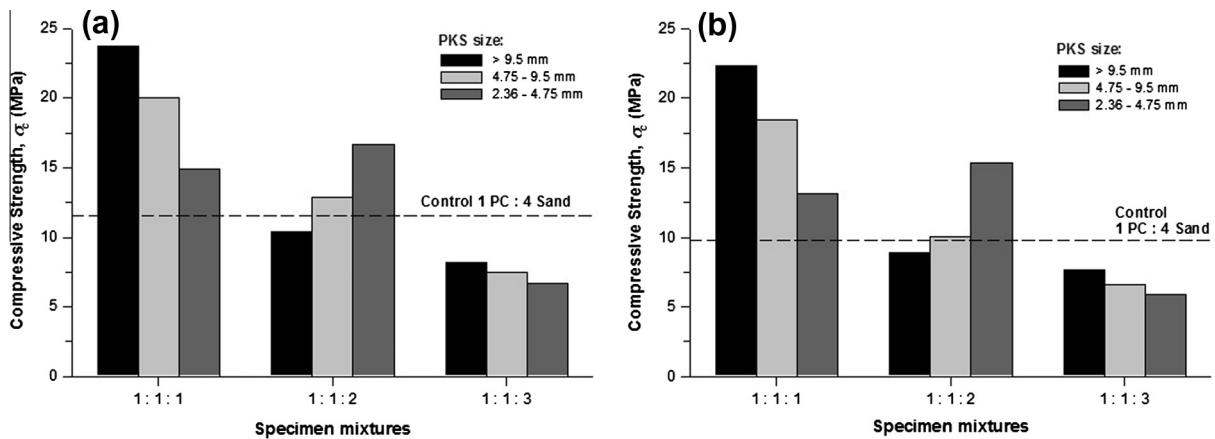**Fig. 6.** The variation of water absorption of the shellcrete.

Fig. 7. The void and fracture observation of the specimen (a) sandcrete (CTRL specimen) and (b) shellcrete (S3C specimen).

Note: The mixture proportion 1:1:1 is 1 part of cement : 1 part of Sand : 1 part of PKS

Fig. 8. The variation of the compressive strength of the shellcrete (a) dry and (b) wet specimens.

cementitious materials will reduce the bonding capability in the mixture. Therefore, the compressive strength decreases with an increase in the number of the PKS. This effect was also discussed in Alengaram et al. [16] that the presence of the cementitious matrix controlled the compressive strength. Smoother skin and convex surface of the PKS contributed to a low compressive strength since the bonding between the PKS reduced. Several researchers reported a poor bond between the PKS and the cement matrix that resulted in bond failure [3,5,7,20]. The second reason, the convex surface, was possibly difficult forming a compact structure. The structure will have a larger void and result in a lower compressive strength of shellcrete.

It was interesting characteristic for shellcrete containing a small size of PKS (size A). The mix proportion of 1:1:2 produced the maximum strength if compared to 1:1:1 and 1:1:3 mix proportions. In the cement-based composites, the strength was contributed by a mechanical bond that the function of quantity and quality of the cement matrix and the aggregate grains [21]. Furthermore, in concrete-like composites, the aggregate grains participate in load bearing together with the cement matrix, relative to the stiffness of both these phases. For 1:1:1 mix proportions, it seems that the aggregate less contribute to the load resistance with the cement matrix. Meanwhile, for mix proportions of 1:1:3, the cement matrix was possible inadequate to produce a mechanical bond with aggregate grains because of a large quantity of small aggregate in the mixtures. In mix proportion of 1:1:3, decreasing strength was possibly caused by close to the aggregate grains that resulted in effective packing of cement particles. On the other hand, the small size PKS have angular and flaky shapes that were well bonded into the cement matrix. This necessary condition—aggregate shape and cement matrix proportions—was sufficient bond strength along the

aggregate–cement matrix interface in mix proportions of 1:1:2. Hence, it might result in increasing the compressive strength.

The results in Fig. 8 also show that the wet specimens produced a lower compressive strength compared to the air dry specimens. The lower compressive strength of the wet specimens can be caused by higher water absorption as shown in Fig. 6. The PKS is organic materials that absorb much water. The condition will generate a higher internal relative humidity and soften the aggregate. Thus, it will reduce the compressive strength. The characteristic indicates that the absorbed water was hindering the hydration of cement for producing a higher strength. Many investigations [16,22,23] reported that immersion in water for a day will not gain a higher strength. But, wet curing for long periods up to 28 days after demoulding of the specimens will contribute to sufficient moisture and suitable vapor pressure for continuing the hydration of cement. This process would produce a high compressive strength.

3.3.2. Effect of the PKS sizes

In general, it was clearly observed in Fig. 8 for mix proportion of 1:1:1 and 1:1:3 that the compressive strength decreased as the PKS size was smaller. In this case, the shellcrete contained large and medium PKS size had higher compressive strength than the smaller size of PKS for both dry and wet conditions. In fact, the large size of PKS had a thicker shell skin than the small sized PKS. Physically, the large particles are parabolic with convex and concave surfaces, while the medium and small sized PKS are mostly flaky and angular respectively. A thicker shell skin had stronger resistance due to applied loads and resulted in higher compressive strength. In contrast, small sized PKS had a thin shell and flaky shape that behave brittle in nature as they were scales from the

large particles. Hence, the smaller size was easier to get crushed due to the impact if compared to the large particle size. As a result, this characteristic reduced the compressive strength. However, the angular and flaky shapes have well bonded into the cement matrix inappropriate mix proportion as discussed in the previous section.

Investigation of the crushed specimens has shown that the both large and small particles were well bonded into the mortar. However, closer inspection on broken specimens reveals that not all large size particles are fractured, while the small size PKS fractured in compression. A microcrack on PKS surface and the mortar were observed on small size PKS in 1:1:3 mix proportions as shown in Fig. 9. The development of microcracks generated a weak zone that decreased the compressive strength. In addition to fracture of PKS, the bond failure occurred between these large size particles and cement matrix. A similar characteristic was reported by Alengaram et al. [24]. However, in this research, the bonding-failure did not reduce the compressive. The condition was possible because of the presence of fibers on the shell surface that prevented the development of crack (Fig. 7b). This "bridge effect" contributes to the higher compressive strength in the shellcrete. However, the presence of fibers on the shell should be given more attention as it may deteriorate easily in the alkaline environment for long-term time. Gram [25] detected that when the composite was subjected to humidity variations, strength was substantially reduced. It was observed that in carbonated concrete with a pH of less than 9, fibers preserved their flexibility and strength, but in noncarbonated zones, the fibers were fragile.

The Indonesian standard SNI 03-0349 [26] classified the concrete building block into four categories of compressive strength. The shellcrete mixtures of 1:1:1, and 1:1:2 meets the requirement of class B2 for masonry block which the minimum compressive strength is 9 MPa. Meanwhile, the shellcrete mixture of 1:1:3 meets the requirement of class A2 for masonry block which the minimum compressive strength is 4 MPa. The materials are suitable to produce low cost residential building. Comparing the result with the Malaysian Standard, all shellcrete samples achieved the compressive strength higher than the required strength by the MS 76 [27] Class 1 for load bearing purposes which the minimum compressive strength is 5 MPa. In exceptional, the shellcrete mixtures of 1:1:1 meet the requirement of class 2 for load bearing proposes.

3.4. Flexural strength and toughness index

The flexural strength of the selected mixtures, which is contained medium size of PKS, is presented in Table 2. The trend of
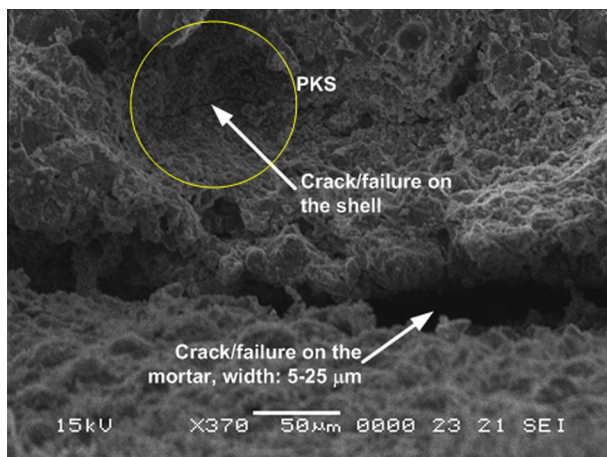
flexural strength is similar to those for compressive strength test. In general, the dry specimens have higher flexural strength than the wet specimen about 17%, 33%, and 36% for 1:1:1, 1:1:2, and 1:1:3 mix proportion respectively. The highest flexural strength was obtained at the mix proportion of 1:1:1 for both dry and wet condition. The flexural strength decreased with the increasing of quantity of PKS in the mixture. The decreasing of the flexural strength is indicated by the decreased in modulus of rupture. It was discussed in the previous section that the failure in flexural of the specimens was governed by tensile crack. The strength was dependent to the strength of PKS and bonding between the PKS and mortar. The wet specimens had lower strength than the dry specimens. A possible reason is that the water absorption softened the bonding between the PKS and the cement matrix which decreased the strength. However, for the greater amount of PKS, the bonding between PKS and mortar was no longer maintained as indicated by very low modulus of rupture that was 0.11 MPa and 0.07 MPa for dry and wet specimen respectively. For this case, the strength of the aggregate becomes less dominant in the overall failure mechanism. Hereafter, the failure was governed more by the strength of the paste and the bond. The results are similar with the research obtained by Okafor [5] and Alengaram et al. [24].

Observation on the load–deflection curve (Fig. 10), the peak load and the mid-span deflection decreased with the increasing PKS proportions in the mixture. The highest load and greatest deflection were obtained by S1B specimen, whereas the S3B specimen experienced failure at the lowest load and smallest deflection. As shown in Fig. 8b, the presence of fibers on PKS surface could act like a bridge across cracks. Hence, these fibers can contribute the ability to absorb energy and to sustain loads after the first crack. Typically, the load–deflection curve exhibits a similar pattern which the strength increases further after the first crack to reach maximum. The S1B specimen with 1:1:1 mixture proportion had greatest energy absorption up to the first crack among the tested specimens as presented in Table 2. The highest toughness was due to the highest strength and deflection. Increasing the quantity of the PKS in the shellcrete decreased the first peak toughness due to the decreasing first crack strength and stiffness of the beam. Reducing the first crack strength and deflection was attributable of the shell surface, for both concave and convex faces, that caused a poor bond between the PKS and the cement matrix. The condition resulted in low mechanical properties of the shellcrete. However, observation on the post peak crack, addition of PKS content increases the flexural toughness of the shellcrete which is indicated by the toughness indices I_5, I_{10}, and I_{20}. It indicates that the presence of PKS was able to hinder the crack by absorbing the energy. The results were alluding to prove that the shellcrete produced a ductile lightweight material. The behavior was also observed by Shafigh et al. [28].

4. The Eco-efficiency of the shellcrete

As global warming is a major concern of the industry, it is important to measure the eco-efficiency of the products in related with embodied carbon dioxide equivalent (ECO_2e). Theoretically, reducing the cement mortar and aggregate to produce a building material will have an advantage to reduce the carbon footprint. The carbon footprint in the shellcrete and sandcrete was calculated using the methodology and inventory of carbon and energy (ICE) developed in Hammond and Jones [29]. The embodied carbon dioxide equivalent for each virtual mix was calculated according to the contribution from each of its constituents, using the values given in Table 3. These values are the most reliable in the available open-access literature. The ECO_2e is presented in kg of CO_2 per kg or tones. However, most of the materials in the construction

Fig. 9. SEM image of the mixture with PKS size A after compression test.

Table 2
The flexural load and strength of the shellcrete.

Mix proportion	Peak-load (kN)	MR (MPa)	First-crack toughness (kN m)	Toughness index		
				I_5	I_{10}	I_{20}
1:1:1 (S1B)						
Dry	10.6	2.22	2835.0	3.001	–	–
Wet	8.9	1.89	2636.6	2.279	–	–
1:1:2 (S2B)						
Dry	4.0	0.78	76.2	6.025	10.943	15.537
Wet	3.2	0.59	45.1	5.923	11.031	16.591
1:1:3 (S3B)						
Dry	0.5	0.11	3.7	5.364	9.045	13.080
Wet	0.37	0.07	2.1	5.175	9.819	16.729
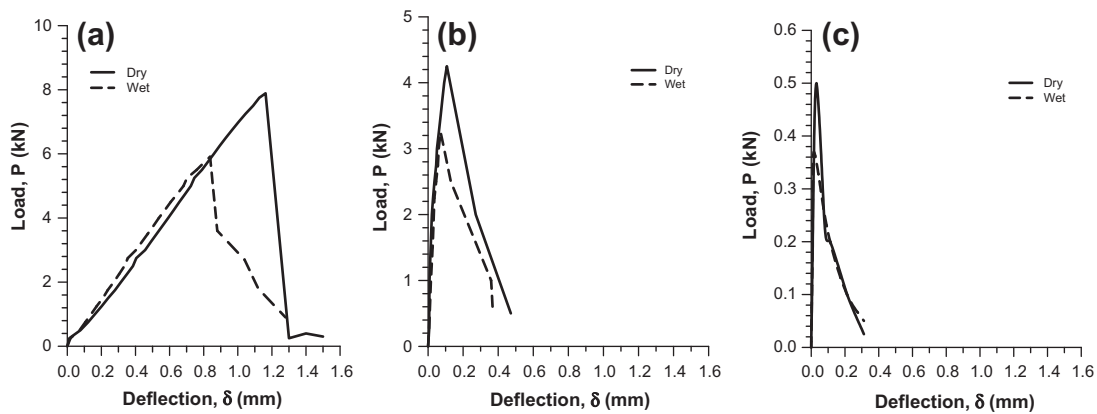
Fig. 10. Load–deflection curve of the flexural test (a) S1B, (b) S2B, and (c) S3B specimens.

Table 3
The embodied carbon dioxide equivalent of materials.

Constituents	ECO_2e (kg CO_2 e/kg)	Reference and remarks
Cement	0.74	[29]
Sand	0.0051	[29]
Water	0.0306	[29]
Palm kernel shell	0.00015	Principally, the ECO_2e of waste materials was zero, but in this study the value was assumed based on the road transport of 0.15 kg CO_2 e/tkm

Note: The energy and carbon requirement of transport are often expressed in the units tonne kilometres, (tkm). These values represent the energy/carbon requirement to transport 1 tonne of material each kilometre [29].

industry are measured in a unit volume m³ thus the carbon footprint in the materials is preferably calculated for each 1 m³. The values can be calculated by multiplying with bulk density of the materials.

The ECO_2 produced from the mortar of 1:4 mixtures are about 0.184 kg CO_2 e/kg. Consider the bulk density of the specimens, the carbon footprint of the sandcrete (1:4 mix) was calculated about 350 kg CO_2/m³. Replacement of natural aggregate with the PKS produced a lightweight masonry block as discussed in the previous section. Hence, the carbon emission of the shellcrete was estimated about 327 kg CO_2 e/m³, 277 kg CO_2 e/m³, and 262 kg CO_2 e/m³ for mix proportion of 1:1:1, 1:1:2, and 1:1:3 respectively. Less carbon reduction, about 6%, was obtained in mix proportion of 1:1:1. Substituting large quantity aggregate with PKS lead to reduce 20–25% in quantity of CO_2 emitted per ton compared to the sandcrete.

As discussed in previous section, addition of large quantity of PKS leads to decrease the compressive and flexural strength. The results also indicated that the CO_2 reduction increased with decreasing the compressive strength. Similar characteristic for concrete has been discussed by other researchers [30,31]. Combine the result of mechanical characteristic and ECO_2 reduction, the proper mix proportion of the shellcrete for building materials is recommended to have 1:1:2 as an optimum mix design for eco-friendly materials. This mix proportion has acceptable strength for building material as illustrated in Fig. 8 and Table 2.

5. Conclusions

A series of investigation of the physical and mechanical properties of the shellcrete has been successfully performed in this study. Three variations of mix proportion have been evaluated incorporating of the effect of the particle size of PKS. The highest compressive strength of the shellcrete was about 23 MPa that was obtained by mixing 1 PC:1 Sand:1 PKS. In general, it can be concluded that the compressive and flexural strength of the shellcrete decreased with increases in the quantity of PKS in mixtures. The greater PKS content tend to have a lower density and absorbed water easily. The shellcrete mixtures of 1 PC:1 Sand:1 PKS yield the highest compressive and flexural strength for lightweight building brick. The high-mechanical performance of shellcrete was attributable to the use of a large PKS size. Another advantage of the PKS was that the presence of fibers on the PKS surface enhanced the post-peak toughness of the shellcrete. As required by building standards, the shellcrete mixtures of 1 PC:1 Sand:1 PKS and 1 PC:1 Sand:2 PKS meets the requirement of class B2 for masonry block. Meanwhile, the shellcrete mixture of 1 PC:1 Sand:3 PKS meets the requirement of class A2 in compliance with Indonesian

standard SNI 03-0349-1989. Furthermore, all shellcrete mixtures achieved the compressive strength more than the required strength as required by the Malaysian Standard MS 76: 1972 Class 1 and 2 for load bearing purposes. The mixing proportion of the shellcrete showed a reduction of 6% to 20% in quantity of CO_2 emitted per ton compared with using sandcrete. Consider the both mechanical characteristic and CO_2 emission reduction, the suitable mix proportion of the shellcrete for building materials is recommended to have 1:1:2 as an optimum mix design. Consequently, the eco-friendly shellcrete derived as the optimum mix proportion is considered to be environmentally friendly.

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