Iranian Journal of Science and Technology, Transactions of Civil Engineering (2019) 43 (Suppl 1):S1–S14
https://doi.org/10.1007/s40996-018-0176-2

REVIEW PAPER

The Effect of Palm Oil Clinker and Oil Palm Shell on the Compressive Strength of Concrete

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Received: 24 November 2017 / Accepted: 20 September 2018 / Published online: 4 December 2018

Abstract
This article reviews the physical, chemical and microstructural properties of palm oil clinker (POC) and oil palm shell (OPS) by-products of palm oil. They are considerably used as lightweight aggregate to produce lightweight concrete so as to conserve the virgin resources and to reduce environmental contamination, whereby sustainability will be achieved. This paper is devoted to explaining the compressive strength behavior of concrete incorporating POC and OPS as lightweight aggregate. It is demonstrated that POC of size below 4.75 mm can be used as a partial fine aggregate replacement. Coarse POC sized 9–4.75 mm can be used as coarse aggregate substitution. POC powder (POCP) showed an improvement in compressive strength of concrete when used as filler. POCP treated at 850 °C showed a distinct increase in compressive strength when added as 30% by weight of cement. Previous studies have investigated the possibility of using OPS as the coarse aggregate replacement in concrete after following certain treatments. However, they have also documented a significant drop in compressive strength of concrete due to the smooth texture surface of the convex and concave of shells, hence weakening the bond between aggregate and mortar. Consequently, the compressive strength of concrete is reduced. On the contrary, coarse POC showed a compressive strength development when used as OPS substitution. Future studies should focus on OPS treatments to remove purities and develop bond strength in concrete. Future investigations should consider a broader usage of POC and OPS as lightweight aggregate in other applications like mortar, tiles, bricks and blocks. All in all, the usage of oil palm by-products as lightweight aggregate has recorded an accepted compressive strength for lightweight concrete.

Keywords Palm oil clinker · Oil palm shell · Lightweight aggregate · Compressive strength

1 Introduction

Construction industry today is the biggest exhauster of restricted virgin resources like water, sand, gravel and crushed rock. It has been documented that the concrete industry will utilize 8–12 billion tons of natural aggregates annually after 2010 (Mefteh et al. 2013). Construction, by its extreme nature, is not really an ecologically amicable action, and this industry has a distinct social, economic and environmental effect (Tu et al. 2006). On the other hand, an increase in populace has led to a more protruding demand on development material which prompts an interminable lack of building materials, whereby construction cost will be dramatically increased (Mannan and Ganapathy 2004). To mitigate this issue, engineers are defied with not only future homebuilding in terms of construction cost control, but also the need to convert industrial waste to valuable building materials (Mannan and Ganapathy 2002). Globally, recycling of waste materials in the construction sector is gaining massive attention. Utilizing by-product materials from various industries in concrete will not only alleviate the issues related to degradations of raw material, but also further improve its ecological and economic advantages (Zaetang 2013). Industrial waste usage holds incredible potential for cleaner production by enhancing energy efficiency, decreasing energy utilization and improving engineering functionality of an industry. In the construction industry, the idea of sustainability energizes the utilization

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of waste products as a substitution to raw materials, like fine and coarse aggregates, cement and fibrous materials. This would then create a sustainable, green and ecologically friendly construction industry, especially with the reduced cost of components (Bravo and Brito 2012).

Malaysia, as one of the major palm oil exporters, has been facing difficulties in dealing productively with waste that causes ecological contamination. As indicated in the Tenth Malaysian Plan (TMP-10), palm oil is recorded as one of the essential products in Malaysia to be exported globally because of the substantial international demand for crude palm oil (Siong et al. 2013). Crude palm oil (CPO) production in 2011 hit a high record of 18.91 million tons. The total amount of fresh fruit bunches processed by more than four hundred palm oil mills was approximately 87.5 million tons. Nearly 61.1 million tons of solid waste in the form of fibers, kernels and empty fruit bunches were produced annually from approximately 70% of fresh fruit bunches processed (Hussin et al. 2010). The large quantity of waste produced is one of the essential contributors to the nation's contamination issues. Palm oil mill in Malaysia burns the above-mentioned palm oil waste to produce steam required for the processing procedure in the mill. Figure 1 exhibits the operation procedure and product of POC from oil palm mill (Jegathish 2016). Palm oil clinker (POC) and palm oil fuel ash (POFA) are wastes created in the oil palm mill through the incineration of oil palm waste (Mohammed et al. 2011). In contemporary practices, this waste is generally dumped onto open land and hence leads to environmental contamination. According to Malaysia Cement Industry Report 2015, the construction industry in Malaysia has been expanded drastically in the last decades. This is because the government has been extensively investing on infrastructure development projects which have imposed additional pressure on the cement production and aggregate extraction industry (Mohammad et al. 2016a). Therefore, researchers have been urged to reuse palm oil by-products in the concrete industry for a sustainable environment, reduction of greenhouse gas emission in ordinary Portland cement (OPC) production and the conservation of natural resources like limestone, clay and iron pyrites (Kanadasan and Hashim 2014).

This paper aims to ascertain knowledge about the physical, chemical and microstructural properties of oil palm waste as palm oil clinker (POC) and oil palm shell (OPS) as per investigation by previous studies. The use of these wastes as lightweight aggregate in concrete was extensively investigated by researchers. Compressive strength is one of the most important properties when virgin components of concrete like sand, gravel and cement are partially or wholly substituted with new waste materials. The compressive strength of concrete is an essential parameter as it measures its ability to endure crushing.

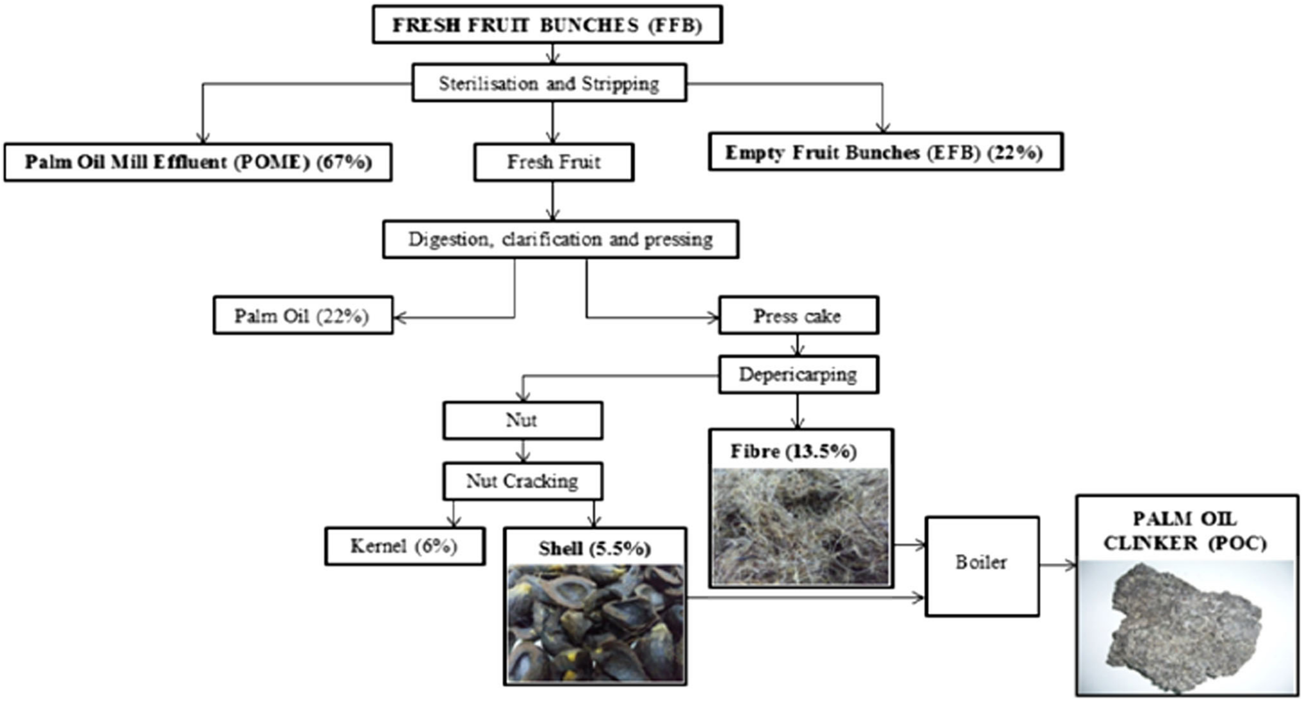

Fig. 1 POC production in oil palm mill (Jegathish 2016)

Strength test results from casted specimens may be used for control quality, acceptance of concrete, or the estimation of concrete strength in a structure for the purpose of scheduling construction operation such as form removal or for evaluating the adequacy of curing and protection afforded to the structure (Taghried et al. 2017). Therefore, the effect of POC and OPS on the compressive strength of concrete will be presented explicitly in this study.

2 Palm Oil Clinker

Palm oil clinker (POC) is a by-product produced through the burning of palm oil shell as fuel to run stream turbines in palm oil mills. It is a light, solid and fibrous material and has the potential to be utilized as a lightweight aggregate for concrete when crushed (Ibrahim and Razak 2016). POC is renounced and has minimal commercial value in Malaysia; therefore, this waste can be transformed into valuable construction materials (Ibrahim and Razak 2016). Recently, several studies have focused on the usage of POC as lightweight aggregate in various types of concrete for different application purposes. It was discovered that the mechanical properties of lightweight concrete can be improved by using POC (Omar and Mohamed 2002). Omar et al. (Jegathish and Hashim 2015) expressed the advantages of using POC as lightweight aggregate in diminishing a dead load of concrete structures without much loss in the strength of the structure. This condition is conceivable because lightweight concrete can lessen the dead load to around 35% and still provide the structural strength. Furthermore, it was demonstrated that the economic and environmental viability of POC in concrete could likewise decrease the cost, energy and greenhouse gas emission (Mohammad et al. 2016a). POC, as produced from palm oil mill, is a large chunk, which is porous, flaky and irregularly shaped, with rough and spiny broken edges, as shown in Fig. 2 (Bashar et al. 2014). The collected POC is squashed with a crushing machine and sieved to create aggregates similar to other sorts of aggregates like sand and granite to be used as an aggregate replacement in concrete (Ibrahim and Razak 2016; Omar and Mohamed 2002; Jegathish and Hashim 2015; Mohammad et al. 2016a; Bashar et al. 2014; Fuad et al. 2016). Figure 3 shows POC aggregate. Physical characteristics of fine POC < 5 mm and coarse POC 5–14 mm comparable with the physical properties of sand and granite are presented in Table 1 (Jegathish and Hashim 2015), (Bashar et al. 2014), (Rasel et al. 2016; Jegathish et al. 2018; Afia et al. 2015). It is evidenced from Table 1 that the specific gravity of fine POC ranged from 2.01 to 2.11, compacted bulk density varied from 811 to 1025 kg/m^3, and fineness modulus ranged from 2.72 to 3.37. However, specific gravity of coarse POC ranged between 1.82 and 1.88, compacted bulk density varied from 732 to 782 kg/m^3, and fineness modulus ranged from 6.72 to 6.78. Based on its physical properties, POC satisfies the criteria for structural lightweight aggregate. According to BSI Document 92/17688 (BSI Document 1768), aggregates with less than 2.2 specific gravity and lower than 1200 kg/m^3 compacted bulk density are classified as lightweight aggregates. The unit weight of POC aggregate is about 25% lighter than river sand and 48% lighter than crushed granite stone. In addition, the water absorption of POC is higher than the natural aggregate. Debieb and Kenai (2008) clarified that lightweight aggregates have higher water absorption compared to traditional aggregates. Accordingly, in the early age of hydration, the impact of poor curing on porous lightweight concrete aggregate is insignificant as compared to conventional concrete aggregates documented by Khalaf and Denny (2004). This condition is due to the extra water absorbed and internally retained in lightweight aggregates. Consequently, hardened concrete advantages from the high water absorption of the POC aggregate. Grading curve of sand and POC is illustrated in Fig. 4 (BSI Document 1768). It was found that the grading curve of POC conforms to the grading size of BS 882, 1992 (Payam et al. 2014).

Fig. 2 POC chunks as collected from oil palm mill (Fuad et al. 2016)

Scanning electron microscopy (SEM) image for surface texture of POC particles and normal sand is identified in Fig. 4 (Payam et al. 2014). It is evident that POC has honeycombed nature and more porosity on the surface and some holes can be seen on the surface. Consequently, when a portion of natural sand is replaced with POC, a part of mixing water is consumed by this lightweight aggregate and hence the effective water-to-cement ratio is reduced. Subsequently, the compressive strength is developed (BS 882 1985). However, SEM for sand showed that the solid and non-porous characteristic of sand particles will massively participate to decrease absorption properties. Furthermore, it is important to know that the presence of the flat-surfaced sand particles produces aggregates with sharp edges. These characteristics play an essential part in the hardened and fresh properties of concrete (Hussein et al. 2017).

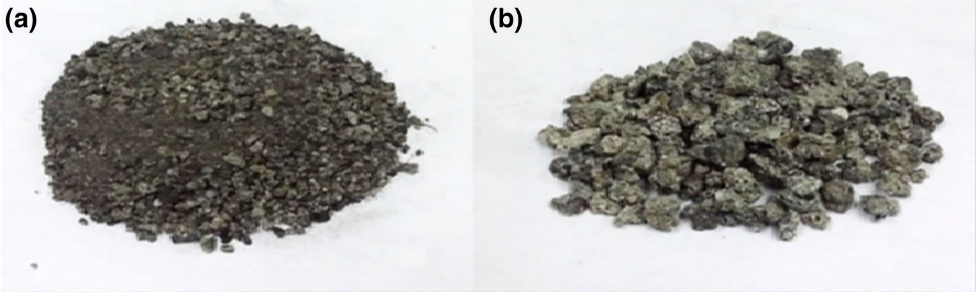

Fig. 3 POC aggregates: **a** POC fine aggregate and **b** POC coarse aggregate (Fuad et al. 2016)

Table 1 Physical characteristics of fine POC and coarse POC

Properties	Fine POC (Bashar et al. 2014)	Fine POC (Jegathish et al. 2018)	Fine POC (Rasel et al. 2016)	Fine POC (Jegathish and Hashim 2015)	Sand (BS 882 1985)	Coarse POC (Ibrahim and Razak 2016)	Coarse POC (Bashar et al. 2014)	Coarse POC (Afia et al. 2015)	Granite (Afia et al. 2015)
Aggregate size (mm)	< 5	< 5	< 5	< 5	< 5	12.5–4.75	5–14	4.95–9.5	5–14
Specific gravity SSD	2.01	2.17	2.12	2.11	2.66	2.08	1.82	1.88	2.65
Water absorption 24 h (%)	26.45	9.88	3.6	10 ± 5	1.2	3.56	4.35	3 ± 2	0.58
Moisture content (%)	0.11	–	–	–	0.08	–	0.7	–	0.28
Aggregate crushing value (%)	–	–	–	–	–	–	56.44	56.40	17.93
Bulk density (kg/m^3)	811	–	1025	–	1524	782.1	786	732	1294
Fineness modulus	3.31	3.37	3.12	2.71	2.89		6.75	6.73	6.33

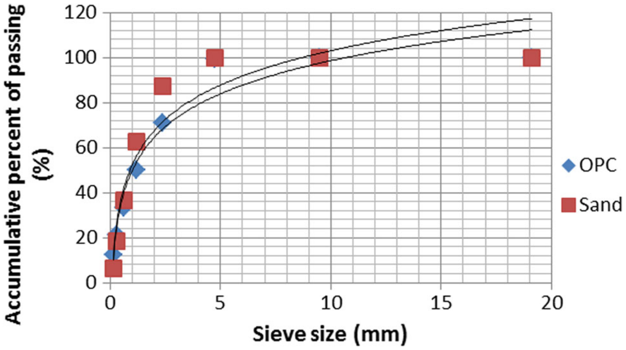

Fig. 4 Grading curve of POC and sand (BSI Document 1768)

2.1 Effect of POC on the Compressive Strength of Concrete

Bashar et al. (2014) studied the influence of coarse POC sized 14–5 mm as coarse aggregate replacement and fine POC below 5 mm as a fine aggregate substitution on flexural behavior of reinforced concrete beams. An experimental work was conducted using eight under-reinforced beams with varying reinforcement ratios (0.34–2.21%). Because of the high water absorption of POC, the aggregates were pre-immersed for 24 h in water before mixing. This was anticipated to avoid further absorption during mixing. The test results for compressive strength ranged between 25.5 and 42.56 N/mm^2. It was approximately 60% higher than the minimum required strength of 17 N/mm^2 for structural lightweight concrete recommended by ASTM: C330. All the experimented under-reinforced POC concrete beams exhibited typical structural ductile behavior. It was demonstrated that the POC concrete beam could provide prior caution to the imminence of failure. However, the ductility ratio of reinforced POC concrete beams dropped as the steel reinforcement ratio grew. It was evidenced that the crack width for POC concrete beams at service loads, ranging from 0.24 to 0.3 mm, was within the maximum allowable value as recommended by BS8110 for durability requirement.

Fuad et al. (2016) utilized coarse POC and fine POC as fine and coarse aggregate substitutions 10–100 % from the whole volume of fine and coarse aggregate. Coarse POC and fine POC were obtained by crushing POC to the required size. POC with a nominal size of 14 mm was recycled as coarse aggregate, whereas that with size below 5 mm was utilized as fine aggregate. Coarse POC and fine POC were prepared for saturated surface dry (SSD) before mixing. Compressive strength at 28 days for fine and coarse POC concretes is explained in Fig. 5. It is interesting to note that compressive strength of coarse POC concrete dropped to around 33.01 MPa at 100% coarse POC can be used as granite replacement in comparison with reference concrete. The highly permeable nature of POC coarse aggregate distinctly influenced the strength-carrying capacity of the concrete. Coarse POC aggregates were irregularly shaped with the huge amount of voids. The poor load-bearing capacity of the POC aggregate may be related to the vigorously porous and honeycombed structure of POC incited quick load expansion to fail easily. The availability of remarkable amount of voids or empty zones within the internal structure of POC aggregate was observed by the authors. Those voids reduced the density of the mix decreasing the load-carrying capacity of the hardened concrete mix (Bashar et al. 2014). In contrast, with 100% fine POC substitute sand, the strength gained was mostly identical to that of the control mix, exhibiting a comparable performance as shown in Fig. 6. In spite of having high amount of pores within the internal structure, aggregate of fine POC recorded higher strengths comparatively with coarse POC, most likely due to the size of the voids in the bulk concrete. In smaller size segments, fine POC was comparable with sand particles because these aggregates could make an identical packing arrangement as well as sand to prevent the massive formation of voids. The results for fine POC inclusions met the required strength of grade 40 concrete. The distinct decrease in the void ratio made POC comparable with sand and helps to preserve the strength of concrete.

Rasel et al. (2017) used POC powder (POCP) as filler and amorphous material in the production of sustainable and environmental friendly lightweight concrete. Furthermore, the entire substitution of virgin crushed granite coarse aggregate with coarser POC was assessed. Coarse POC was obtained by smashing large chunk of POC procured from oil palm mill using the laboratory jaw crusher and then sieved to various sizes between 5 and 12.5 mm. POC of size below 5 mm was further ground in Los Angeles (LA) grinding machine to enlarge its surface area so as to produce POC powder. POC powder was added as 5, 10, 15 and 20 % by weight of cement. Compressive strength after 56 days was improved for the entire mixture. POC concrete which consists of 5–15 % POC powder enhanced compressive strength in the scope of 53–67 % on

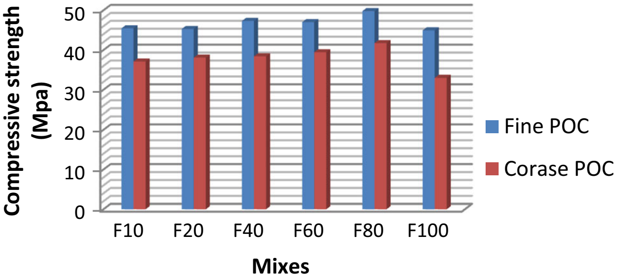

Fig. 6 Compressive strength for coarse POC and fine POC mixes

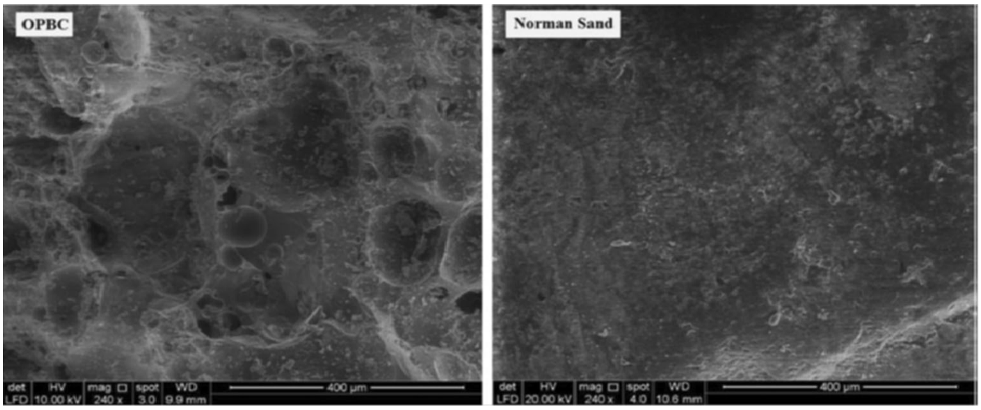

Fig. 5 SEM for surface texture of oil palm boiler clinker (OPBC) and normal sand (BS 882 1985)

the 1st day age of curing comparatively with reference mixture. POCP mixture which contained 15% powder recorded the highest compressive strength approaching 57 MPa which is 29% higher than the reference mixture. This juvenile was attributed to the nature of POC aggregate which is porous, and thus, the strength and stiffness of POC are low. In this way, the addition of POCP as filler would empower the concrete to achieve the most extreme compaction by filling the pores, become active as pozzolanic materials and improve the compressive strength. He declared that lightweight aggregate concrete (LWAC) of grade 45 can be produced using POC as lightweight aggregates with or without POC powder. Justs et al. (2015) illuminated that the addition of POC powder for decreasing effective w/c ratio had a constitutional effect on concrete by improving its compressive strength. Furthermore, the water absorption of POC aggregate was useful as it developed the internal curing of concrete, which demonstrated the process of concrete aggregates holding water and discharging it during cement hydration. Internal curing decreases autogenous shrinkage, and permeability consequently increases the durability of concrete by preventing microcracks.

Hussein et al. (2017) investigated the strength properties of pervious concrete (PC) containing palm oil clinker (POC) coarse aggregate under different curing regimes. Materials used in this study were cement and 10 mm nominal size of POC coarse aggregate as 0%, 25%, 50%, 75% to 100% by weight of granite. POCP was selected as appropriate filler to pre-coat the voids on the surface of the POC coarse aggregate. POCP was added as 3, 5, 10 and 18 % by weight of the binder. Elected curing regimes followed for palm oil clinker previous concrete (POCPC) were full water curing, air curing, 3- and 5-day water curing consecutively. Compressive strength at 28 days for POCPC generally decreased with the increasing level of POC replacement. It might be related to the high aggregate crushing value of 55.40% compared to granite with an aggregate crushing value of 17.93% as illustrated in Table 1. Besides that, the presence of pores inside POC and on its surface could decrease the compressive strength. However, the compressive strength of POCP achieved almost 90% of its strength at 100% POC substitution. Compressive strength showed less magnitude with merely 3.43 MPa for 100% coarse POC compared to reference concrete which has 9.51 MPa. However, compressive strength for full water and 3 and 5 days of water curing was somewhat higher than the specimens cured in air for each level of replacement. Compressive strength for samples cured in water, air and 3-day water curing was 9.5 MPa, 9.46 MPa and 9.5 MPa, respectively. Despite that, the strength values recorded a slight reduction in compressive strength for the air-cured samples with a maximum loss in strength of merely 5% as compared with the above curing. This finding was attributed to the fact that higher water absorption property of POC aggregate allows the water to be stored inside the pores of the aggregate which reduced the influence of swift loss of initial water needed for hydration of the concrete. In addition, an average temperature of 30.50 °C and 70.57% humidity were recorded throughout the period of air curing, whereas the temperature of water-cured specimen was 25 °C. Hussein concluded that exposing POCP to humid air during curing could aid in minimizing the strength loss.

Muhammed et al. (2016b) studied the effect of thermal activation on POC powder and its effect on compressive strength of cement mortar. POC obtained from palm oil mill contained 1–3 % of moisture; hence, it was oven-dried prior to crushing at a temperature of 100 ± 5 °C for half an hour. Firstly, the big chunks of POC were crushed using the jaw crusher. The smaller segments subsequent to crushing were then ground in a ball mill for 3 h at 150 RPM to make POC powder (POCP). This powder was sieved through 150 μm, and the powder passing sieve 150 μm was utilized for thermal activation. POCP was exposed to various heating patterns from room temperature to 300 °C, 650 °C and 580 °C, consecutively at the rate of 10 °C per minute, and maintained steadily for 3 h. The powder produced by thermal activation named as TPOCP. However, POCP was further ground in a ball mill for 30 min before mixing with cement. Two mixes were combined to make cement mortar by mixing sand with 70% cement and 30% POCP, TPOCP300, TPOCP650, TPOCP850, respectively. The chemical composition of POCP, TPOCP300, TPOCP650 and TPOCP850 is listed in Table 2 along with POC based on previous investigations. It is significant that the oxide substances grew within the heat treatment from 300 to 850 °C. This is mainly due to the unburned reduction which expels water and other impurities. However, most of the inorganic oxide still exists in the waste material (Jumaat et al. 2015). Different chemical compositions for POC are observed in Table 2. This may be attributed to the incineration temperature, operating circumstances and detention time of palm oil shell and fiber in the boiler of palm oil mills (Kanadasan and Razak 2015). Muhammed observed that the compressive strength of TPOCP850 mortar is higher than that of POCP mortar, which approached 60 MPa. He related it to the percentage of inorganic oxide which increased in TPOCP850 during thermal activation. The growing rate of SiO_2, Al_2O_3 and Fe_2O_3 in TPOCP was 3.4, 3.5 and 3.4%; consecutively, fibers were removed and porosity was significantly reduced; and eventually, compressive strength was enhanced.

Table 2 Chemical composition of POC and POCP and TPOCP

Oxides	POC (Payam et al. 2014)	POC (Jegathish and Hashim 2015)	POCP (Hussein et al. 2017)	POCP (Rasel et al. 2017)	$TPOCP_{300}$ (Mohammad et al. 2016b)	$TPOCP_{650}$ (Mohammad et al. 2016b)	$TPOCP_{850}$ (Mohammad et al. 2016b)
SiO_2	59.63	59.90	60.29	59.90	63.07	64.91	65.07
Al_2O_3	3.7	3.89	5.83	3.89	3.43	3.53	3.53
Fe_2O_3	4.62	6.93	4.71	6.93	6.52	6.71	6.73
CaO	8.16	6.73	3.27	6.73	6.92	7.12	7.14
P_2O_5	5.37	3.47	3.10	3.47	–	–	–
MgO	5.01	3.30	3.67	3.30	3.54	3.64	3.65
SO_3	0.73	0.30	0.11	0.39	0.09	0.11	0.11
TiO_2	0.22	0.29	0.13	0.29	0.22	0.22	0.22
L.O.I	–	–	–	1.89	3.51	0.12	0.11
K_2O	11.66	15.11	7.79	15.11	10.59	10.91	10.94

3 Oil Palm Shell (OPS)

In palm oil mills, the hard shells were directly obtained by breaking the palm kernel shells with machinery (Basri et al. 1999). OPS in various shapes was utilized as a coarse aggregate (Shafigh et al. 2010; Payam et al. 2011). The thickness of shells varied from 0.15 to 8 mm (Shafigh et al. 2010). Bigger sizes of OPS aggregates had a maximum thickness as exhibited in Fig. 7 (Payam et al. 2011). Mannan and Ganapathy recorded that high flakiness index of OPS approached 65% (Mannan and Ganapathy 2004). However, by squashing the bigger sizes of OPS aggregate, its flakiness evidently reduced and, as a result, brought about the superior performance of coarse aggregate and better compressive strength of concrete (Abdullah 1984). OPS was firstly used as lightweight aggregate to produce lightweight concrete in 1985 by Abdullah in Malaysia (Mannan and Ganapathy 2001a). Based on the outcomes of several studies, oil palm shell has the potential to be used as coarse aggregate so as to produce structural lightweight aggregate concrete (Mannan and Ganapathy 2001a, b). Original OPS (OPS directly procured from oil palm mill) has high flakiness index and a wide range of thickness. A lightweight concrete produced using OPS aggregate has normal compressive strength (Shafigh et al. 2010). The shape of OPS aggregate is differentiated between irregularly flaky shaped, angular and polygonal. The surface texture of the shell is genuinely smooth, and the broken edges are rough and pointy (Mohamed et al. 2017). However, if large sizes of OPS are discrete and then crushed, the crushed OPS will be hard and have a strong physical bond with hardened cement paste. Consequently, it is conceivable to produce high-strength lightweight concrete utilizing this agricultural solid waste (Shafigh et al. 2010). Pretreatments were performed on OPS aggregate; the raw OPS was washed, dried, crushed in crushing machine, sieved, immersed in water for 24 h and then dried to saturated surface dry condition before utilizing for casting (Basri et al. 1999; Shafigh et al. 2010; Payam et al. 2011; Mannan and Ganapathy 2001a, b, 2004; Abdullah 1984; Mohamed et al. 2017; Javad et al. 2017; Mohd et al. 2009; Alengaram et al. 2011; Kim et al. 2015, 2016). Physical properties of OPS are presented in Table 3. It is evident from Table 3 that the specific gravity of OPS ranged from 1.2 to 1.37, compacted bulk density varied from 600 to 678 kg/m^3, and

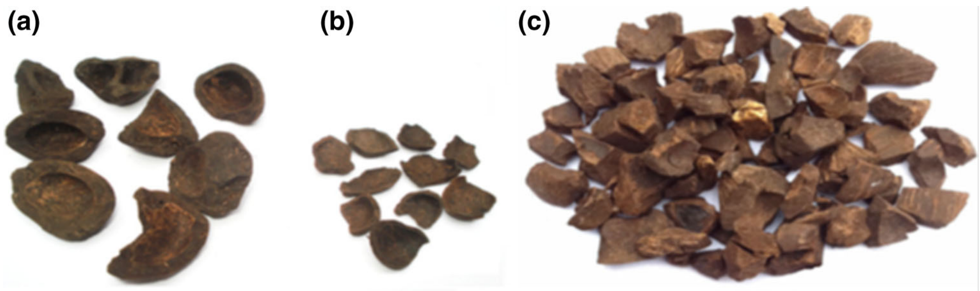

Fig. 7 OPS aggregates: **a** original large size, **b** original small size and **c** crushed from original large size (Payam et al. 2011)

Table 3 Physical properties of OPS

Properties	OPS (Ibrahim and Razak 2016)	OPS (Afia et al. 2015)	OPS (Payam et al. 2014)	OPS (Payam et al. 2011)	OPS (Mannan and Ganapathy 2004)	OPS (Abdullah 1984)	OPS (Mohamed et al. 2017)	OPS (Mohd et al. 2009)	OPS (Javad et al. 2017)	PS (Kim et al. 2015)
Maximum size (mm)	12.5–4.75	14–2.36	9–4.75	12.5	12.5	9–2.36	12.5	14–3.35	14–3.35	9–2.36
Specific gravity (SSD)	1.22	1.30	1.22	1.17	1.19	1.22	1.19	1.37	1.31	1.20
Water absorption 24 h (%)	23.52	20.25	18.7	23.30	20.67	18.73	20.60	23.8	19.3	28
Bulk density (compacted)	683	–	626	590	673	678	674	620	–	600
Fineness Modulus	6.23	5.98	5.98	6.24	5.78	5.72	5.87	6.54	–	–

fineness modulus ranged between 5.72 and 6.54. The above variations in physical properties of OPS within the literature may be explained as the previous researchers crushed OPS aggregate and sieved it to various sizes as shown in Table 3. According to BSI Document 92/17688 (BSI Document 1768), if the aggregates have less than 2.2 specific gravity and 1200 kg/m^3 bulk density, then the aggregates are classified as lightweight aggregates. Accordingly, OPS satisfies the criteria for structural lightweight aggregate. OPS recorded the highest magnitudes of water absorption from 18.7 to 28%. High water absorption of OPS can be explained through microscopic analysis using scanning electron microscope (SEM) as exhibited in Fig. 8. It indicates minimal pores of size varied from 16 to 24 µm on the convex surface of OPS surface which is accountable for high water absorption (Alengaram et al. 2011). The chemical composition of OPS is illustrated in Table 4 (Ibrahim and Razak 2016).

Table 4 Chemical composition of OPS (Ibrahim and Razak 2016)

Oxides	OPS
SiO_2	46.61
Al_2O_3	3.33
Fe_2O_3	10.19
CaO	14.76
P_2O_5	1.95
MgO	2.91
Na_2O	1.15
SO_3	7.84
Cr_2O_3	1.38

3.1 Effects of OPS on the Compressive Strength of Concrete

Kim et al. (2016) studied the compressive behavior of lightweight oil palm shell concrete (OPSC) consisting of

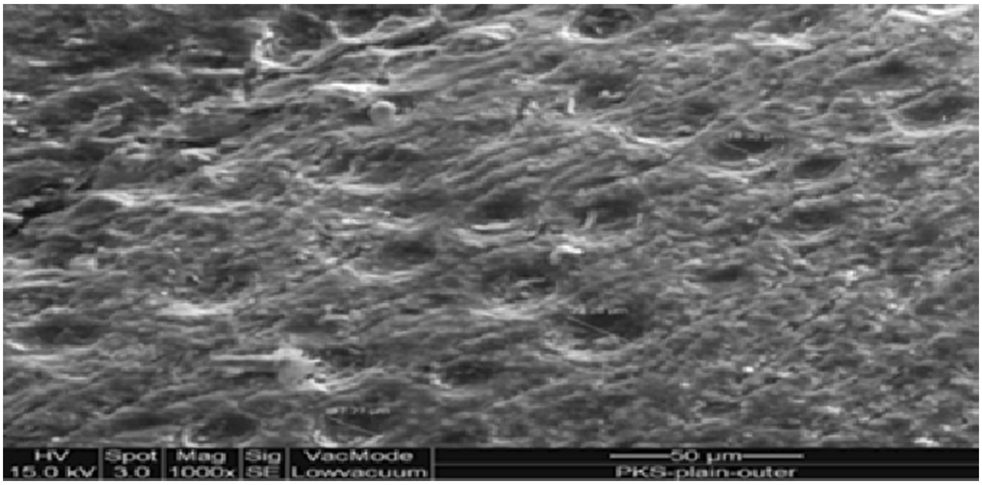

Fig. 8 Micropores on the outer surface of OPS (Alengaram et al. 2011)

ground granulated blast furnace slag (GGBS) as 20–60 % cement replacement. OPS with 1.35 specific gravity and sizes between 2.36 and 9 mm was utilized as coarse aggregate mixed along with quarry dust, cement and GGBS. OPS concrete (OPSC) was exposed to air and water curing. Results of compressive strength in air and water curing regimes are illustrated in Fig. 9. All OPSC samples exposed to water curing recorded higher compressive strength compared to the specimens cured in air curing. The water curing regime simplified continual hydration of the binder (OPC and GGBS), while the insufficiency of moisture for hydration in the samples exposed to air curing caused compressive strength reduction in the concretes. Essentially, a distinct variation in the compressive strength of around 40% was found between the OPSC specimens cured in water and air. This might be related to the sensibility of OPSC toward poor curing.

Mannan and Ganapathy (2004) examined the influence of using OPS as coarse aggregate on the compressive strength of OPSC. OPSC is made of cement, fly ash, OPS and sand cured in full water, partial water and full plastic. At the early stages, up to 56 days, the manner of compression failure in OPSC specified that OPS aggregates ruled the failure due to the broken cubes. It was related to the bond collapse between the paste and OPS aggregates. It stated that the bond between OPS and cement paste was weak because of organic effect and smooth surface of OPS. Possibly, it could pass through if OPS aggregates were treated with a lime solution before mixing (Elnaz et al. 2016). However, after 90 days of curing, the failure was more controlled by the bond strength of OPS paste rather than by the strength of OPS aggregate itself. OPS concrete was lighter than normal concrete. OPS concrete has higher porosity compared to traditional concrete as evidenced by air content of 5.1% in fresh OPS concrete (Mannan and Ganapathy 2001a). The porosity distinctly influenced the compressive strength. Mannan (2004) clarified that the strength, stiffness, thickness and density of OPS aggregate were the governed parameters for compressive strength of concrete. However, those parameters were lower for OPS in comparison with natural coarse aggregate. In addition, OPS aggregates consist of various shapes like roughly parabolic, circular or semicircular, flaky and other irregular shapes; hence, it also manipulates the development compressive strength of concrete (Mannan and Ganapathy 2001b). Mannan (2004) explained that the compressive strength of concrete was likewise manipulated by both the strength of aggregate and the strength of paste and relied on the first one to fail. Normal weight concrete has constant w/c ratio, but lightweight aggregate requires a lot of water due to its high absorption capacity. Compressive strength grew with the increase in cement content and based on the kind of aggregate used for a given workability. Therefore, the development of compressive strength of OPS concrete was lower than normal concrete. Payam et al. (2011) adopted a modern methodology to fabricate high-strength lightweight aggregate concrete (HSLWAC) using (OPS). OPS was washed and screened with a 9.5-mm sieve. OPS aggregates sized 9.5 mm were gathered and then squelched using jaw crusher available in the laboratory. Then, the squelched OPS aggregate was screened using sieve 2.36 mm to remove the OPS aggregate of less than 2.36 mm. They were weighed in dry room conditions and then soaked in water for 24 h. After that, they were air-dried in the laboratory to achieve almost saturated surface dry condition. Squelched OPS sized 2.36 mm and non-squelched OPS sized 12.5 mm were used. Compressive strength was investigated at various w/c ratios (0.350, 0.305, 0.354, 0.448 and 0.347). Compressive strength was found to have significantly increased with decrease in w/c as shown in Fig. 10. Overall, compressive strength smashed OPS concrete at 28 days was within the scope of 34–53 MPa which is 18% and 21% lower than normal concrete, respectively. By utilizing squelched OPS aggregate, it was conceivable to produce grade 30 OPS concrete with distinctly lower cement content comparatively with past detections. This is attributed to the fact that current OPS suggested in this study was bigger and thicker, and hence stronger and harder. Hence, detaching the greater size of OPS aggregates and then crushing them with a crushing machine will not only reduce flakiness index remarkably but also achieve higher stiffness for OPS

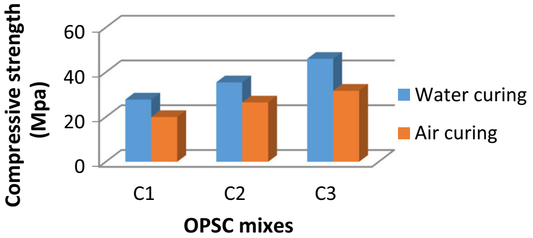

Fig. 9 Compressive strength of OPSC in air and water curing (Kim et al. 2016)

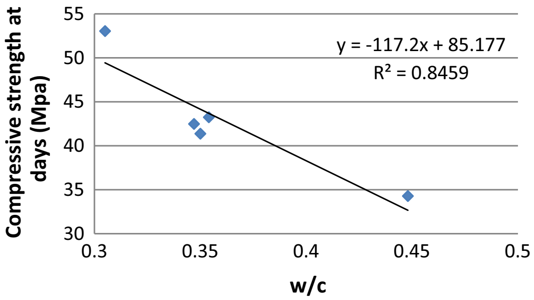

Fig. 10 Relationship between w/c and compressive strength (Payam et al. 2011)

aggregates. In spite of the fact that the surface texture of the concave and convex faces of OPS is completely smooth, the broken edges are rough and spiny (Mohamed et al. 2017) which creates a sturdy physical bond between the aggregate and the hydrated cement paste. Mechanical interlocking has significant contribution in strengthening the interface (Mannan and Ganapathy 2004). Consequently, by squashing the greater size of OPS aggregate, a big smooth surface will be separated into several smaller surfaces. Besides that, the entire broken edges of OPS aggregate will increase. In this investigation, squashed OPS aggregate with a supreme size of 8 mm was used.

Elnaz et al. (2016) produced a sustainable lightweight pervious concrete by substituting common coarse aggregate sized 6.30–9.50 mm with 4.75–6.30 mm and 6.30–9.50 mm OPS. OPS was sifted and separated into two diverse size classes: 4.75–6.30) mm passing from sieve 6.30 mm and retained on sieve 4.75 mm, and 6.30–9.50 mm passing from sieve 9.5 mm and retained on sieve 6.30 mm. Thereafter, they were washed and soaked in water for 24 h and then they were air-dried in the laboratory till saturated surface dry condition (SSD) was fulfilled. OPS sized (4.75–6.30) mm and (6.30–9.50) mm were used as 25–75% by weight of limestone. Compressive strength at age of 28 days for 25, 50 and 75 % OPS showed remarkable decline with a ratio of 27, 52 and 60% consecutively as well as compared with reference concrete. This was due to the replacement of gravel with OPS since OPS was capable of increasing the total void tenor of pervious concrete. Actually, original gravel had a round shape which permitted an ideal packing density of mix, while OPS possessed a curve and smooth shape and hence avoided the approach of virgin aggregates and criticized the granular arrangement, which eventually reduced the compactness. Furthermore, the porosity of OPS played a significant role in decreasing the compressive strength of pervious concrete as explained in Fig. 8, and SEM of OPS showed an extremely porous structure of OPS. In addition, the high absorption capacity of OPS was also accountable for decreasing the compressive strength of concrete. Payam et al. (2014) suggested a cleaner and more sustainable concrete using two types of agricultural waste procured from the palm oil industry as coarse and fine aggregates. For this objective, common sand was substituted with fine POC aggregate sized below 4.75 mm at 0, 12.5, 25, 37.7 and 50 % and OPS sized 9.5–4.75 mm was used as 100% coarse aggregate. Five curing environments were selected to investigate the effect of curing circumstances on the 28-day compressive strength of concretes. Curing regimes were air curing, water curing and partially water curing for 3, 5, and 7 days of water curing and then continued curing in a laboratory. The temperature of the laboratory was kept at 30 °C with 73% relative humidity. Compressive strength results indicated that OPS concrete comprised up to 25% POC aggregate gave an identical compressive strength to the reference concrete. Consequently, 25% POC as coarse aggregate was selected to become an optimum replacement level. It should be noted that strength and stiffness of aggregate were less than normal aggregate due to the porous nature of POC aggregate. However, it was observed that the replacement of natural sand with POC for more than 25% did not affect the compressive strength of concrete. The compressive strength for dry curing distinctly declined for reference concrete, whereas OPS concrete containing POC which underwent air curing had a slight reduction in compressive strength compared to the controlled mix. The only explanation for this behavior was the availability of conserved water inside the POC aggregate which provides internal curing for concrete. The compressive strength of partial water curing for 3 W, 5 W and 7 W is presented in Fig. 11. Partial water curing enhanced the 28-day compressive strength of all mixture comparatively with the air curing regime. The enhancement rate of compressive strength for 3 W, 5 W and 7 W was 1.7–4 MPa, 3.3–4.7 MPa and 3.2–4.7 MPa, consecutively. It was observed that the efficiency of the curing methods of 5 W and 7 W was higher than 3 W, while the 5 W and 7 W curing regimes exhibited an identical effect on the compressive strength of concrete. Therefore, 5 W was recommended for partial water curing.

Ibrahim and Razak (2016) investigated the compressive strength of high-strength lightweight concrete (HSLWC) using coarse POC as the substitution for OPS. POC was used as 25–100 % OPS as coarse aggregate in concrete. Both OPS and POC were obtained from oil palm mill and squashed using stone crusher. Particles of size ranging between 12.5 and 4.75 mm were used as coarse aggregate in concrete. Compressive strength was dramatically improved with the growth of POC content as shown in Fig. 12; the most extreme compressive strength was recorded at 100% POC replace OPS. The strength capacity of lightweight aggregate concrete (LWAC) depended on the strength of lightweight aggregate (LWA), the hardened

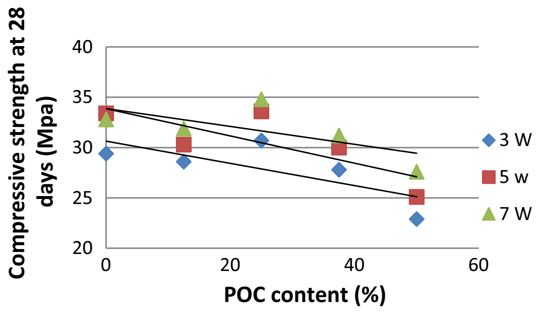

Fig. 11 Results of compressive strength at various POC contents (Payam et al. 2014)

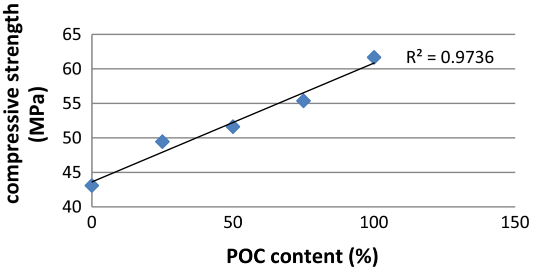

Fig. 12 Compressive strength at various POC contents (Ibrahim and Razak 2016)

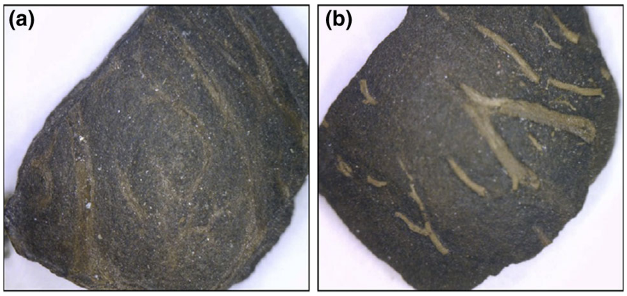

Fig. 13 **a** Concave of OPS and **b** convex of OPS (Ibrahim and Razak 2016)

mortar and the powerful bond between mortar and aggregate in the interfacial zone of aggregate. Alengaram et al. (2011) related the fail of OPS concrete at 28 days to the bonding collapse between aggregate and mortar. One of the essential shortcomings of OPS was the weak bond between the flat concave and convex surfaces of OPS as identified in Fig. 13. Mannan and Ganapathy (2001b) stated that the weaker interfacial bond is caused by the smooth concave and convex surfaces of the OPS aggregate. De-bonding between aggregate surface and mortar caused concrete deterioration and therefore decreased compressive strength of concrete. On the other hand, POC permeable surface texture developed the bonding of POC aggregate and mortar. Since the mortar occupied the pore, it reinforced the bond. In addition, the load-carrying mechanism was improved by the sustained reaction of POC because of the agglutinating mortar that transported the load to POC.

Afia et al. (2015) studied the mechanical properties of local OPS lightweight geo-polymer concrete. Six mixes were adopted in this study: Mixes M1–M5 have 50% quarry dust + 50% POC as fine aggregate, and OPS was used as coarse aggregate of 100, 80, 60, 40, 20, 0 % by weight of granite. However, mix M6 has 100% granite as coarse aggregate, and 25% quarry dust and 75% POC as a fine aggregate was used as granite replacement of 0–100 % by weight of granite. Compressive strength at 28 days significantly increased from M1 to M5 and recorded 25, 26.04, 30.4, 36.0, 38.0 MPa, respectively. Compressive strength decreased with the increase in OPS content. However, M6 had a remarkable drop in compressive strength to merely 17 MPa. Afia explained the compressive strength reduction of OPS concrete to the de-bonding between mortar and aggregate, and the smooth surface of OPS weakened the bond, while M6 which contained 75% POC and 25% quarry dust had gained less strength because of the high water absorption of POC and packing ability. However, results for compressive strength lightweight concrete satisfied Eurocode 2 which recommended minimum compressive strength for structural lightweight concrete to 20 MPa (Table 4).

4 Discussion

A summary of previous investigations on effects of POC and OPS on compressive strength of concrete within the previous literature is presented in Table 5. Considerable studies were conducted on POC as lightweight aggregate. POC recovered from oil palm mill in the form of a big chunk, however, was crushed using jaw crusher and sieved to either around 9–4.75 or below 4.75 mm to be recycled as coarse and fine aggregate, respectively. According to Shafigh et al. (2010), the water absorption of POC was higher than common aggregate due to the permeable texture of POC grain. Hence, POC possessed a larger surface area compared with the sand particles. This outcome is proven in Figs. 5 and 6 which exhibits the scanning electron microscopy image for surface texture of POC and sand particle. It is evident from Figs. 5 and 6 that POC had higher porosity trend; besides, some holes were found on POC surface. Consequently, when a fraction of virgin sand was replaced with POC, a portion of mixing water was sucked by POC aggregate whereby the active water-to-cement ratio decreased and compressive strength developed. Accordingly, the advantages obtained from POC aggregate for decreasing the active water-to-cement ratio were more than the shortcomings of POC when the common aggregate was replaced by weak POC. Table 5 shows the summary of the previous detections on utilizing POC and OPS as lightweight aggregate in concrete. It is evident that fine POC could be used as a partial replacement to fine aggregate in the range of 25–50% by weight of sand (Kanadasan and Hashim 2014; Ibrahim and Razak 2016), (Payam et al. 2014). Coarse POC could be used as 50% by weight of granite in concrete according to Hussein et al. (2017). POCP was introduced as a valuable filler material which showed a significant enhancement on compressive strength of concrete when used as 15% cement additive (Rasel et al. 2017). It should have a superior compressive strength in concrete approaching 55 MPa when used as 30% cement replacement (Mohammad et al. 2016b) as

Table 5 Summary of the use of POC and OPS in concrete

Author	Replacement ratio	w/c	Range of compressive strength	Optimum dose
Bashar et al. (Bashar et al. 2014)	Coarse POC as 100% granite replacement and fine POC as 100% sand replacement	–	25.50–42.56 MPa	–
Fuad et al., (Fuad et al. 2016)	Fine POC 10–100 % sand and coarse POC 10–100 % as granite	0.53	41.75–33.01 MPa for coarse POC mixes and 47.34–44.96 MPa for fine POC mixes	12% coarse POC and 100% fine POC
Rasel et al. (Rasel et al. 2017)	Coarse POC as 100% granite replacement and POCP as filler of 5,10,15, and 20 % by weight of cement	0.45	57.70–45.15 MPa	15% POCP
Hussein et al. (Hussein et al. 2017)	Coarse POC as 0–100% by weight of granite	0.3	3.43–9.51 MPa for CPOC cured in water, 3.37–9.46 MPa for CPOC cured in air and 3.39–9.5 MPa for CPOC cured in water for 3 days	50% of coarse POC as granite replacement and for POC concrete cured in water
Muhammed et al. (Mohammad et al. 2016b)	POCP, TPOCP$_{300}$ TPOCP$_{600}$, TPOCP$_{850}$ as 30% cement replacement	0.40, 0.50	60 MPa for TPOCP$_{850}$ 55 MPa for POCP	30% TPOCP$_{850}$ by weight of cement
Kim et al. (Kim et al. 2016)	OPS as 100% coarse aggregate and 20–60 % GGBS as cement replacement	0.40	24.4–46.0 MPa for water-cured OPSC and 12.5–20.2 MPa for OPSC cured in air	20% GGBS at water curing regime.
Mannan et al. (Mannan and Ganapathy 2004)	OPS as 100% coarse aggregate	0.4	12.61–30.05 MPa for OPSC cured in water, 12.61–24.74 MPa for OPSC cured in partially in water, 11.51–29.69 MPa for OPSC cured in plastic film	OPS as 40% of concrete volume with 480 kg/m^3 and 10% fly ash
Payam et al. (Payam et al. 2011)	OPS as 100% coarse aggregate	0.35, 0.30, 0.35, 0.44, 0.34	34–53 MPa	–
Elnaz et al. (Elnaz et al. 2016)	0–75 % OPS as coarse aggregate + limestone as 25–75 % by weight of OPS sized 6.30–9.5 mm	0.32	6–12 MPa	25% OPS of size 4.75–6.30 mm and 25% limestone of size 6.30–9.5 mm
Payam et al. (Payam et al. 2014)	OPS as 100% coarse aggregate and 0, 12.5, 25, 37.5, and 50 % of POC as sand replacement	0.38	37.8–31.2 MPa for water curing, 27.8–30.7 MPa for 3 W, 25.1–33.6 MPa for 5 W and 27.6–34.8 MPa for 7 W	25% POC
Rasel et al. (Ibrahim and Razak 2016)	Coarse POC as 0–100 % by weight of OPS	0.36	43.09–61.67 MPa	Coarse POC as 100% by weight of OPS
Afia sharmin et al. (Ibrahim and Razak 2016)	OPS as 0–100 % by weight of granite, 50% quarry dust and 50% POC as fine aggregate	0.5	24–38 MPa	50% quarry dust and 50% POC

shown in Table 5. The compressive strength of concrete incorporated OPS as coarse aggregate replacement deteriorated beyond 25% OPS as granite replacement (Elnaz et al. 2016) although it was 20 MPa higher than the range of compressive strength required for structural lightweight concrete (LWC) as indicated in Table 5. This is explained by Mannan and Ganapathy (2001a, b) that OPS concrete collapse at 28 days essentially relied on the bond breakage between aggregate and mortar, whereas OPS concrete failure was restricted upon failure of OPS aggregate at later ages of 90 days. It can be concluded from the literature that the flat surface texture of the OPS for both concave and convex faces represented the essential cons of OPS aggregate. The strength, stiffness, thickness and density of OPS aggregate were the influential parameters for compressive strength of concrete. However, those parameters were lower for OPS compared to natural coarse aggregate. In spite of that, most of the compressive strength values were within the normal range, which is about 20 MPa as shown in Table 5. The compressive strength of LWC mainly relied on the hardened cement paste, the strength of LWA and bond strength between aggregate and mortar in the interfacial zone (Alengaram et al. 2011). However, coarse POC has been introduced as coarse aggregate replacement of OPS (Ibrahim and Razak 2016). The compressive strength of concrete was improved upon using 100% coarse POC as a replacement to OPS as evidenced in Table 5. By comparing physical properties of OPS and coarse POC of size 12.5–4.75 mm from Tables 1 and 3, it is interesting to observe that POC had higher specific gravity, fineness modulus and compacted bulk density which were significantly higher than OPS. On the other hand, the lower 24 h water absorption of 3.56% obtained for POC aggregates was dramatically less than water absorption of OPS which was about 24%. In addition, it was demonstrated that the use of POC lightweight aggregate in concrete mixture provided internal curing for concrete, which helped to promote the hydration of cement. Hence, the recommended early age curing might be reduced when using POC in the lightweight aggregate concrete; thus, the curing cost will also be significantly reduced.

5 Conclusions and Future Recommendations

Based on the above review on the effects of palm oil clinker and oil palm shell as a lightweight aggregate on the compressive strength of concrete, conclusions and future recommendations will be addressed accordingly:

1. The accumulations of palm oil clinker and oil palm shell have resulted in a hazardous menace; hence, reusing these wastes in constructions has significantly lessened their negative impacts on the surroundings.
2. POC was utilized as fine and coarse aggregate replacements. However, evidently the compressive strength of 100% fine POC decreased. Therefore, approximately 50% of fine POC gave sufficient compressive strength for lightweight concrete.
3. POCP, as filler, showed significant improvement in the compressive strength of concrete. The optimum dose of POCP as the powder was fixed at 15% by weight of the binder. Furthermore, TPOCP was presented as 30% cement replacement. The recycling of POCP as cementitious materials will distinctly reduce the amount of carbon dioxide (CO_2) emission through cement production.
4. Oil palm shell (OPS) is an agricultural waste procured from oil palm mill through the breakage of oil palm kernel shell. An OPS was used to produce lightweight concrete as coarse aggregate replacement. However, the compressive strength generally decreased with the increment of OPS as coarse aggregate due to the smooth surface texture of the shell for both concave and convex faces, hence weakening the bond between aggregate and mortar.
5. Coarse POC showed a good inclination to be used as coarse aggregate instead of OPS because of the rougher surface of POC which produced a good bond between aggregate and mortar. Moreover, POC had less water absorption comparatively to OPS; hence, higher water absorption negatively affected the compressive strength.
6. Future studies should focus on methods of treatments for OPS so as to enhance the properties of OPSC when used as coarse aggregate in concrete. Further detections should focus on using POCP as a cementitious material in various cement composites.

Acknowledgements The authors of this work would like to express their utmost gratitude and appreciation to the Centre for Graduate Studies (CGS) in Universiti Tun Hussein Onn Malaysia (UTHM) for their financial support.

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