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A review on application of oil palm shell as aggregate in concrete - Towards realising a pollution-free environment and sustainable concrete

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ABSTRACT

The considerations for using alternative materials as coarse aggregate in construction industry is driven by the needs to conserve natural resources, reduce the huge amount of greenhouse gas emission and environmental degradation related to conventional aggregate. Efforts to alleviate food insecurity has resulted in increased agricultural activities across the world. However, the processing of agricultural produce generates huge amount of residues as by-products the disposal of which is of great concern. Oil palm shell (OPS) which is a by-product from oil palm industry has shown potentials as an alternative to the conventional aggregate in concrete production. OPS is a suitable material for the production of structural lightweight aggregate concrete having better thermal insulation, reduced density of roughly 20 to 25% less than conventional aggregate concrete, and a 28-day compressive strength greater than 17 N/mm^2. Previous studies on the properties of OPS, fresh and hardened properties of OPS concrete, as well as its eco-efficiency and environmental aspects are summarized in this paper. In addition, the various improvement techniques employed on OPS and OPS concrete that resulted in improved OPS concrete performance are also highlighted. With large quantities of OPS produced in tropical parts around the world, its total adoption as aggregate in these regions is still fairly limited. Long-term studies on mechanical strength, thermal and durability properties of OPS concrete are recommended to promote the usage of OPS as aggregate in actual structures.

1. Introduction

The concrete components which are in granular or particulate form are generally regarded as aggregates (Alexander and Mindess, 2010). Aggregates are considered the most-abundantly-used materials, besides soil and water since it constitutes up to 75% of the total volume of concrete (Neville, 2008; Deepa et al., 2010). Aggregates are employed in construction industries as ingredients in concrete production, asphalt mixtures, ballast and fill materials, for road bases and formations, for decorative purposes, filter and drainage media, and for various manufacturing processes such as metal casting, fluxing amongst others. Therefore, the use of aggregates is related to the infrastructural development of a country.

According to Bamigboye et al. (2020), the rising trend in the use of conventional materials used for construction worldwide is largely attributed to the continuous growth in the global economy and standard of living. However, the extraction and production of conventional aggregates used for construction results in carbon dioxide (CO_2) emission through fuel, electricity and explosives during processing and transportation. Depletion of natural resources and environmental issues such as soil erosion, noise pollution, loss of natural ecosystem, poor water quality and lowering of water table are other challenges resulting from over dependence on conventional aggregates as construction material (Hamada et al., 2020). Numerous studies have been conducted in recent decades to identify alternative construction materials based on natural resource protection needs and the environmental and economic consequences associated with the continued use of conventional materials. Various synthetic or manufactured materials such as foamed slag expanded clay, expanded shales, expanded perlite, expanded slate, expanded polystyrene and sintered fly ash (Leyte), artificial cinders, coke breeze, bloated clay, exfoliated vermiculite, thermo Cole beads were found applicable as alternative to conventional aggregates especially where lightweight aggregate concrete (LWAC) is anticipated (Vakhshouri and Nejadi, 2017). However, these materials are not economical and their production is also a source of environmental pollution. According to Owen and Newman (2003), manufactured lightweight aggregates (LWAs) have been constrained for use in concrete production by not only the raw materials and method of processing but also the high cost of these materials. Therefore, attentions have been shifted to agricultural by-products instead of synthetic or manufactured as alternative to conventional aggregates.

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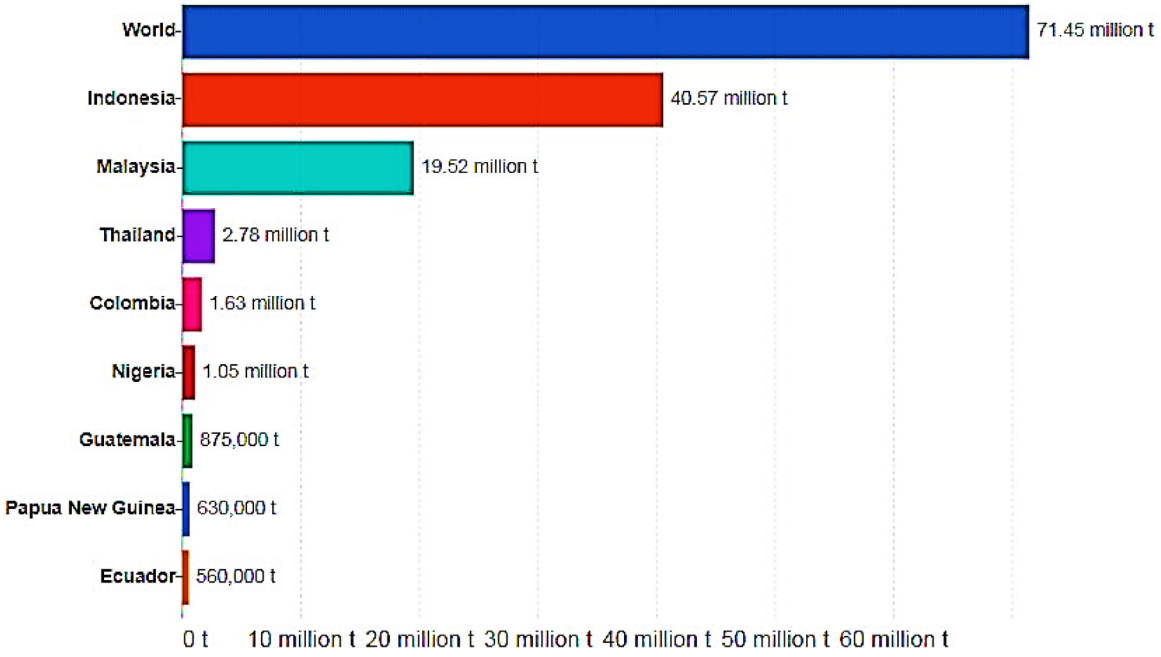


Fig. 1. Oil palm production in the eight (8) leading producing countries, 2018.
Source: Ritchie and Roser (2021).

Solid agricultural by-products such as OPS, coconut shell, periwinkle shell, date seed, walnut are the suitable alternative to synthetic or manufactured materials for use as LWA in concrete production because of their low cost, environmental friendliness and availability in the area where they are being produced in large quantity. Several studies have shown that the use of these materials in concrete production began around three decades ago, and since then, a large and growing body of studies have been carried out using these materials as alternative to conventional aggregates (CAs) for the production of concrete. The global oil palm production was estimated as 71.45 million tonnes in 2018 (FAO, 2018). The oil palm production from the eight (8) leading oil-producing countries is presented in Fig. 1. Nigeria was ranked the fifth largest oil palm producer in the world after Indonesia, Malaysia and Thailand and the first in Africa with the total output of 1.05 million tonnes in 2018 (FAO, 2018). Oil palm is grown in the southern part of Nigeria especially in the wet rain forest and savanna belt and also in the wet parts of North Central Nigeria (Ekenta et al., 2017).

The processing of palm fruit for palm oil and palm kernel extraction creates many wastes (empty bunches of fruit, palm oil fibre, palm oil effluent, OPS) which, when not properly disposed of to the environment, are toxic to living organisms (Das et al., 2016). OPS is a solid waste material which is obtained as a by-product from the processing of oil palm fruit (Kareem et al., 2022). The cross-section of oil palm fruit consists of the outer skin, the exocarp, follow by three inner layers (Fig. 2). The first inner layer or mesocarp provides the palm oil while the layer next to mesocarp is the hard shell, the endocarp known as OPS which housed the inner layer identified as palm kernel, the source of palm kernel oil and palm kernel cake used as livestock feed. OPSs constitute an estimate of 5.5% of the palm fruit bunches from oil palm trees (Teo et al., 2006; Afeti, 2016) and 10–11% of palm fruit from palm fruit bunches (Poku, 2002).

In the developing countries that constitute the world's main oil palm producers, the use of some of these wastes has not been extensively explored. Thus, large quantity of these shells is still stockpiled and subsequently dump as residue thereby constituting a nuisance and environmental pollution especially in an area where they have been accumulated in large quantities (Fig. 3). However, dried broken OPS has been found to be useful as a source of fuel for cooking, boiling and burning bricks (Obeng et al., 1997), but alternative sources of fuel are sought instead of OPS due to silicates that form a scale in the boilers, especially when too many shells are fed to the furnace. This limits the amount of shells that can be used in the boiler (Poku, 2002). Therefore, the use of these materials for construction purposes as an environmentally sustainable means of disposal has been considered.

The potential of OPS as full or partial replacement for CA in the production of structural lightweight aggregate concrete (SLWAC) and affordable concrete with good insulation and thermal properties have been established in several studies (Yew et al., 2014; Khan et al., 2016; Williams et al., 2014; Maghfouri et al., 2018; Aslam et al., 2017). Furthermore, the use of OPS is a useful measure for minimizing the use of CAs. The incorporation of OPS into normal weight aggregate (NWA) generally results in lower workability and mechanical strength concrete which further decrease with increasing addition of OPS in concrete based on the findings from past researches. Furthermore, the higher water absorption rate of oil palm shell concrete (OPSC) compared with normal weight concrete (NWC) which further increases with increasing OPS content is responsible for the poor durability performance of OPSC. Numerous studies in recent past have shown the possibility of achieving the minimum of 17 MPa specified by ASTM C 330/C330 M (2014) for SLWAC at the optimum level of replacement of NWA with OPS at 28-day curing age. In addition, the performance of OPSC has been enhanced to develop high-strength OPSC capable of fulfilling several engineering applications through various improvement techniques such as pre-treatment of OPS or blending of mineral admixture with OPSC.

The use of OPS as an alternative aggregate in concrete production is a positive development towards achieving a sustainable concrete production as it requires little or no energy in sourcing for it, whereas NWA, which demands a significant amount of energy during extraction and processing, resulting in CO_2 emission. The techno-economic advantages of OPSC include reduced concrete self-weight and structural member sizes, increased construction progress, and lesser haulage and handling charges, all of which translate into lower construction costs with OPSC. The socio-economic benefits of OPSC include the reduction of environmental pollution as it provides environment-friendly way of disposing OPS, motivation for expand oil palm production by the produc-

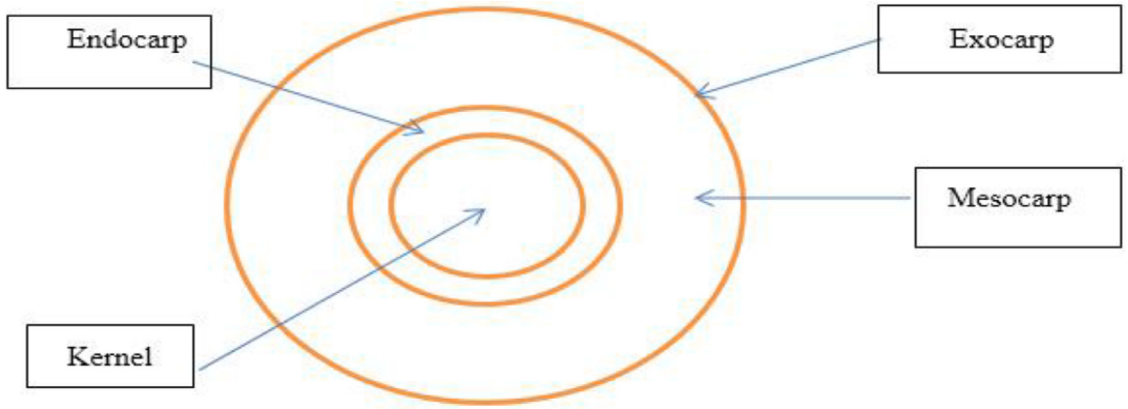




Fig. 2. The palm fruit.
Source: Afeti (2016).



Fig. 3. Sections of OPS deposit at oil palm processing industries.
Source: Teo et al. (2006).

ing areas, leading to increase in farmers earnings, economic incentive of the growing community and the country's gross domestic product. The socio-economic benefits of OPSC include reduced environmental pollution because it provides an environment-friendly method of disposing of OPS, motivation for expanding oil palm production by producing areas, resulting in increased farmer earnings, and economic incentive for the growing community, and increase in the country's GDP. This review discusses the chemical, structural, and physical properties of OPS as well as the functional, eco-efficiency and environmental aspects of OPSC. Recommendations are made to facilitate the widespread acceptance of OPS as aggregate in concrete production.

2. Preparation of OPS

The significance of preparing OPS is to remove the fibres, oil, dust, mud particles, organic impurities and other undesirable materials before using it for concrete production. OPSs are generally prepared by cleaning its surface by natural weathering and washing with detergent.

The presence of surface coatings like oil, clay, silt or fine dust interfaces with bond and cement paste and leads to increase in the quantity of water necessary for hydration (Neville and Brook, 2010). The presence of fibres in OPS increases its water demand and reduces the contact area between OPS and mortar resulting in weak interfacial transition zone (ITZ) which consequently affects the properties of OPSC. Old type of OPSs which has been discarded in the open air for more than six months contains fewer fibre content than the fresh OPS (Khan et al., 2016; Williams et al., 2014; Maghfouri et al., 2018; Mannan et al., 2006; Shafigh et al., 2011; Yew et al., 2014). The choice of detergent for washing OPSs was due to its ability to boost OPS washing performance and decrease its environmental effect by up to 50% (Foong et al., 2015).

Pre-treatment protects OPSs against water penetration and provide better adhesion between OPS and cement matrix. Mannan et al. (2006) achieved OPS with low water absorption rate and better mechanical strength after treating OPS with Polyvinyl alcohol (PVA). Similar observations were also revealed by Thong et al. (2015, 2017), Saranya et al. (2018), and Chai et al. (2014b, 2014a). The surface treatment has influence on the quality of OPSC. Djima et al. (2018) also reported the possibility of using lime for the treatment of OPS. Traore et al. (2018) found significant improvement in mechanical properties of OPSC using various pre-treatment and coating systems of OPS. Ramasamy et al. (2008) observed positive effects after the treatment of OPS with sodium hydroxide (NaOH) compared with those treated with acid, salt and normal water. Yew et al. (2014) found improved mechanical properties for OPSC with, and without, mineral admixture by using OPS heat-treated at 60 °C over a period of 0.5 h. Furthermore, Lee et al. (2019) observed higher mechanical strengths which were significant at the early age for the OPSC produced with OPS treated by soaking in hot water at the temperature of 50 ^{O}C compared with that produced with OPS treated with common laboratory water at room temperature of 26 ^{O}C for 20 min. Similar pre-treatment method was adopted by Sofyani et al. (2018).

3. Properties of OPS

3.1. Structures of OPS

OPSs shape can be convex and concave with smooth surface on the outer convex side and usually hard and porous in nature (Wasiu et al., 2015; Teo et al., 2007; Alengaram et al., 2011). Crushed OPSs have spiky edges compared with raw OPSs (Sobuz et al., 2014; Khankhaje et al., 2016). OPS is heterogeneous in nature and consists of micro-pores at the smooth outer surface as illustrated in the scanning electron microscope image in Fig. 4. However, the pores in OPS could be of significant benefit in the production of pervious concrete and SLWAC with better acoustic and insulation properties (Khankhaje et al., 2016; Okpala, 1990; Serri et al., 2014; Serri et al., 2014; Khankhaje et al., 2017; Traore et al., 2017). Several studies (Shafigh et al., 2012; Olanipekun et al., 2006; Mo et al., 2015) have attributed the high rate of water absorption and permeability of OPSC to high porous nature and connectivity of the pores in OPS. It was also reported that the water absorption rate increases as the content of OPS in concrete mix increases (Maghfouri et al., 2018; Shafigh et al., 2012; Olanipekun et al., 2006).

3.2. Chemical properties of OPS

The chemical analysis of OPS revealed that it contains several oxide, chemical compounds and elements as shown in Table 1. The variations observed in OPS properties can be attributed to several which include species or varieties, climate, geographical location, origin of OPS, treatment and processing methods (Hamada et al., 2020). Typically, OPS contains SiO_2 followed by Al_2O_3, CaO and MgO contents as the major component. The chemical properties of OPS are influenced after the surface treatment of OPS as it exhibits higher CaO and MgO but lowers SiO_2, Al_2O_3, SO_3, loss on ignition compared to the untreated OPS. According to Krishnamurthy and Vandanapu (2019), high Al_2O_3 is responsible for the higher water absorption rate of OPS while lower MgO is responsible for its lower crushing value than the NWA. The major elemental constituents present in OPS are carbon, lignin and hemicellulose. Thus, the quantity of OPS to be used for structural application should be examined due to its possibility of generating high amount of heat when exposed to elevated temperature. The XRD pattern (Fig. 5) shows that OPS is largely amorphous which indicates the presence of high lignin and hemicellulose in OPS. The crystal peaks observed in the XRD pattern revealed the presence of SiO_2, oleic acid which are components derived from OPS, palm oil and palm kernel oil.

3.3. Physical properties of OPS

The physical properties (shell appearance, shape thickness and size, water absorption, specific gravity, bulk density, moisture content, fine modulus, flakiness index and elongation index) of OPS are presented in Table 2.

3.3.1. Shell appearance, shape, thickness and size

The shape, surface texture, size and thickness of OPS are important factors influencing the performance aggregates in plastic and hardened state in terms of its workability, water requirements, cement content, strength and durability (Alexander and Mindess, 2010; ACI Education Bulletin E1 1999; McNeil and Kang, 2013). OPS is dark grey to black in colour and has shell thickness approximately 0.15 to 8.0 mm as revealed in Table 2. OPS thickness varies, depending on the species and age categories (Hamada et al., 2020; Yew et al., 2014; Okpala, 1990). OPS thickness is generally lower than that of NWA (Alengaram et al., 2011, 2010; Mahmud et al., 2009). OPS has no definite shape and its edges could be rough or spiky and often varies from irregular, angular and polygonal depending on the method of breaking the nut (Hamada et al., 2020; Okpala, 1990; Basri et al., 1999; Shafigh et al., 2010; Adesina et al., 2020).

3.3.2. Particle gradation, fineness modulus

The choice of suitable aggregate for concrete mix is determined from particle-size distribution analysis (Hamada et al., 2020). As shown in Fig. 6, the OPS used in past researches for OPSC and mostly within the upper and lower limits specified by ASTM C 33/C 33 M (2013)) and BS 882 (1992) indicating the uniformity of OPS. The inclusion of larger size OPS usually affects the compactness and reduces the workability of concrete resulting to the production of less dense concrete with many voids (Djima et al., 2018). However, increasing in the proportion of sand with respect to cement content or increasing the proportion of fine content of OPS, relative to the maximum size OPS content, can enhance the compactness and workability of concrete (ACI Education Bulletin E1 1999).

The fineness modulus is a useful parameter necessary for the estimation of the proportion of aggregates in concrete mixture (Kosmatka and Wilson, 2011). It is also useful in identifying the variation in aggregate from the same source which can impact the workability of fresh concrete. Table 2 reveals that the fineness modulus of OPS varies from 5.64 to 6.53%. According to Kosmatka and Wilson (2011), a higher value of fineness modulus indicates coarser grading with wide variations of particle which greatly affect the workability of concrete. However, more water and cement are required for the concrete mix to have smaller size aggregate due to the increase in total aggregate surface area.

3.3.3. Percentage of voids, specific gravity and bulk density

Void ratio of aggregate is a factor which determines the tendency of material to allow the ingress of liquids and gases under a pressure gradient. The use of aggregate with high percentage of voids results into the production of concrete which is highly porous and has low density and high water-absorption. However, the high void contents allow OPS to hold more water in its pores than NWA

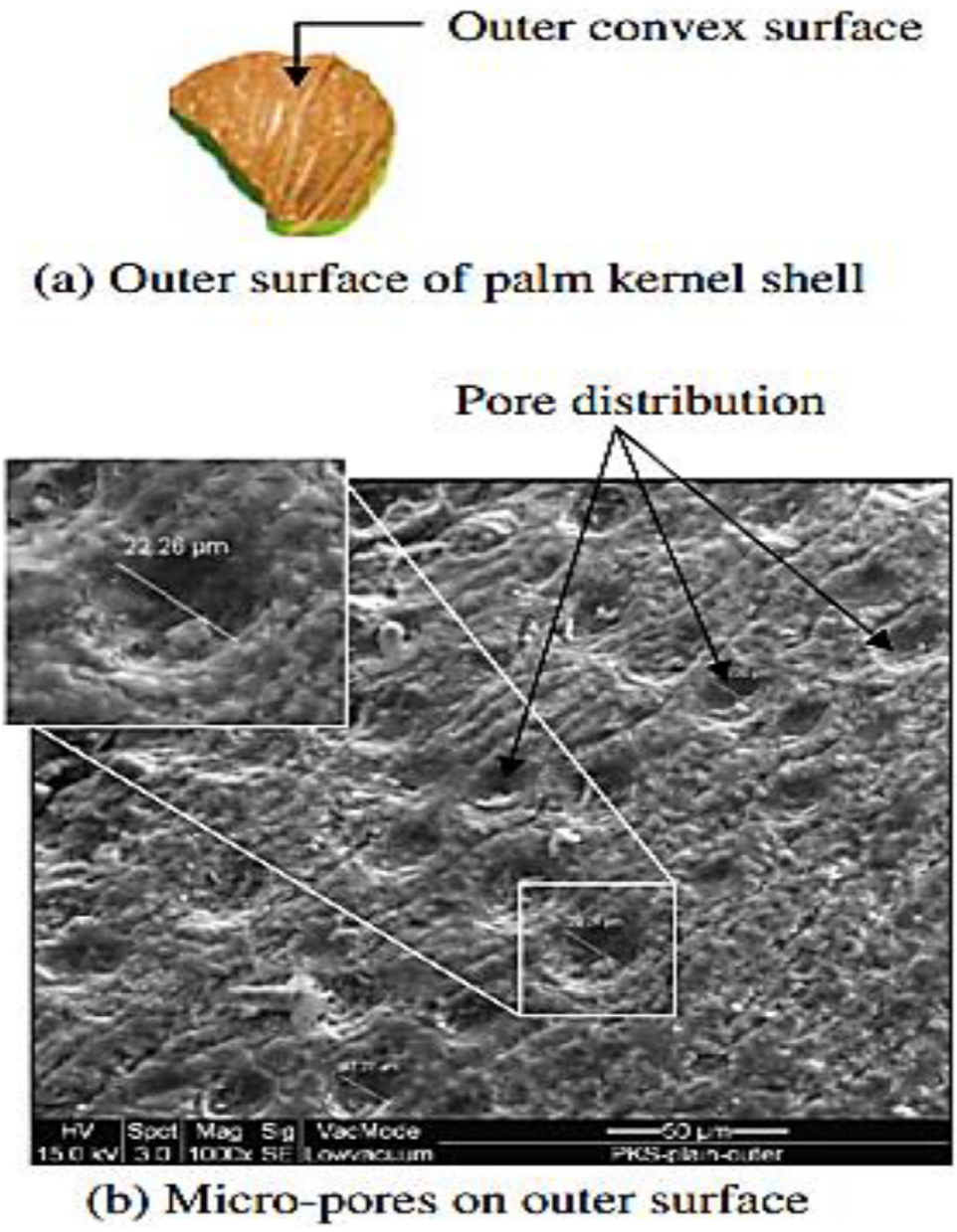


Fig. 4. OPS and its SEM image>.
Source: Alengaram et al. (2011).

(Alengaram et al., 2011, 2010, 2010; Zanariah et al., 2018; Ndoke, 2006; Mannan and Ganapathy, 2002, 2004; Jumaat et al., 2015; Mahmud et al., 2009). The porosity of aggregate increases with increase in aggregate void ratio. Therefore, the porosity of aggregate is important due to its influence on the overall permeability of concrete (Alexander and Mindess, 2010). OPS has loose and compacted void ratio of 63% and 57%, respectively which are higher compared to those of NWA in the range of 30–45% and 40–50%, respectively (Kosmatka and Wilson, 2011).

The specific gravity of concrete component is a useful factor in mix design calculation (Adesina et al., 2020). OPS has the specific gravity ranging from 1.17 to 1.58 as shown in Table 2. This value is far less than 2.0 (BS 882 1992) and lower compared to those of NWA in the range of 2.4–3.0, 2.6–2.8 and 2.3–3.1 as specified by Neville (2008), ACI Education Bulletin E1 (1999) and Shetty (2005), respectively. The variation in OPS-specific gravity was due to OPS particle size variation, cellular structure and porous nature of OPS (ACI Education Bulletin E1 1999; Prusty and Patro, 2015). Thus, there is high tendency of producing low density concrete with significant reduction in the dead weight of concrete and construction cost which is generally denoted as LWAC with OPS aggregate (Teo et al., 2007). According to Adesina et al. (2020), absolute volume method of mix design is most suitable for concrete incorporating OPS due to high disparity between its specific gravity and other concrete constituents (cement and NWA).

The shape and gradation have influence on aggregate packing density which results in the differences in bulk density with a particular specific gravity (Hamada et al., 2020). Table 2 reveals that the loose bulk density of OPS is approximately 480.52–600 kg/m^3 while the compacted bulk density ranges between 500 and 673 kg/m^3 which is generally lower than that of NWA with the normal range of 480–1040 kg/m^3 for NWA (ACI Education Bulletin E1, 1999). The range of bulk density indicates that OPS is approximately 60% lighter compared with NWA (Hamada et al., 2020; Shafigh et al., 2010). The low bulk density is due to the porous nature of OPS which results in concrete which exhibits lighter weight compared with NWC (Alengaram et al., 2010, 2013; Shetty, 2005).

3.3.4. *Water absorption and moisture content*

The needs to give consideration to density, porosity and rate of water absorption of aggregate are important for developing an effective

Table 1
Chemical properties of OPS reported in past researches.

Properties	Krishnamurthy and Vandanapu (2019)*	Krishnamurthy and Vandanapu (2019)	Krishnamurthy and Vandanapu (2019) *	Ahmad et al. (2014)	Okoroigwe et al. (2014)	Traore et al. (2017)
Oxide composition (%)						
SiO_2	58.43	51.4	50.2	46.61	–	–
Al_2O_3	13.46	27.5	15.72	3.33	–	–
Fe_2O_3	8.33	7.2	7.2	10.19	–	–
CaO	7.17	4.3	5.9	14.76	–	–
MgO	6.00	2.8	4.63	2.91	–	–
SO_3	0.09	0.2	0.18	7.84	–	–
Na_2O	1.89	–	–	1.15	–	–
K_2O	–	–	–	9.88	–	–
P_2O_5	–	–	–	1.95	–	–
ZnO	–	–	–	–	–	–
Loss on ignition	2.4	4.3	3.8	–	–	–
Chemical composition (%)						
Hemicellulose	–	–	–	–	26.16	25.0
Cellulose	–	–	–	–	6.92	9.1
Lignin	–	–	–	–	53.85	52.3
Elemental analysis (%)						
Carbon	–	–	–	44.29	46.75–49.79	–
Hydrogen	–	–	–	9.01	5.58–5.92	–
Oxygen	–	–	–	43.12	34.66–37.97	–
Nitrogen	–	–	–	2.37	0.68–0.72	-
Sulphur	–	–	–	1.20	<0.08	=
Chloride (ppm)	–	–	–	=	84–89	=

Note: * Values varied for treated and untreated OPS.
[a]NWA.

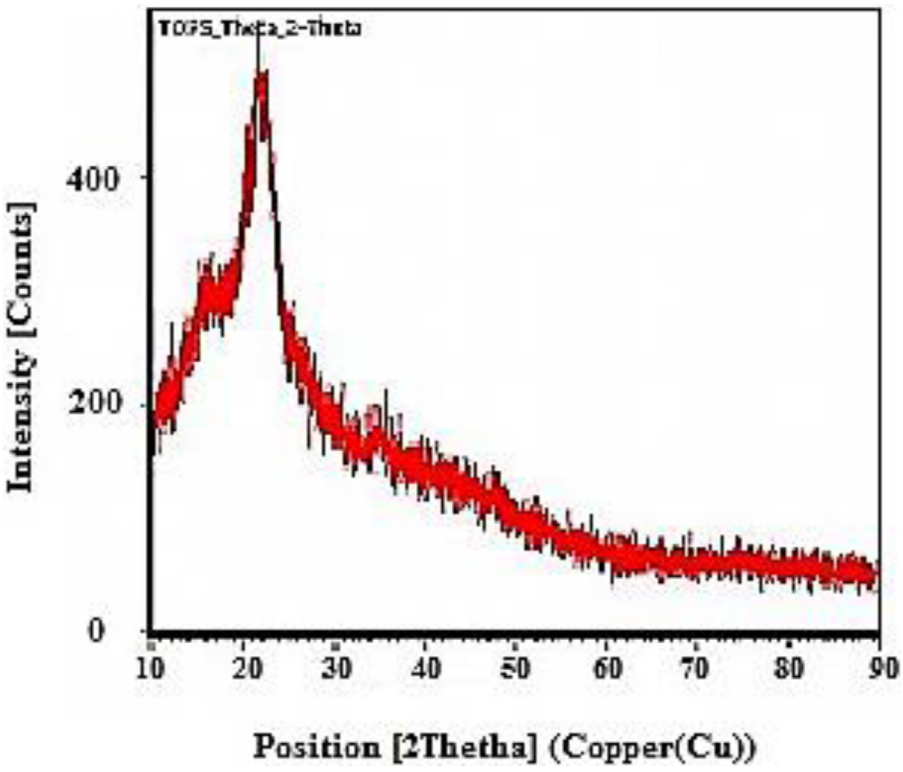


Fig. 5. XRD pattern of OPS.
Source: Krishnamurthy and Vandanapu (2019).

and optimum mix proportioning of LWAC. As shown in Table 2, the water absorption values of OPS ranged from 10 to 12% for 1 h and 12.47–35.64% for 24 h absorption. These values are higher compared with those of NWA in the range of and 0–10% and 0–8% as specified by Neville (2008) and ACI Education Bulletin E1 (1999), respectively. Recent studies have shown that treatment OPS has influence on water absorption rate of OPS. Ramasamy et al. (2008) found lower water absorption rate for OPS treated with salt solution (3% sodium chloride) than the untreated OPS and those treated with potable water, acidic (1% hydrochloric acid) and alkaline (NaOH) solutions. Similarly, Mannan et al. (2006) and Chai et al. (2014) observed a significant reduction in water absorption of PVA treated OPS compared with the untreated OPS. Traore et al. (2018) also found reduction in water absorption for PVA, lime and sodium silicate solutions. Djima et al. (2018) reported a similar trend for lime treated OPS.

The moisture content of the aggregate is useful in the estimation of mix design of concrete (Neville and Brook, 2010). The determination of aggregate moisture content is important for quality control of concrete

Table 2
Physical Properties of OPS reported in past researches.

Properties	Data	Reference(s)
Colour	Dark grey to black	(Wasiu et al., 2015; Okpala, 1990)
Shell thickness (mm)	0.15–8.0	(Maghfouri et al., 2018; Teo et al., 2007; Alengaram et al., 2011; Sobuz et al., 2014; Khankhaje et al., 2016; Okpala, 1990; Okafor, 1988; Oti et al., 2017)
Maximum shell Size (mm)	2–20	(Yew et al., 2014a, 2014b; Djima et al., 2018; Teo et al., 2007; Sobuz et al., 2014; Traore et al., 2017; Alengaram et al., 2010a, 2010b; ; Zanariah et al., 2018)
Voids ratio (%)	63 (Loose) 57 (Compacted)	(Okafor, 1988) (Okafor, 1988)
Porosity (%)	28–37	(Wasiu et al., 2015; Okafor, 1988; Ndoke, 2006)
Specific gravity (saturated surface dry)	1.17–1.62	(Maghfouri et al., 2018; Aslam et al., 2017; Shafigh et al., 2011, 2012; Wasiu et al., 2015; Shafigh et al., 2012; Okafor, 1988; Ndoke, 2006; Mannan and Ganapathy, 2002, 2004; Eziefula et al., 2017; Fapohunda et al., 2015)
Water Absorption (%)	10-12 (1h) 24h 12.47–35.64	(Alengaram et al., 2011; Oti et al., 2017; Shafigh et al., 2016b, 2016a)
Bulk density	514–600 (Loose) 500–740 (Compacted)	(Eziefula et al., 2017; Jumaat et al., 2015) (Maghfouri et al., 2018; Aslam et al., 2017a, 2017b; Shafigh et al., 2011b, 2011a; Djima et al., 2018; Wasiu et al., 2015; Teo et al., 2007; Traore et al., 2017; Shafigh et al., 2012a, 2012b; Okafor, 1988; Ndoke, 2006; Mannan and Ganapathy, 2002; Mannan and Ganapathy, 2004; Eziefula et al., 2017; Fapohunda et al., 2015)
Moisture Content (%)	6.12–12.45	(Oti et al., 2017; Ndoke, 2006; Fapohunda et al., 2015)
Thermal Conductivity W/m^{O}C	0.19	(Okpala, 1990)
Fineness Modulus	5.64–6.53	(Alengaram et al., 2011; Sobuz et al., 2014; Shafigh et al., 2012; Mannan and Ganapathy, 2002, 2004)
Flakiness Index (%)	37–65.17	(Mannan and Ganapathy, 2002, 2004)
Elongation Index (%)	12.36	(Mannan and Ganapathy, 2002, 2004)

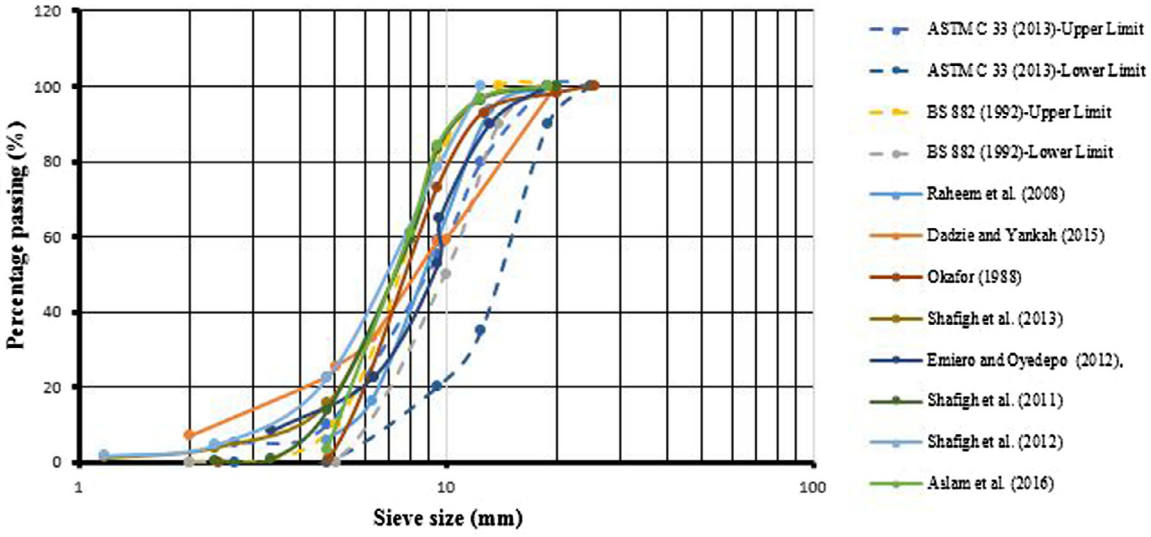


Fig. 6. Gradation curves of OPS from the previous studies (Dadzie and Yankah, 2015 and Emiero and Oyedepo, 2012).

towards better the workability and strength (Shetty, 2005). In effect, the mass of mixing water for concrete decreased as the aggregate content increased by an equal amount of moisture content. The moisture content of OPS which varies between 6.12 and 12.45% as shown in Table 2 is within the range of 0–10% which is higher than those of NWA which is ranging from 0 to 2% (ACI Education Bulletin E1 1999) and 3% for NWA specified by Nemati (2020).

3.3.5. *Flakiness and elongation indexes*

Flakier aggregates may increase the harshness of concrete mix which can be largely overcome by adopting appropriate mix proportion (Perrie, 1994). Flakiness index of OPS varies in the range of 37–65.17% as shown in Table 2. The flakiness index of OPS is higher compared to those of NWA (Mannan and Ganapathy, 2002, 2004). The maximum flakiness index value of 40% is specified by BS 882 (1992) for crushed rock and crushed gravel when the flakiness index is determined according to BS 812: Part 105.1 (1990).

The elongation index of 12.36% for OPS shown in Table 2 indicates that it has lower elongation index compared to NWA (Mannan and Ganapathy, 2002, 2004). Concrete made with aggregates that contain flat and elongated particles requires additional mixing water which can lead to reduction in concrete strength. The value of flakiness index of OPS is within the range of 40% as the maximum flakiness index value specified by BS 812: Part 105.1 (1990) for crushed rock and crushed gravel when the flakiness index is determined according to BS 812: Part 105.2 (1990).

3.3.6. *Thermal conductivity*

The thermal conductivity is a property which determines the insulating properties of aggregate. The thermal conductivity of the aggregate has an effect on the heat transfer propensity of the concrete. The thermal properties of OPS, reported by Okpala (1990), was 0.19 W/m ^{O}C. The thermal conductivity of LWA is generally low compared with that of NWA (Oktay et al., 2015). The specified range of thermal conduc-

Table 3
Mechanical Properties of OPS reported in past researches.

Properties	Data	Reference(s)
Impact Value (%)	2.36–18.18	(Maghfouri et al., 2018; Djima et al., 2018; Sobuz et al., 2014; Okafor, 1988; Mannan and Ganapathy, 2002, 2004; Eziefula et al., 2017)
Crushing Value (%)	0.2–14.84	(Maghfouri et al., 2018; Djima et al., 2018; Sobuz et al., 2014; Okafor, 1988; Eziefula et al., 2017; Aslam et al., 2016)
Abrasion Value (%)	3.05 –7.6	(Maghfouri et al., 2018; Djima et al., 2018; Sobuz et al., 2014; Traore et al., 2017; Okafor, 1988; Mannan and Ganapathy, 2002, 2004; Eziefula et al., 2017; Kupaei et al., 2014)

tivity of granite is 1.9–4.0 W/m ^{O}C (ACI 122R-02 2002) while, for the LWA, the specified range of thermal conductivity is 0.12–0.52 W/m ^{O}C (Shetty, 2005). According to Okpala (1990), the low thermal conductivity of OPS implies that OPSC can help in reducing indoor temperatures in buildings in a hot weather environment.

3.4. Mechanical properties of OPS

The OPS mechanical characteristics are the characteristics that describe its response when it is subjected to external load. The results of tests conducted by the researchers on the mechanical properties (aggregates impact, aggregates crushing and abrasion values) are presented in Table 3.

3.4.1. Aggregate impact and crushing value

The impact value is one of the parameters used to assess the strength of aggregate and the lower the impact value the higher its resistance of such aggregate. Thus, lower strength aggregates may limit the strength of concrete (Alexander and Mindess, 2010). The impact value of OPS, shown in Table 3 which varies between 2.36 and 18.18%, is lower impact values compared to those of NWA (Djima et al., 2018; Alengaram et al. 2010, 2011; Mannan and Ganapathy, 2002, 2004; Eziefula et al., 2017; Jumaat et al., 2015; Alengaram et al., 2011). According to Ramasamy et al. (2008), the higher water absorption rate of OPS made it more flexible with better shock absorber and consequently reduced the OPS aggregate impact value. The impact value of OPS is lower than the maximum of 25% specified by BS 882 (1992) for aggregate applicable for heavy-duty concrete floor finishing. Those with maximum impact value of 30% are useful for pavement-wearing surface, while those with up to 45% are applicable for other concretes other than wearing surface.

The lower the crushing value, the better the resistance of aggregate to crushing load (Djima et al., 2018). As shown in Table 3, the crushing value of OPS, in the range of 0.2–14.84%, is lower crushing values compared to those of NWA (Maghfouri et al., 2018; Okafor, 1988). According to Krishnamurthy and Vandanapu (2019), the lower magnesium oxide content in OPS compared with NWA is responsible for low crushing value of OPS (Krishnamurthy and Vandanapu, 2019). The crushing value of OPS is less than the maximum of 30% specified by BS 812: Part 105.1 (1990); (Perrie, 1994). Studies have shown that treatment OPS has influence on aggregate impact value of OPS. Ramasamy et al. (2008) found higher reduction in impact and crushing values of NaOH treated OPS compared to the untreated OPS. Teo et al. (2006) and Thong et al. (2015) also reported decrease in impact and crushing values of PVA-treated OPS compared with the untreated OPS.

3.4.2. Aggregate abrasion value

The abrasion value is used to evaluate the wear resistance of aggregate especially when the aggregate is being considered for concrete production for road construction, warehouse floors and pavement construction. The lower the abrasion value, the higher is its resistance of such aggregate. OPS has lower abrasion values in the range of 3.05–7.6 as shown in Table 3 compared to those of NWA (Traore et al., 2017; Oti et al., 2017; Mannan and Ganapathy, 2002, 2004; Eziefula et al., 2017; Basri et al., 1999). The abrasion value of OPS is below the maximum abrasion value of 30% recommended by BS 882 (1992).

4. Mix design for OPSC

Different mix proportioning methods were employed in the preparation of concrete mix containing OPS. The singular objective for determining the suitable mix proportioning method is to obtain the optimum mix proportion for OPSC. Absolute volume method is considered as the most-suitable mix-design method for OPSC due to the difference in the specific gravity of OPS compared to other concrete component (cement and NWA) as noted by Adesina et al. (2020). For the OPSC with full replacement of NWA with OPS, the normal mix designs applicable to other LWAC are not suitable for OPSC due to the nature of OPS (i.e., grading properties and other characteristics) compared with other LWA (Thong et al., 2015; Teo et al., 2007; Shetty, 2005; Mannan and Ganapathy, 2001). As a result of this, LWAC mix design is usually developed by trial mix. Some of the earlier researches developed mix design for OPSC by conducting trial mix and these mixes were adjusted to arrive at optimum mix. Abdullah (1996) produced OPSC of 1:2:0.6 mix ratio by weight. Okafor (1988) used 1:1.70:2.08 mix ratio by weight with cement content of 335 kg/m^3 and water-to-cement ratio of 0.48. Okpala (1990) produced OPSC with 1:1:2 mix ratio by volume with water-to-cement ratio of 0.5 and 0.6, respectively and 1:2:4 mix ratio by volume with water-to-cement ratio of 0.5.

Mannan and Ganapathy (2001) developed a mix design for OPSC based on absolute volume method according to ACI 211.2 (1998) and achieved the mix ratio of 1:1.71:0.77 by weight and water-to-cement ratio of 0.41 with the cement content of 480 kg/m^3 and superplasticizers (SP) content of 1.4%. Teo et al. (2007) conducted a trial mix design by modifying the optimum mix design developed for OPSC by Mannan and Ganapathy (2001) and attained at the mix ratio of 1:1.66:0.60 by weight, water-to-cement ratio of 0.38 with the cement content of 510 kg/m^3 and SP content of 1.41%. Gibigaye and Godonou (2018) also developed a mix design with the minimum possible cement content when compared to the previous mix design developed by Alengaram et al. (2011) and Teo et al. (2007) without SP. The optimum mix design obtained was 1:1.53:0.99 by weight with the cement content of 450 kg/m^3 and w/b of 0.65. Nominal mix designs of 1:1:2, 1:1$\frac{1}{2}$:3, 1:2:4; 1:3:6 (cement: fine: coarse aggregates) with water-to-cement ratio ranging between 0.5 and 0.75 were used for OPSC containing OPS as partial replacement for CA (Khan et al., 2016; Fapohunda et al., 2015; Raheem et al., 2008).

5. Physical properties of OPSC

5.1. Workability of fresh OPSC

The understanding of fresh properties of concrete is important due to its usefulness in controlling the rheology, rate of setting, hardening and durability of concrete (Mindess et al., 2003; ACI 212.3R-10, 2010). Workability which is the parameter used for the evaluation of fresh concrete properties is determined through slump test (Hamada et al., 2020; Alengaram et al., 2013). Table 4 shows the influence of OPS as

Table 4
Slump and densities of OPSC reported in past researches.

Reference	Replacement level of OPS in NWC (%)	Slump (mm)	Fresh density (kg/m^3)	Demoulded density (kg/m^3)	28-day Air-dry density (kg/m^3)	28-day Oven-dry density (kg/m^3)	28-day Saturated surface dry density (kg/m^3)
Fapohunda et al. (2015)	0, 25, 50, 75, 100	102 - 2	-	-	2587–1461	-	-
Khan et al. (2016)	0, 10, 15, 20, 25, 30 40	168 - 90	-	-	2285–1908	-	-
Maghfouri et al. (2018)	0, 25, 50, 75, 100	205 – 40	-	-	2396–1940	-	-
Shafigh et al. (2013)	100	35–75	–	1927–1946	1867–1928	1802–1826	-
Yew et al. (2014)	100	90–158	-	-	1871–1876	1983–1986	-
Yew et al. (2014)	100	145–175	-	-	1973–1988	1928–1948	-
Alengaram et al. (2010)	100	50–120	1721–1790	-	-	1525–1597	1735–1810
Foong et al. (2015)	100	85–156	-	-	-	1766–1933	1934–2044
Shafigh et al. (2011)	100	20–255	1931–2063	-	-	1868–1988	-
Farahani et al. (2017)	100	85–110	-	1858–2000	-	1590–1840	-
Mahmud et al. (2009)	100	60–160	1845–1930	-	-	1630–1728	1875–1961
Shafigh et al. (2012)	100	33–230	-	1893–2016	1877–1976	1790–1922	-

reported in previous studies. Teo et al. (2007) noted the slump ranging between 50 and 75 mm which is considered good workability for LWAC by Mehta and Monteiro (2006). Studies have shown that the workability of OPSC is lower compared with NWC and further decreases with increase in replacement level of NWA by OPS for a given w/b ratio (Khan et al., 2016; Maghfouri et al., 2018; Fapohunda et al., 2015). Olusola and Babafemi (2013) found that the OPS size influenced the workability of OPSC in addition to its replacement level. Similar trend was also observed by Raheem et al. (2008) whose study revealed that the OPSCs produced with OPS as FA exhibited lower workability, compared to those with OPS as CA. The presence of higher proportion and increase in surface area of OPS leads to increase in water demand to achieve higher workability (Fapohunda et al., 2015, Foong et al., 2015, Maghfouri et al., 2019, Mehta and Monteiro, 2006). Alengaram et al. (2010) reported the highest workability for OPSC with 70% of OPS size above 10 mm and 30% below 5 mm. Mo et al. (2014) found lower slump for OPSC produced with crushed OPS compared with uncrushed OPS. The rough texture, irregular, flaky, elongated or angular shape prevent full compaction of fresh OPSC mix, leading to the reduction in workability (Yew et al., 2014; Mannan and Ganapathy, 2004). Improvement in workability of OPSC is possible with higher water-cement ratio as applicable to NWC since additional water in the mix will result in higher slump of fresh concrete mix. Okafor (1988) and Adeyemi et al. (2017) noted that the workability of OPSC increased as the water-cement ratio increased from 0.45 to 0.6. However, the compressive strength decreased with increase in water-cement ratio. Thus, the use of SP is widely recommended to improve the workability of OPSC and attain the preferred slump (Adesina et al., 2020). Mannan and Ganapathy (2004) noted that the slump of OPSC with SP increased about 14 times than that without SP. Yew et al. (2014) reported the slump values in the range of 90–158 mm with 28-day compressive strength values ranging from 40.4 to 54.4 MPa for OPSC with OPS as full replacement for NWA and SP as chemical admixture. In addition to the use of SP, other factor which further enhanced the workability of OPSC is the use of maximum size of OPS. Shafigh et al. (2011) found that an increase in slump of up to 250 mm with 28-day compressive strength values of 45.4 MPa when the maximum size of OPS was changed from 9.5 to 12.5 mm in addition to the use of SP. Okafor (1991) reported that SP has appreciable fluidifying action in the fresh concrete so that, under appropriate conditions, it either considerably improved the workability of the fresh concrete at normal water content or permitted a water reduction of at least 9% to be made while maintaining a given workability. The inclusion of 0 to 40% palm oil clinker (POC), as substitute for OPS, was found to enhance the workability of concrete from 85 to 100 mm by Aslam et al. (2017). The round shape of POC is responsible for the improvement in workability of OPSC.

Yew et al. (2014) also reported improvement in the workability of OPSC by 20% with a rise in the temperature and heat treatment of OPS aggregate from 30 °C at room temperature to 150 °C for 1 h. It was also found that the addition of mineral admixtures such as fly ash is advantageous towards enhancing the OPSC's workability (Shafigh et al., 2013). Oriola et al. (2021) noted that the workability of OPSC of different mix ratios incorporating fixed content of rice husk ash decreased with increase in OPS contents. Islam et al. (2016) also achieved the highest slump with 10% palm oil fuel ash as replacement for cement but decreased with further addition of palm oil fuel ash. However, Farahani et al. (2017) noted a reduction in workability with high-volume of rice husk ash and fly ash of 70% as replacement for cement. The inclusion of fibres has negative influence on the workability of OPSC. Mo et al. (2017) reported the reduction in workability of OPSC with the addition of steel fibres. Yew et al. (2015) also found reduction in the workability of OPSC with the inclusion of different types of polypropylene fibres.

5.2. Density of OPSC

The fresh concrete density gives the indication whether hardened concrete is ultra-lightweight, lightweight or structural lightweight or normal weight or heavy weight (Mannan and Ganapathy, 2004). The hardened concrete density is significant factor which determines the concrete quality; therefore, it is taken into account in design of concrete structures (Mo et al., 2015). It can be observed from Table 4 that the lower limit of OPSC densities fulfilled the requirement of SLWAC while the upper limit is in close proximity of the maximum value of densities for concrete to be categorised as SLWAC as specified in BS BS EN 201-1 (2000). Studies have shown the reduction in concrete density as the substitution ratio of OPS increases (Khan et al., 2016; Maghfouri et al., 2018; Shafigh et al., 2012; Fapohunda et al., 2015). The decrease in density has been largely attributed to the lower relative density of OPS compared with NWA. Alengaram et al. (2010) reported the lowest fresh density for OPSC with higher proportion of OPS of larger size than those with higher proportions of OPS of smaller size. These reductions were attributed to the fact that more voids are created by large-sized particles with low-compacted bulk density (Khankhaje et al., 2016; Alengaram et al., 2010). Shafigh et al. (2013) found that the addition of fly ash decreased the density of OPSC. Oriola et al. (2021) reported a decrease the density for OPSC varying OPS contents with different mix ratios incorporating rice husk ash. The findings are in line with Mannan and Ganapathy (2004) where the 28-day air-dry density

of OPSC containing up to 15% fly ash decreased by 22% with respect to NWC.

Shafigh et al. (2016) reported a reduction in OPSC density from 2011 to 1727 kg/m^3 with inclusion of high-volume fly ash of 70% as replacement for cement. Mo et al. (2014) also reported that the incorporation of high-volume ground granulated blast furnace slag (GGBS) of 50–70% contents decreased the oven-dry density of OPSC. Aslam et al. (2017) found a decrease of 9.5% in oven-dry density of OPSC after substituting OPS with up to 60% POC. Yew et al. (2014) noted that the rise in the temperature and heat treatment of OPS aggregate from 30 ˚C at room temperature to 150 ˚C for 1 h decreased the air-dry and oven-dry density of OPSC by 0.8% and 1% at 28 days. The observation was attributed to the weight loss due to increase in heat treatment temperature. Yew et al. (2015) found that the addition of twisted polypropylene bundles results in OPSC reduction. Yew et al. (2015) discovered that the density of OPSC decreases with increase in fraction of PVA fibres addition. Yap et al. (2013) reported a similar finding in which OPSC density reduction was observed with the addition of polypropylene fibres. The low specific gravity of PVA fibres was responsible for the reduction in density. However, Yap et al. (2017) noted that the density of OPSC increased from 1970 to 2070 kg/m^3 with addition of 0 to 0.5% steel fibres.

6. Mechanical properties of OPSC

6.1. Compressive strength

Compressive strength is a significant property of concrete due to its effect on all other properties (splitting tensile strength, flexural strength and modulus of elasticity) of concrete (Das et al., 2016; Fahrizah et al., 2014). It is used to measure the resistance of concrete under the application to compressive load. The strength of concrete is directly proportional to the aggregate strength, stiffness and density and inversely proportional to the porosity of aggregates (Sobuz et al., 2014; Mannan and Ganapathy, 2002; Fahrizah et al., 2014). Addition of OPS generally caused a decrease in compressive strength of concrete based on the findings from previous studies (Maghfouri et al., 2018; Sobuz et al., 2014; Shafigh et al., 2012; Olanipekun et al., 2006; Raheem et al., 2008; Farahani et al., 2017; Sulymon, 2005; Aiswarya et al., 2018). However, the compressive strength increased with increase in curing ages as applicable to NWC. The reduction in the strengths of OPSC has been largely attributed to the breakdown of the weaker bond between OPS and cement paste because of the smooth surface and the presence of micro pores on the outer surface of OPS (Maghfouri et al., 2018; Mannan et al., 2006; Okpala, 1990; Alengaram et al., 2010; Osei and Jackson, 2012; Shafigh et al., 2013, 2011; Fahrizah et al., 2014; Aiswarya et al., 2018; Daneshmand and Saadatian, 2011). Fig. 7 shows the image of SEM analysis conducted by Traore et al. (2017) which confirmed the voids and cracks and illustrated the weak bond between OPS-cement paste interfaces. The minimum of 17 N/mm^2 for SLWAC specified by ASTM C 330/ C 330 M (2014) and ACI 213R (2003) for SLWC were achieved at the optimum replacement level of 25% OPS at the curing age of 28 days.Raheem et al. (2008) reported the compressive strength of 19.33 N/mm^2 for OPSC of 1:2:4 mix proportions and water-to-cement ratio of 0.6 at the optimum of 25% OPS contents while further addition of OPS resulted in the decrease in compressive strength. Khan et al. (2016) also obtained a compressive strength of 18.31 N/mm^2 after 28 days for OPSC of 1:2:4 mix proportions and water-to-cement ratio of 0.65 at the optimum OPS content of 25%. According to Olanipekun et al. (2006), the optimum of 25% and 50% OPS is appropriate for achieving OPSC of grade 20 and 15, respectively.

Past studies in the last few decades have developed structural OPSC of different strength grades with OPS as full replacement for NWA. Abdullah (1996) produced OPSC of 1:2:0.6 mix ratio by weight and achieved a compressive strength of 20.50 N/mm^2 after 28 days of curing. Okafor (1988) reported the 28-day compressive strength of 23.0 for OPSC of 1:1.70:2.08 mix ratio by weight with cement content of 335 kg/m^3 and water-to-cement ratio of 0.48. Okpala (1990) achieved the 28-day compressive strength of 19.8 N/mm^2 and 22.2 N/mm^2 for OPSC of 1:1:2 mix ratio by volume with water-to-cement ratio of 0.5 and 0.6, respectively and 18.9 N/mm^2 for OPSC of 1:2:4 mix ratio by volume with water-to-cement ratio of 0.5. Mannan and Ganapathy (2001) used the mix ratio of 1:1.71:0.77 by weight and water-to-cement ratio of 0.41 with the cement content of 480 kg/m^3 and SP content of 1.4%. The compressive strength of 24.20 N/mm^2 was obtained after 28 days with the mix design developed. Teo et al. (2007) developed a mix ratio of 1:1.66:0.60 by weight, water-to-cement ratio of 0.38 with the cement content of 510 kg/m^3 and SP content of 1.41%. The mix proportion produced OPSC of 1985 kg/m^3 and 28.0 N/mm^2, respectively. Gibigaye and Godonou (2018) used the optimum mix design arrived at was 1:1.53:0.99 by weight with the cement content of 450 kg/m^3 and w/b of 0.65 which resulted in OPSC with the density 1844 kg/m^3 and cylindrical compressive strength of 18.63 N/mm^2.

Recent studies have shown the possibility of realising structural OPSC of higher strength grades. Maghfouri et al. (2018) found that 28-day compressive strength decreased from 64.2 to 40.5 N/mm^2 as the OPS content increases from 25 to 100% with the addition of SP as chemical admixture. Aslam et al. (2017) found the compressive strength of 53.3 N/mm^2 for OPSC with 50% Oil-palm-boiler-clinker (OPBC) which represents 30.7% increase compared to the control OPSC at 28-day curing age. Mo et al. (2014) obtained the 28-day compressive strength ranging between 37 and 49.4 MPa for OPSC with and without fibres. Shafigh et al. (2013) observed that the compressive strength OPSC, under water curing condition, decreased from 46.08 to 30.04 N/mm^2 as the fly ash contents increased from 10 to 50% after 28-day curing age. Mannan et al. (2006) achieved the highest 28-day compressive strength of 32.84 N/mm^2 for OPSC produced using 20% PVA. Foong et al. (2015) found that the 28-day compressive strength of OPSC with 50% and 100% manufactured sand as replacement for mining sand and fixed rice husk ash content of 15% ranged from 46.43 to 51.49 MPa and the maximum was found for OPSC containing 15% RHA and 100% manufactured sand.

6.2. Splitting tensile strength

The determination of tensile strength of concrete is significant in estimating the load under which cracks can develop and reduce the failure of concrete in tension (Neville, 2008; Mo et al., 2014; Singh, 2012). Factors such as aggregate size, curing age and replacement level of crushed granite are responsible for decrease in splitting tensile strength of concrete (Farahani et al., 2017; Oyejobi et al., 2012). The splitting tensile strength of OPSC decreased as observed for its compressive strength as the replacement level of OPS and this is responsible for early crack development when loaded (Khan et al., 2016; Fapohunda et al., 2015; Adesina et al., 2020; Olusola and Babafemi, 2013). Recent studies have shown the prospect of improving the splitting tensile strength of OPSC to achieve and exceed the limit of 2.0 MPa specified by ASTM C 330/ C 330 M (2014) for structural grade LWAC as shown in Table 5. Maghfouri et al. (2018) found the splitting tensile strength of OPSC ranging between 3.90 and 2.7 N/mm^2 as the OPS content increases from 25 to 100% in the presence of SP as chemical admixture. Aslam et al. (2017) observed the splitting tensile strength values of 3.29 MPa and 3.59 MPa for OPSC, with and without 50% OPBC as CA, with the addition of SP at 28-day curing age. Mo et al. (2017) reported an increase in splitting tensile strength for OPSC incorporating steel fibres in the range of 0% to 1.0% volume fraction.

Similarly, Mo et al. (2015) reported the inclusion of optimum volume fraction of acrylic fibres of 0.1% for the enhancement of splitting tensile strength for OPSC incorporating 20% GGBS. This finding also agrees with Yap et al. (2013) where the increase of 83% in splitting tensile strength with the inclusion of 0.1% polypropylene hybrid fibre

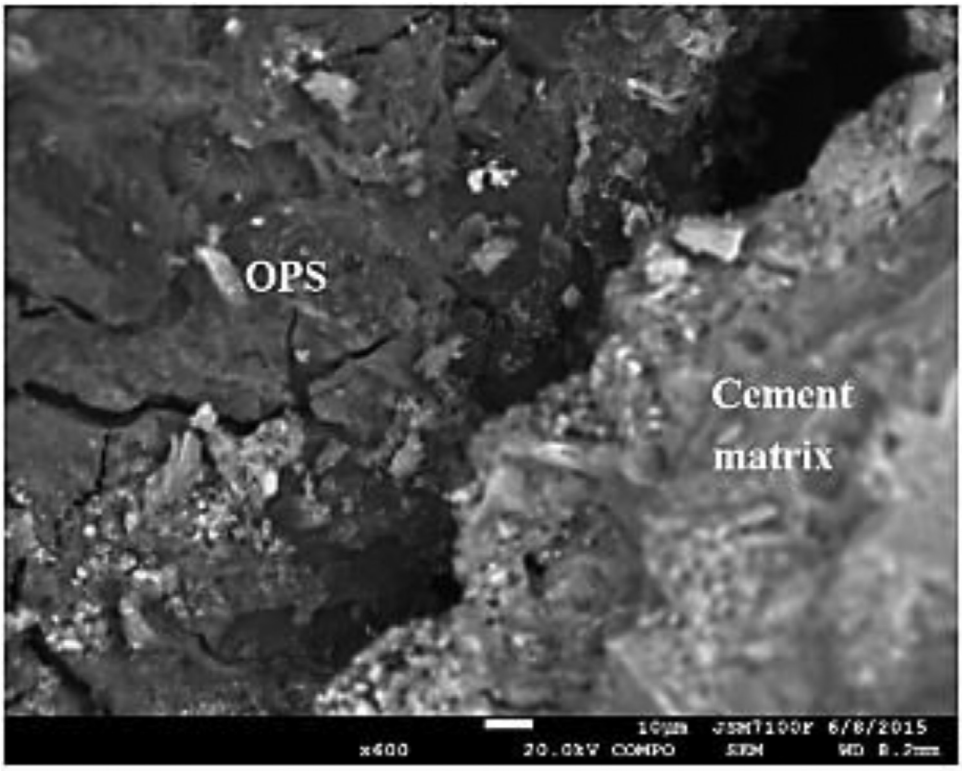


Fig. 7. SEM showing bond between cement matrix and OPS.
Source: Traore et al. (2017).

Table 5
Mechanical properties of OPSC reported in past researches.

Reference	Replacement level of OPS (%)	28-day compressive strength (N/mm^2)	28-day splitting tensile strength (N/mm^2)	28-day flexural strength (N/mm^2)	28-day modulus of elasticity (N/mm^2)
Fapohunda et al. (2015)	0, 25, 50, 75, 100	22.08–5.78	1.50–0.75	–	–
Khan et al. (2016)	0, 10, 15, 20, 25, 30 40	36.89–13.67	–	–	–
Maghfouri et al. (2018)	0, 25, 50, 75, 100	74.4–40.5	5.10–3.40	–	–
Traore et al. (2018)	100	20.1–25.5	-	4.0–4.7	6.65–12.08
Foong et al. (2015)	100	44.42–51.94	2.7–3.45	5.13–6.04	14.1–17.8
Shafigh et al. (2011)	100	42.75–48.33	-	–	-
Alengaram et al. (2010)	100	36.70–37.41	1.95–2.10	3.50–3.83	10.05–11.15
Mo et al. (2014)	100	33.4–45.1	2.31–3.51	4.03–5.71	12.6–17.6
Mahmud et al. (2009)	100	26.98–37.79	1.90–2.35	2.27–4.10	7.08–16.69
Shafigh et al. (2013)	100	30.04–44.49	1.98–3.22	2.702–4.946	-
Shafigh et al. (2012)	100	34.29–53.05	2.85–3.54	4.42–6.99	-
Yew et al. (2014)	100	42.90–49.04	-	-	15.2–16.4

and 0.9% steel fibre in OPSC was found. Mo et al. (2014) found that the splitting tensile strength and splitting tensile to compressive strength ratio ranged from 2.31 to 3.51 MPa and 6.9–8.3% as the GGBS content increased from 0 to 70% at an interval of 10% as the curing age of 28 days. Foong et al. (2015) observed that the 28-day splitting tensile strength of all the OPSC ranged from 2.70 to 3.45 MPa and the maximum value of 3.45 MPa which was achieved for OPSC containing 15% RHA and 100% manufactured sand. The improvement of bond at the ITZ between cement paste and OPS caused by the pozzolanic reaction of rice husk ash is responsible for the increase in tensile strength. However, Mo et al. (2014) observed that the splitting tensile strength decreased from 3.51 to 2.31 MPa for OPSC containing 0, 20, 30, 40, 50, 60 and 70% GGBS as partial replacement for cement and 1% SP. It was mentioned that the decrease in splitting tensile strength with increase in GGBS content was attributed to the porous nature of OPS which resulted in rapid initiation and propagation of cracks under tensile loading. Similarly, Shafigh et al. (2016) found that the 28-day splitting tensile strength of OPSC containing 0, 10, 30 and 50% fly ash were lower compared to the control OPSC without fly ash. This was attributed to the poor quality of ITZ between the OPS and cement paste. Table 6 shows the equations developed in previous researches for predicting splitting tensile strength of OPSC from its compressive strength.

6.3. *Flexural strength*

Flexural strength or modulus of rupture is a measure to resist failure in bending in beam or slab (Das et al., 2016; Fapohunda et al., 2015; BS 1881–201, 1986). It can be seen from Table 5 that the flexural strength of OPSC followed similar trend as the compressive strength and splitting tensile strength as observed past in researches, that is, the flexural strength of OPSC decreases as the percentage of OPS substitution increases (Sobuz et al., 2014; Sulymon, 2005; Oyejobi et al., 2012). The flexural strength of concrete depends on coarse aggregate contents and the distribution of moisture in concrete (Hamada et al., 2020). Mannan and Ganapathy (2002) found that the 28-day flexural strength values ranged between 2.75 and 4.00 N/mm^2 which was approxi-

Table 6
Expression proposed in the previous studies to predict splitting tensile strength of OPSC.

References	Aggregate type (s) / OPS content	Admixture	Splitting tensile strength, f_t (MPa)
Shafigh et al. (2011)	OPS and Granite	SP	$f_t = 0.4887\sqrt{f_{cu}}$
Nemati (Nemati, 2020)	OPS/ 100	-	$f_t = 0.20\sqrt[3]{f_{cu}^{\ 2}}$
Mehta and Monteiro (2006)	OPS and oil-palm-boiler/	SP	$f_t = 0.27 f_{cu}^{\ 0.63}$
Mo et al. (2014)	OPS	GGBS, SP	$f_t = 0.27 f_{cu}^{\ 0.63}$

f_t = splitting tensile strength (MPa), f_{cu} = cube compressive strength (MPa).

Table 7
Expression proposed in the previous studies to predict flexural strength of OPSC.

References	Aggregate type	Admixture	Flexural strength, f_r (MPa)
Shafigh et al. (2011)	OPS and Granite	–	$f_r = 0.12 f_{cu}^{\ 1.03}$
Mahmud et al. (2009)	OPS	SF, F-A, SP	$f_r = 0.3\sqrt[3]{f_{cu}^{\ 2}}$
Yusuf et al. (2018)	OPS		$f_r = 0.8995 f_{cu}^{\ 0.4515}$
Mo et al. (2014)	OPS	GGBS, SP	$f_r = 1.74\sqrt{f_{cu}} - 6.13$
			$f_r = 0.69\sqrt[3]{f_{cu}^{\ 2}} - 3.37$
Shafigh et al. (2013)	OPS	F-A	$f_r = 0.09 f_{cu}$

f_r = flexural strength (MPa), f_{cu} = cube compressive strength (MPa).

mately 14–17% of their compressive strength. The lower ratio of flexural strength to compressive strength was attributed to lower stiffness and strength of OPS (Adesina et al., 2020). Shafigh et al. (2016) showed that the inclusion of 25% and 50% OPS, as substitute for expanded clay, as CA increased the flexural strength values by 13.2% and 28.8% compared to expanded clay without OPS. Aslam et al. (2017) reported an increase of 8% of flexural strength with addition of 50% OPBC as CA with the ratio of flexural strength to compressive strength of 14.6% and 13.2% for OPS, with and without 50% OPBC, at 28-day curing age. The higher strength of OPS concrete with 50% OPBC was attributed to rough surfaces of OPBC which improve the interlocking between cement matrix and aggregate. In addition, OPBC grains have round shape and their substitution improved the workability of concrete and the water to cement ratio is reduced for the same workability.

Mo et al. (2014) found the flexural strength and flexural to compressive strength ratio range between 4.03–5.71 MPa and 11.7–12.7% as the GGBS content increased from 0 to 70% at the curing age of 28 days. Yap et al. (2017) found that the addition of steel fibres at the optimum level of 1% enhanced the flexural strength of OPSC up to 8.2 MPa. Additionally, Yew et al. (2015) reported that the flexural strength of OPSC was enhanced with the addition of optimum of 0.25% polypropylene hybrid fibres. Similar improvement in flexural strength was reported for OPSC with polypropylene fibres or nylon fibres was also reported by Yap et al. (2013). Traore et al. (2018) found that the flexural strength of OPSC increased by 6% and 4% with the use of OPS treated with lime and heat. Shafigh et al. (2013) found that the OPSC containing 10% fly ash content exhibited the highest 28-day flexural strength value (46.08 MPa) compared with that of OPSC without fly ash (44.49 MPa). Foong et al. (2015) reported the maximum value of 28-day flexural strength of 6.04 MPa was achieved for OPSC containing 15% RHA and 100% M-sand. Table 7 shows the equations developed in previous researches for predicting flexural strength of OPSC from its compressive strength.

6.4. Modulus of elasticity

Modulus of elasticity (MOE) is an important material property used to measure the material resistance to the axial deformation. It denotes the highest permissible stress limit of the material before undergoing permanent deformation. The lower the MOE value of concrete, the higher is the tendency to produce greater deflection (Aslam et al., 2017). The types of aggregate, stiffness of coarse aggregate, ITZ between the aggregates and the paste and the properties of constituent materials (Neville, 2008; Alengaram et al., 2011; Sobuz et al., 2014; Traore et al., 2017; Mannan and Ganapathy, 2002; Shafigh et al., 2016; Aslam et al., 2016). MOE of OPSC decreased as the percentage of OPS substitution increased, as observed for compressive strength (Sobuz et al., 2014; Traore et al., 2017; Shafigh et al., 2016). However, Mannan and Ganapathy (2002) reported a rise in MOE values of OPSC over the curing age of 28–90 days, which is lower compared with the control concrete. Aslam et al. (2017) found that the MOE value of OPSC with 50% OPBC increased by 50% compared to the control OPSC.

Traore et al. (2018) found that the OPSC produced with the use of OPS treated with CH exhibited the highest MOE value of 12.08 GPa. Foong et al. (2015) reported the maximum MOE for OPSC containing 15% RHA and 100% M-sand. Yew et al. (2014) found the MOE values in the range of 15.2–16.4 GPa for OPSC containing OPS which is heat-treated at optimum temperature and duration of 60 ^{O}C and 0.5 h, using a controlled laboratory oven, was higher which falls within the range of NWC and NLWA concrete. Mo et al. (2014) reported that the MOE decreased from 16 to 12.6 GPa for OPSC containing 0, 20, 30, 40, 50, 60 and 70% GGBS as partial replacement for cement and 1% SP. The decrease in MOE value with increase in GGBS content was attributed to the presence of high of GGBS content in OPC and the stiffness of OPS and the weaker bond between the OPS and cement matrix. The proposed equations developed in previous studies for predicting the static MOE from compressive strength and also from dynamic MOE are presented in Table 8.

6.5. Ultrasonic pulse velocity

Ultrasonic pulse velocity (UPV) test is a non-destructive test used for the evaluation of concrete quality (Yew et al., 2014). According to BS 1881–201 (1986), concrete uniformity, cracking and honeycomb, strength development, concrete deterioration and layer thickness can be determined from UPV method. Concrete with UPV value of 4.5 and above, 3.5–4.5 km/s, 3.0–3.5 km/s, 2.0–3.0 km/s and below 2.0 km/s are categorised as excellent, good, doubtful, poor and very poor as specified by Whitehurst (1986). According to Yew et al. (2014), OPS species, size and age categories has insignificant effect on UPV of OPSC. Serri et al. (2014) found that the UPV of OPSC increased with increase in cement content (300–500 kg/m^3) and cement/sand ratio (1.7–1.9). Mo et al. (2014) reported the UPV of 3.14 – 4.26 km/s from 1 to 28 days for OPSC with increase of 0 to 70% volume fraction of GGBS as

Table 8
Proposed equation for prediction of Moduli of elasticity of OPSC in the previous studies.

References	Aggregate type	Admixture	Moduli of elasticity, E (GPa)
Shafigh et al. (2012)	OPS and Granite	–	$E_s = 0.4887\sqrt{f_{cu}}$
Alengaram et al. (2011)	OPS	SF, F-A, SP	$E_s = 5{f_{cu}}^{0.33}(w/2400)$
			$E_s = 0.30(E_d)^{1.25}$
Mahmud et al. (2009)	OPS	SF, F-A, SP	$E_s = 1.2(E_d)^{0.76}$
Aslam et al. (2017)	OPS and OPBC	SP	$E_s = 6{f_{cu}}^{0.33}(\rho/2400)$

f_{cu} = cube compressive strength (MPa), E_s = static MoE (GPa), E_d = dynamic MoE (GPa), w = dry density (kg/m^3), SF = Silica fume, F-*A* = fly ash.

Table 9
Expression proposed in the previous studies to predict compressive strength of OPSC.

References	Aggregate type/OPS content (%)	Admixture	Compressive strength $f_{cu,}$ (MPa)
Mo et al. (2014)	OPS/ 100	GGBS, SP	$f_{cu} = 0.137e^{1.395(UPV)}$
Yew et al. (2014)	OPS/ 100	SP	$f_{cu} = 0.563(V_t)^{3.2}$
Yew et al. (2014)	OPS/ 100	SP	$f_{cu} = 0.816(UPV)^{2.9}$

f_{cu} = cube compressive strength (MPa), V_t = cube transverse UPV (km/s).

replacement for cement. The refinement of OPSC pores structure, due to increase in GGBS hydration, is responsible for higher UPV values at 28 days. Mo et al. (2014) found the UPV value ranging from 3.17 to 4.11 km/s for the steel and polypropylene fibres reinforced OPSC panels as the curing age increased from 1 to 180 days. The higher improvement in UPV values at early age compared to those of later age was attributed to the addition of silica fume which is also responsible for high early strength development.

Yap et al. (2013) observed little difference between the UPV of OPSC as the volume fraction of propylene and nylon fibres reinforcement increased. However, the UPV of OPSC with both fibres attained condition at the age of 7 days. Traore et al. (2018) found higher UPV for OPSC with OPS subjected pre-treatment methods (lime solution and heat treatment) compared to the untreated OPS. The lower UPV recorded for OPSC than that of NWC (4207 m/s) irrespective of the treatment method was attributed to the porous and organic nature of OPS which have reduced the propagation of ultrasonic wave. Yew et al. (2014) reported an insignificant improvement in UPV values of OPSC containing OPS with or without heat treatment. However, the UPV values of all the OPSC are in the range of 3.50–4.50 km/s which is considered to be categorised as "good" condition after 3 days. The empirical expression relating to the pulse velocity and compressive strength of OPSC are presented in Table 9.

7. Durability properties

Durability of concrete refers to concrete ability to resist the deterioration caused by the environment and perform satisfactorily throughout the duration of its service life (Teo et al., 2010). Severe deterioration of concrete can easily be observed in concrete and this can be caused by external and internal forces within the concrete (Adesanya and Raheem, 2010).

7.1. Water absorption

Water absorption is an important concrete property which greatly influences the durability of concrete (Teo et al., 2010). The absorption characteristics of concrete is an indication of its durability (Teo et al., 2010). OPSCs have higher water absorption rate than the NWC and increase with increase in the addition of OPS (Khan et al., 2016; Maghfouri et al., 2018; Yew et al., 2014; Olanipekun et al., 2006; Shafigh et al., 2011). Mannan and Ganapathy (2002) observed that the water absorbed by the OPSC is higher (12–40%) compared with the control concrete, depending on the type of curing environment and curing age. However, the water absorption of the OPSC under full water curing decreases as the curing age decreases from 28 to 90 days. Maghfouri et al. (2018) found that OPSC containing OPS below 50% of total volume of CA are within the specified water absorption rate of limit of 5% classified as better quality of concrete by CEB/FIP (1997). The higher water absorption rate of OPSC is due to higher porosity of OPS compared to NWA. The water absorption of OPSC is shown in Fig. 8. Khan et al. (2016) also confirmed similar trend but the concrete, with up to 40% OPS replacement level, exhibited water absorption in the range specified for good quality concrete. Aslam et al. (2017) reported the reductions of 45% and 42% of the initial and final water absorption of OPSC containing OPS with 50% OPBC as CA in the presence of SP. Similar trend was also reported by Aslam et al. (2016).

Islam et al. (2016) reported the reduction in initial water absorption of OPSC containing palm oil fuel ash from 28 to 90-day curing age and attributed it to continuous hydration process due to pozzolanic reaction of palm oil fuel ash which increased with curing age. Mo et al. (2015) observed that OPSCs containing GGBS slag as replacement for cement have initial water absorption below 3% indicating good concrete according to CEB/FIP (1997). In addition, the water absorption of the OPSC at 28 and 90 days ranged from 7.5 to 7.8% and 6.3 to 7.3%, respectively with OPSC containing 40% GGBS exhibiting the lowest water absorption rate. This was attributed to the denser pore structure which inhibit ingress of water into the pore system of OPSC with increase in hydration process as the GGBS contents increased up to 40%.

Mo et al. (2017) found that OPSCs with 20% GGBS as replacement for cement with 0.1% acrylic fibres subjected to different curing condition exhibited water absorption below 10% specified by Neville (2008) for good quality concrete. According to the authors, the addition of 0.1% acrylic fibres caused lower increment in OPSC water absorption and UPV values compared to those with higher acrylic fibres volume fraction which leads to entrapment of air during mixing which induced voids in concrete. Ramasamy et al. (2008) observed that water absorption rate of concrete under the different exposure conditions decrease with age and the lowest water absorption rate was observed for the OPSC exposed to salt solution. Shafigh et al. (2013) found lower water absorption for OPSC containing 10% fly ash compared with those with higher fly ash contents. Furthermore, OPSC with low water-to-cement ratio and up to 50% fly ash were categorised as good quality based on the water absorption values. Thong et al. (2017) observed a reduction in water absorption of concrete with PVA-treated OPS than the concrete with untreated OPS. The enhancement in water absorption of concrete was attributed to the improvement in the aggregate-paste interface zone as a result of the PVA coat on the surfaces of OPS which caused the flocculation of

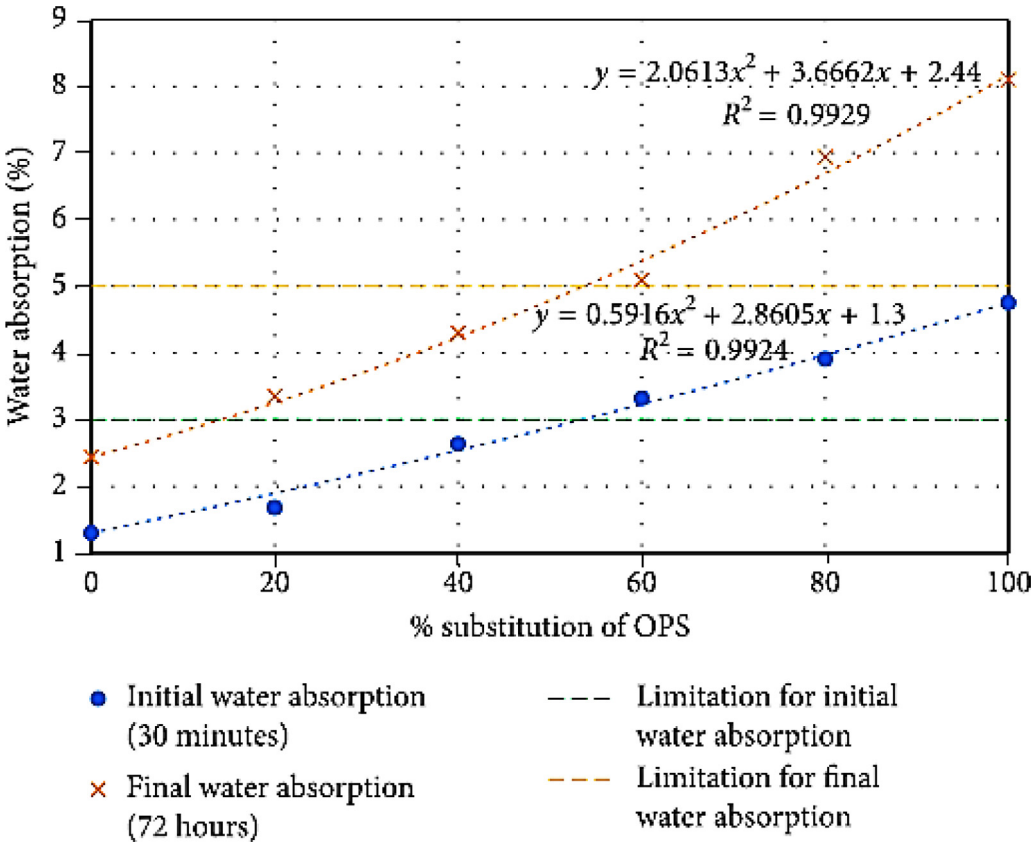


Fig. 8. Variation of water absorption of OPSC.
Source: Maghfouri et al. (2018).

cement particles surrounding the OPS leading to the production of a denser aggregate-paste interface.

7.2. Permeability

Permeability is another indicator of concrete durability which determine the penetration rate of moisture that may contain harmful chemicals causing the corrosion of the steel embedded in concrete (Teo et al., 2007). Other factors include: water-to-cement ratio, aggregate, cement paste and interfacial zone between them (Neville, 2008; Chia and Zhang, 2002). OPSCs exhibited higher water permeability especially with higher OPS contents. However, the permeability decreases with increase in curing age (Teo et al., 2007, 2010; Shafigh et al., 2013). Factors which influence the water absorption and permeability of OPSC are: pore structure, curing age and condition, presence of micro cracks in concrete matrix, shape and size of OPS (Hamada et al., 2020; Teo et al., 2007, 2010). Similar trend was observed with the same experimental approach. The permeability of OPSC could be enhanced by curing condition as the permeability of OPSC specimens under water curing condition was lower than that under air-dried curing condition (Teo et al., 2007, 2010). The variation of water permeability and curing ages of OPSC under various curing conditions is shown in Fig. 9. Serri et al. (2015) found that the air permeability of OPSC increases in the same trend as the porosity as the OPS volume fraction increased and decreased as the curing age increased from 7 to 28 days.

7.3. Sorptivity

Sorptivity is a parameter which indicates the pore structure of a concrete (Khatib and Mangat, 1995). As a result, it is used to assess the ability of concrete to transmit and absorb water via capillary suction (Islam et al., 2016). A sorptivity value of less than 0.1 mm/min$^{0.5}$ is specified for high-quality concrete (EuroLightCon 2000). The lower the concrete sorptivity value, the greater the concrete's resistance to water absorption (Teo et al., 2010). Teo et al. (2010) reported the sorptivity values of 0.06–0.14 mm/min$^{0.5}$ for OPSC at different curing conditions and ages which were to be comparable to other lightweight concretes made from expanded shale and sintered pulverised fuel ash aggregates. Islam et al. (2016) reported that the sorptivity values of 0.06–0.17 mm/mm$^{0.5}$ obtained for OPSCs with 0–50% Palm oil fuel ash (POFA) at 28 days decreased to 0.05–0.10 mm/mm$^{0.5}$ at the curing age of 90 days. Similar trend was also reported by Thong et al. (2017) while reduction in sorptivity was observed as the curing age increases. The enhancement of sorptivity of OPSC was attributed to film of PVA formed on the surfaces of OPS resulting in the decrease in sorptivity value of OPSC which is more significant in OPSC subjected to air-drying condition compared with those fully immersed in water. Mo et al. (2015) found that the sorptivity of OPSC decreased with the addition of GGBS as replacement for cement with OPSC containing 40% compared with the control OPSC. The sorptivity values obtained were found lower than those of other lightweight concrete produced from OPS geopolymer, expanded clay and pumice aggregates. The reduction in sorptivity with the addition of GGBS was due to refinement of OPSC pore structures leading to the blockage of capillary and discontinuity of capillary porosity with continuous hydration during the prolonged curing period. The improvement of sorptivity of OPSC was more pronounced with increase in GGBS contents up to 40%.

7.4. Drying shrinkage

Drying shrinkage is a time-dependent deformation denoted as the strain measured without the application of external stress

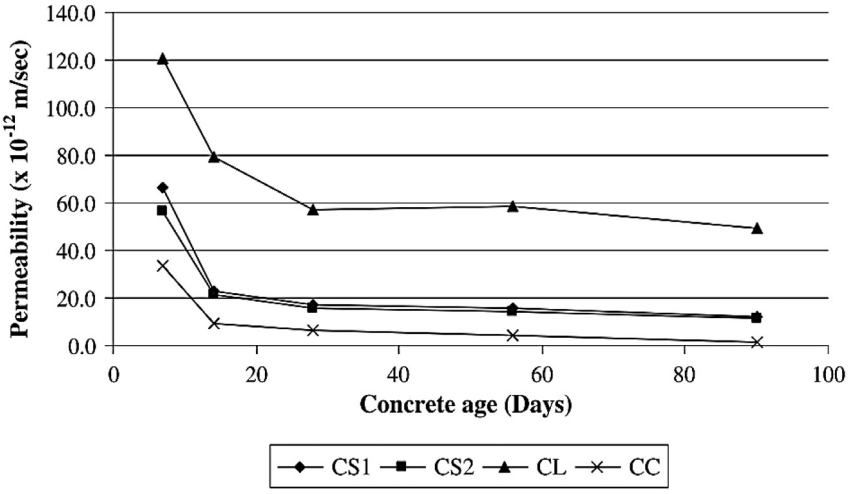


Fig. 9. Variation of water permeability and curing ages of OPSC under different curing conditions.
CS1 = Curing by exposure to site with plastic cover; CS2 = Curing by exposure to site with plastic covered with wet burlap.
CL = Curing by air-drying in Laboratory; CC = Full water curing.
Source: Teo et al. (2007).

(Samouh et al., 2017). According to Clarke (1993), the drying shrinkage of LWAC are generally 1.4–2.0 times that of NWC. However, it is a long-time process, it increases with increase in curing age. High drying shrinkage of LWAC decreases with decrease in MOE of aggregate which offers less restraint to the potential shrinkage of cement paste (Neville, 2008; Fujiwara, 2008). Other factors responsible for higher drying shrinkage of OPSC are moisture content, surface texture, shape, stiffness, type and quantity of aggregates, type of aggregate and its stiffness, contents and volume/surface ratio, curing methods, temperature and duration, moisture content, admixture, relative humidity, rate of duration of drying, degree of hydration, and w/b ratio (Maghfouri et al., 2018; Shafigh et al., 2013; Mindess et al., 2003; Aslam et al., 2016). Previous studies have shown that OPSC exhibited higher drying shrinkage compared with NWC (Maghfouri et al., 2018; Aslam et al., 2017; Mannan and Ganapathy, 2002; Abdullah, 1996).

Shafigh et al. (2016) claimed that the higher drying shrinkage strain of OPSC causes micro-cracks between the OPS and cement matrix to occur in the ITZ. Mannan and Ganapathy (2002) reported the increment of 6% and 14% in drying shrinkage of OPSC than NWC at 28 and 90 days, respectively. The higher drying shrinkage of OPSC occurred due to loss of free water in plastic concrete, by the settlement of solids, chemical reaction of cement paste and drying of concrete. Maghfouri et al. (2018) studied the drying shrinkage of concrete incorporating 20, 40, 60, 80 and 100% OPS as replacement for NWA and reported that the drying shrinkage of concrete increased with the inclusion of OPS compared with control concrete (Fig. 10). Aslam et al. (2017) studied the drying shrinkage of OPSC containing OPBC and found that the substitution of OPS with OPBC resulted in the reduction of drying shrinkage of OPBC. Further reduction in drying shrinkage of OPS-blended OPBC was achieved with the reduction in water-to-cement ratio.

Adeyemi et al. (2017) attributed the higher drying shrinkage strains of OPSC containing POFA than that of the control OPSC to higher content of pores within the concrete which enables water to escape to the atmosphere more easily via evaporation. Traore et al. (2018) found that OPSC produced with OPS treated using SAT and PVA exhibited lowest shrinkage deformations compared with untreated OPS. The shrinkage of concrete is thereby minimised. Shafigh et al. (2013) found that the OPSC containing 10% and 50% F-A showed similar drying shrinkage patterns relative to up to 28 days without fly ash. It has been concluded that F-A has no major effect on OPSC drying shrinkage. According to Maghfouri et al. (2020), the prediction of early and long-term drying shrinkage of hardened concrete is the approach used to predict the serviceability of concrete structure and access the risk of deflection and cracking. Aslam et al. (2018) developed a model for predicting the drying shrinkage of OPSC and OPS-OPBC concrete by comparing the experimental results and the results obtained from different prediction models for the same concrete. The prediction models considered included ACI 209–97 (1997)), EN 1992 (2010) (Eurocode 2), CEB/FIB90 (2001), AASHTO-LRFD (2004), Gardner and Lockman (2001), (GL-2000), AS3600 (2001), JSCE3600 (2007), Sakata et al. (2001) and Bazant and Baweja (1996) shrinkage prediction models. The error percentage and coefficient of variation was used to achieve the best prediction models for the concrete. It was found that the predicted models estimated similar results as the experimental results at the early age while only few of models predicted similar results at the later age. For the OPS-OPBC concrete, the SAK model predicted 100% similar results as the experimental values while GL 2000, MC 2010 and AASHTO models predicted similar results as the experimental results with the accuracy of about 89 to 94%.

Maghfouri et al. (2019) proposed to developing a prediction model based on experimental results and those obtained from two different shrinkage prediction models: ACI 209–97 (1997) and EN 1992 (2010) for NWC and OPSC with 100% OPS aggregate. It was noticed that the drying shrinkage strain of NWC increase with the substitution of NWA with OPS at the early age leading to higher drying shrinkage strain at later age. Both ACI 209–97 (1997) and EN 1992 (2010) shrinkage prediction models showed similar results as the experimental results for the NWA whereas both models predicted lower results compared with the experimental results at early and later ages. Maghfouri et al. (2020) determined the suitable drying shrinkage prediction models by comparing the experimental results with those obtained using five different

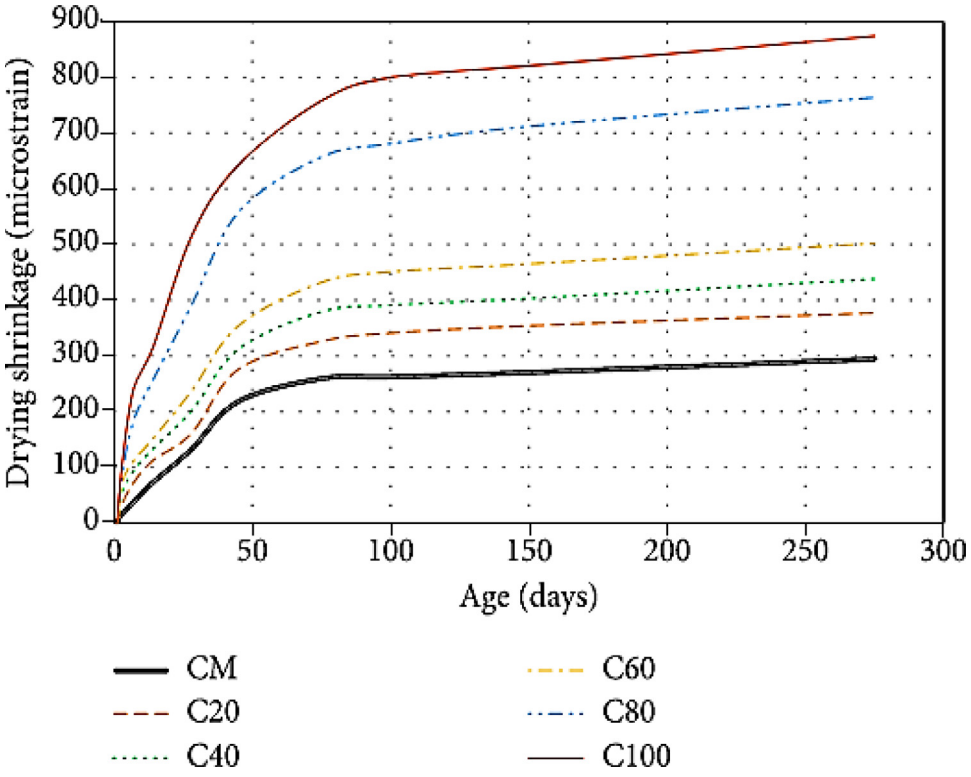


Fig. 10. Variation of drying shrinkage of OPSC.
Source: Maghfouri et al. (2018).

shrinkage prediction models for OPSC containing different OPS volume fractions ranging from 0 to 100%. EN 1992 (2010) shrinkage prediction model was found to be the most-precise prediction model for drying shrinkage for OPSC which showed similarity for the experimental and predicted results at early age whereas GL2000 was the most-precise prediction model for drying shrinkage which showed similarity for the experimental and predicted results at later age. However, Bazant and Baweja (1996) shrinkage prediction model was found to be the least-precise model at both early and late ages.

7.5. Creep behaviour

Creep is another time-dependent deformation that starts immediately but continues at a decreasing rate as long as the concrete load is applied (Kosmatka and Wilson, 2011). Quantity and maximum aggregate size, types of cementing materials, quantity of paste, size and shape of the concrete product, volume to surface ratio of the concrete element, quantity of steel reinforcement, prior curing state, ambient temperature and humidity are the factors influencing the creep of concrete (Olayinka and Ewaen, 2020). Past researches studies have revealed that OPSC exhibited higher creep values than NWC (Mannan and Ganapathy, 2001; Oti et al., 2015). Abdullah (1996) reported a creep value of 400×10^{-5} mm/mm for OPSC compared to 45×10^{-5} mm/mm found for NWC. The creep of OPSC continued to increase without achieving a fixed value after 3 months. Similar trend was reported by Olayinka and Ewaen (2020) where the creep values of 0.00057% and 0.00094% were found for OPSC with 25 and 50% OPS compared to that of NWC (0.00018%). This performance of OPSC may be related to the frictional loss at the ITZ of cement paste and PKS and, thus, requires further in-depth studies. The use of different techniques to enhance the quality of OPSC to increase its creep resistance will be appropriate.

7.6. Chemical resistance

The extent of deterioration in concrete is influence by the interaction between the aggressive agent present in the external environment to which the concrete is exposed and the constituent of hardened cement paste (Teo et al., 2010). The lower resistance of OPSC to chemical attack compared to NWC was largely attributed to the weak bond between OPS and cement paste due to the surface texture of OPS (Chai et al., 2014; Islam et al., 2016; Oti et al., 2015). Muthusamy and Zamri (2015) studied the sulphate resistance of OPSC incorporating 0, 10, 20, 30 and 40% POFA as replacement for cement by submerging the specimens in sodium sulphate solution up to 45 weeks. It was observed that the increased in POFA up to 20% increased the compressive strength of OPSC than the control OPSC indicating better resistance against sulphate resistance (Fig. 11). However, the compressive strength of OPSC decreased with further increase in POFA contents. According to the authors, at the optimum level of replacement of 20% POFA in OPS concrete mix, the pozzolanic reaction between of POFA in cement paste in the presence of moisture is sufficient to consume the by-product of hydration of cement which is $Ca(OH)_2$ to form secondary calcium-silicate-hydrate (C-S-H) gel that fills the voids in concrete-making it denser, thus, the resistance to sulphate attack is improved.

Muthusamy et al. (2021) determined the acid resistance of OPSC containing 0, 10 and 30% coal bottom ash as a substitute for cement after exposure to 3% sulphuric acid solution. It was found that the OPSC containing coal bottom ash exhibited lower mass loss and better strength than the control OPSC at all curing ages, and the OPSC with 10% coal bottom ash showed the least mass loss and highest compressive strength. The improvement in resistance of OPSC to acid attack was attributed to the pozzolanic effect caused by the presence of coal bottom ash which increased the denseness of the concrete internal structure. Islam et al. (2016) investigated the sulphate attack of OPSC incorporating varying POFA contents (0, 10, 30 and 50%) as replacement for cement after soaking in sulphate solution containing nearly 5% $MgSO_4$. The specimens were removed after every two weeks and dried for another two weeks in a normal laboratory condition. It was reported that the compressive strength loss of OPSC with up to 50% POFA and w/b ratio of 0.3 decreased as the curing age increased from 28 to 90 days curing age with the highest reduction achieved at 30% POFA. The reduction in compressive strength loss was attributed to the reaction of

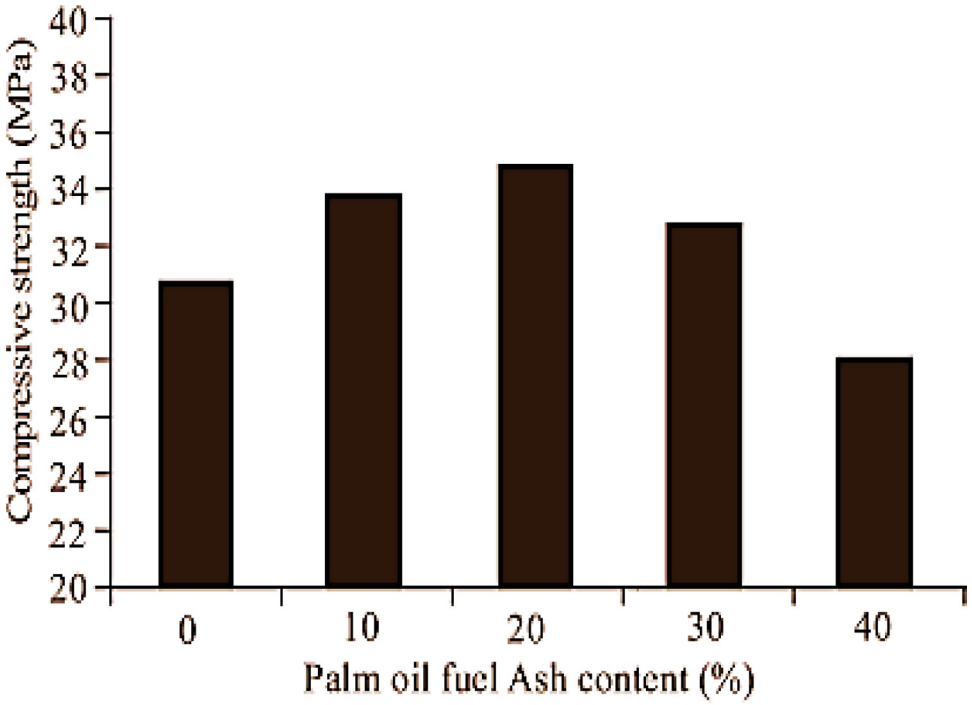


Fig. 11. Compressive strength of OPSC with different POFA content after exposure to sulphate solution.
Source: Muthusamy and Zamri (2015).

POFA with the large amount of available $Ca(OH)_2$, thus, the pozzolanic reaction which produced more calcium-silicate-hydrate gel which prevent $Ca(OH)_2$ to react with magnesium sulphate. However, the OPSC with 70% POFA showed higher compressive strength loss than the control OPSC with w/b of 0.4. Muthusamy et al. (2018) studied the sulphate resistance of concrete containing 0, 10, 20, 30 and 40% fly ash as replacement for sand after exposure to sodium sulphate for the period of 5 months. It was found that the OPS concrete containing 10% fly ash as replacement for sand exhibited the lowest mass change than the control OPSC whereas the mass change increased above that of the control OPSC with further increase in fly ash beyond 10%. According to the authors, at optimum level of 10% fly ash in concrete mix, the pozzolanic reaction consumes the calcium hydroxide, a by-product of hydration of cement can be easily attacked by sulphate ion. In addition, the secondary C-S-H gel generated from the pozzolanic reaction fills the voids and further strengthens the concrete and makes it stronger, denser and more durable during its service life.

7.7. Chloride ion penetration

The main factors that influence the corrosion of steel in concrete are related to the permeation characteristics of concrete (Teo et al., 2010). The penetration of chloride ion into concrete may be through diffusion due to concentration gradient or absorption in solution form (Raharinaivo et al., 1986). The resistance of concrete against chloride ion penetration is determined from rapid chloride penetration test (RCPT) which measures the current passing through cement-based materials for 6 h (Hamada et al., 2020). Teo et al. (2007) found the RCPT values, ranging from 3581 to 4549 Coulombs at 28 days for different curing conditions, indicating a moderate to high chloride ion penetrability according to ASTM C 1202 (2000). The values of charged passed decreased as the curing age increased from 28 to 90 days which gives the impression that chloride penetrability reduced as the curing age increases. This was attributed to the refinement of pore structure in the OPS concrete matrix due to continuous hydration of cement.

Teo et al. (2010) reported that the chloride concentration of OPSC decreased with increase in depth intervals from the ponding face of the specimens under different curing environment. Islam et al. (2016) found the highest charge passed for OPSC with 10% palm oil fuel ash while the lowest charge was found for OPSC without palm oil fuel ash as replacement cement with w/b of 0.4 after exposure to magnesium sulphate for 90 days. Yew et al. (2017) investigated the chloride ion penetration of OPSC produced with two OPS species (dura and tenera) heat-treated at 60 °C and 130 °C over a period of 1 h and without heat treatment. It was observed that the OPSC with heat-treated dura OPS showed greater resistance against ion penetration than the heat-treated tenera OPS. This was attributed to the reduction in inner conductivity of pores and less capillary porosity, which creates the bars of concrete to be more secure from corrosion. Nonetheless, the RCPT values at 28 and 90 days recorded for heat treated dura and tenera OPS indicate a low to very low chloride ion penetrability according to ASTM C 1202 (2000).

7.8. Electrical resistivity

Electrical resistivity is a volumetric property that indicates the ability of material to allow the passage of charges through it (Brandt, 2009). In concrete structures, it is an indication of its susceptibility for corrosion of reinforcement as it characterises the microstructure and is used to control the possibility of chloride penetration (Salvato et al., 2003; Brandt, 2009). Resistivity of concrete is influence by aggregate types, w/b ratio, cement content, moisture content, curing age (Neville, 2008; Ampadu and Torii, 2002). The resistivity of concrete increases with curing age with an inversely correlation existing between the concrete resistivity and chloride diffusion rate. Previous studies have demonstrated that LWAC exhibited higher electrical resistivity with respect to the NWC. Traore et al. (2017) reported higher than that of control and increases as the OPS content in concrete mix increases. The concrete with 50% OPS and 100% contents in concrete mix with the electrical resistivity between the ranges of 100–200 Ω.m as specified by Singh and Singh (2016) can be considered less susceptible to corrosion.

7.9. Fire resistance

The fire resistance of concrete is the concrete's residual compressive strength after exposure to high temperatures for a specific time period (Umasabor and Okovido, 2018). OPS contains higher quantities of

volatile matters (66–78%), fixed carbon in substantial amount (13–23%) and relatively low moisture content to ash ratio (Nizamuddin et al., 2016). Previous studies have shown that the compressive strength of OPSC decreases as the OPS replacement ratio in the concrete mix increases and the rate of heat exposure increases (Umasabor and Okovido, 2018). According to BS 8110–2 (1985), the factors that influence the fire resistance of concrete element are: size and shape of element, disposition and properties of reinforcement, load supported, types of concrete and aggregate, protective cover provided to reinforcement or tendons and conditions of end support.

Olaoye et al. (2011) found that the density and compressive strength decrease with increase in temperature and as the OPS content increases from 5 to 30% at the interval of 5%. Jong and Teo (2015) reported compressive strength of concrete OPSC and POFA after exposure to temperature of 500 ^{O}C was lower with a decrease of 64.15% with respect to that at room temperature (without exposure to heat) at the curing age of 28 days compared with OPS without POFA with a reduction of 74.18% after exposure to elevated temperature. In the study carried out by Jumaat et al. (2015), the control OPSC without POC exhibited higher weight loss compared with those containing POC as the temperature rise from 300 to 500 °C for 30 min and 60 min, respectively. The strength reduction in the range of 22–5% was observed for the OPSC as the replacement level of POC increases from 0 to 100% after exposure to elevated temperature in the range of 150–500 °C for 30 min. Similar trend was reported for the OPSC with and without POC after exposure to the same temperature range for 60 min. According to the authors, the reduction in weight and strength losses OPSC with POC was attributed to the ability of POC to absorb heat without any sign of deterioration as it is produced at a temperature of about 850 °C during the process of burning of OPS and palm oil fibres. Thus, the high heat absorbing capacity of POC present in OPSC enables it to retain its shape without deterioration. Furthermore, POC exhibited better performance at elevated temperature due to increase in content of POC having rough surfaces which improved the bonding between aggregate and cement paste.

8. Structural performance of OPSC

The knowledge of structural behaviour of OPSC is important for the understanding of the influence of concrete constituent on the performance of structural members. Evaluation of structural properties of concrete incorporating OPS substituted for NWA served as a measure to determine the viability of application of OPS and its influence on the large-scale structures (Mo et al., 2014).

8.1. Bending moments and shear capacity

Alengaram et al. (2011) reported higher shear strength for OPSC with shear reinforcement compared with NWC. Despite the insignificant variation, better shear performance of OPSC was attributed to improved shear resistance of the concrete through aggregate interlock resulting from the mortar adhere to the concave portion of OPS which comprises of particles of different shapes that range from parabolic to angular. Fapohunda et al. (2015) found the reduction in both the experimental and theoretical moments with increase in the replacement level of OPS in concrete mix from 0 to 100% suggests that OPS has a relative reducing influence on the concrete. Kupaei et al. (2014) noted that the reinforced OPSC beams had up to 49% higher shear strength than the conventional reinforced NWC beams, which they attributed to the reinforced OPSC beams' enhanced dowel action as well as the better aggregate interlock. Similar findings were reported by Jumaat et al. (2009), who discovered that reinforced foamed OPSC beams had up to 10% higher shear strength than conventional reinforced NWC beams, which were also ascribed to OPS's good aggregate interlock. Yap et al. (2017) reported that OPS fibre-reinforced concrete beams with steel fibres up to 3% showed distinct improvements in the flexural behaviours compared to the control OPSC beams.

8.2. Crack behaviour

Fapohunda et al. (2015) reported that the OPSC reinforced beam failed in flexure with most cracks forming on the beam surface in vertical direction. Kupaei et al. (2014) observed that the OPSC beams showed large number both flexural and shear cracks that had closer spacing (closer widths) compared with NWC beams. The early cracks in the OPSC beam were caused by the lower modulus of rupture of the OPSC. The close spacing and large number of cracks in OPSC beams, on the other hand, resulted in smaller crack widths than in NWC beams. The OPSC crack widths at service loads meet the BS 8110–1 (1997) and BS 8110–2 (1985) durability requirements. Yap et al. (2017) found that OPSC with steel fibre reinforcement up to 3% produced notable increments in the moment capacity and crack resistance. The performance of OPS fibre-reinforced concrete beams was attributed to the crack-bridging effect of steel fibres blunts, changes in the direction of crack propagation and decreased crack opening for the beams under flexural loading which eventually improves the crack resistance of OPS fibre-reinforced concrete beams significantly.

8.3. Deflection

Alengaram et al. (2011) reported greater deflection for OPSC beams with and without shear reinforcement than that of NWC. The higher deflection of OPSC beams was attributed to the lower MoE of OPSC compared with NWC. Fapohunda et al. (2015) observed an increase in deflection with increase in OPS contents. Alengaram et al. (2008) observed brittle failure in conventional reinforced NWC beams, whereas reinforced OPSC beams showed extended deflection and thus failed ductilely. The reinforced OPSC beams, on the other hand, had a larger failure zone in the concrete compression region. The reinforced OPSC and NWC beams' serviceability limit state deflections were very close to those obtained from EN 1992 (2010). Teo et al. (2006) discovered that the steel reinforced OPSC beam provided acceptable serviceability deflection because the span-deflection ratio ranged between 252 and 263, which was within the BS 8110–2 (1985) and Alengaram et al. (2008) limit. Yap et al. (2017) noted that the span to service deflection limits of EN 1992 (2010) and ASTM C1609/C1609M-19 (2019) were met by the OPS fibre-reinforced concrete beams. As a result, the OPS fibre-reinforced concrete beams met the serviceability limit state deflection criteria specified in EN 1992 (2010).

8.4. Ductile behaviour

Traore et al. (2017) found that the concrete strain values increased as the replacement level of OPS in concrete increases. However, OPSC demonstrated a progressive failure with an increase in the load applied. It was, therefore, concluded that the use of OPS as CA improved concrete's ductility behaviour. Alengaram et al. (2011) observed that a reinforcing concrete beam under the applied load, underwent a continuous increasing trend of strain in steel after the formation of cracks and prior to failure with higher strain of about 3500–4500 microstrains for the OPSC beams compared with 3000 microstrains found for NWC beams. Alengaram et al. (2016) investigated the ductility performance of OPSC with and without fibre by conducting a series of quasi-static and blast tests. It was found that OPSC fibre-reinforced concrete exhibited higher ductility and energy-absorption capacity under blast loading which indicates the effectiveness of OPS as alternative aggregate in concrete for resisting both quasi-static and blast loads.

8.5. Bond behaviour

The composite action of reinforcing bars and concrete which leads to the formation of reinforced concrete is as a result of bond between the reinforcing bar and concrete (Mo et al., 2016). Teo et al. (2006) found that the bond strength of OPSC was 2.4 to 3.9 times higher compared with

the design bond strength obtained as specified in BS 8110–1 (1997). Teo et al. (2007) reported that the bond strength values ranged from 3.00 - 5.59 and 6.32–9.36 MPa, respectively depending on the curing condition. Odeyemi et al. (2019) found that the optimum bond strength value of OPS self-compacting concrete (SCC) produced was comparable to that obtained in the similar study for NWC and SCC with 100% crushed granite. It was concluded that OPS can be safely used as substitute for NWA in SCC preparation for structural applications. Alengaram et al. (2010) found that up to 86% of the bond strength of grade 30 NWC was achieved by the OPSC at 28 days curing age.

9. Functional properties

9.1. Thermal properties

The thermal properties of concrete are significant when dealing with concrete durability and energy-efficient building design. Factor which makes SLWAC suitable for high fire rating are low thermal expansion, low strength reduction at high temperature, better insulating properties (Newman, 1993). The thermal properties of concrete include thermal conductivity, diffusivity and coefficient of thermal expansion is influence by the mineral constituent of the aggregates used (Kosmatka and Wilson, 2011).

9.1.1. Thermal conductivity

Thermal conductivity is property which determines the ability of a material to conduct heat (Aurangzeb et al., 2006). Concrete with low thermal conductivity is suitable for reducing the heat losses through the building envelope. Building materials with low thermal conductivity are suitable for thermal insulation because it reduces the amount of energy needed to heat or cool a space (Adesina et al., 2020). The variations in thermal conductivity of LWACs are due to concrete density, aggregate types and moisture content (ACI 122R-02 2002; Newman, 1993; Kodur and Sultan, 2003). LWAs are generally characterised as materials with better insulating and thermal properties. Thus, inclusion of LWA with cementitious matrix improve thermal and insulation in building and structures (Okpala, 1990; Newman, 1993; Sengul et al., 2011). The thermal conductivity of OPSC is within the range (0.05–0.69 W m^{-1} $^{O}C^{-1}$) specified by Neville (2008). According to Okpala (1990), PKS thermal conductivity can be as low as 0.19 W/mK whereas the thermal conductivity of NWA varied from 1.16 W/mK to 8.56 W/mK (Khan, 2002). The thermal conductivity of OPSC is generally lower than that of NWC and decreased with increase in OPS content as revealed in previous studies (Okpala, 1990; Serri et al., 2014a, 2014b; Khankhaje et al., 2017; Traore et al., 2017).

Okpala (1990) found the thermal conductivity value of 0.45 W m^{-1} $^{O}C^{-1}$ for OPSC. Traore et al. (2017) used a Hot-disk probe TPS2500 to measure the thermal conductivity of concrete based on the Transient Plane Source decreased by 28% and 9% with increase in the addition of 50% and 100% OPS and decrease in density of the concrete. Serri et al. (2014) observed that the thermal conductivity of concrete decreases with decrease in cement content and cement/sand ratio and increase with decrease in volume OPS in the concrete mix. Serri et al. (2014) reported the lowest thermal conductivity value of 0.59 W/mk for OPSC with raw shape OPS. Traore et al. (2018) found that the OPSC produced with PVA-treated OPS exhibited lowest thermal conductivity followed by that treated using SAT while the use of OPS treated with CH, SS and TH treatments had no significant influence on the thermal conductivity of OPSC when compare with OPSC produce with untreated OPS. Raheem et al. (2021) reported that the thermal conductivity values of concrete containing 20 to 100% OPS with fixed rice husk ash content of 15% were lower than that of the control at 28 days. The reduction in thermal conductivity was attributed to the lower concrete density due to the structure and porosity of OPS. Also, the presence of RHA contributed to the reduction in thermal conductivity of concrete owing to its lower specific gravity.

9.1.2. Specific heat

The properties that measure the index of the capabilities with which concrete can resist temperature changes is referred to as the specific heat (Traore et al., 2018; Oktay et al., 2015). The specific heat of concrete is also affected by factors similar to the thermal conductivity which are moisture content, types of aggregate and its density. According to Oktay et al. (2015), specific heat is an important property for determining the temperature stability of a structure. Previous studies (Oktay et al., 2015; Mannan and Ganapathy, 2001; Abdullah, 1996) have shown that concretes with low density are characterised with low thermal conductivity and thermal diffusivity but high specific heat. Traore et al. (2018) observed that the specific heat of concrete increases with increase in the content of OPS in the concrete mix and decreases in density of the concrete. Traore et al. (2017) reported the reduction of 43%, 24% and 21% of specific heat of OPSC produced with OPS treated using polyvinyl alcohol and heat compared to OPSC made with untreated OPS.

9.1.3. Thermal diffusivity

Thermal diffusivity is the rate of temperature change in a material and is used to calculate the temperature distribution under transient conditions (Incropera and DeWitt, 1985). Previous studies have shown that thermal diffusivity of concrete shows is affected by similar factors (density, aggregate types and moisture content) as thermal conductivity and specific heat and the behaviour of thermal diffusivity at different temperature level also depends on the same factors influencing these properties. Traore et al. (2017) observed that thermal diffusivity of concrete increases with increase in the content of OPS in the concrete mix and decreases in density of the concrete. The thermal diffusivity of 0.65 mm^2 s^{-1} was found for concrete with 50% OPS in concrete mix is lower than that for 100% OPS with 0.66 mm^2 s^{-1} Serri et al. (2014) reported lower thermal diffusivity of OPSC compared with that of control concrete. The lowest thermal diffusivity value of 0.44 mm^2 s^{-1}. Serri et al. (2014) attributed the decrease in thermal conductivity of concrete mix to the decrease in density of concrete as the content of OPS in the concrete mix increases. Traore et al. (2017) found that the thermal diffusivity of concrete produced using OPS subjected to different pre-treatment methods ranged between 0.59 and 0.79 mm^2/s and were lower compared with that of NWC (1.13 mm^2/s). Raheem et al. (2021) noted that the thermal diffusivity of concrete, incorporating 20 to 100% OPS with fixed rice husk ash content of 15%, was lower than that of the control at 28 days. The reduction in thermal conductivity was attributed to the lower concrete density due to the structure and porosity of OPS.

9.2. Acoustic behaviour

Acoustic characteristics is of particular importance influenced by the constituent materials of concrete. It is a concrete property described either by sound absorption or sound transmission. Sound absorption coefficient is a measure of proportions of sound energy striking a surface which is absorb by that surface (Neville, 2008; Khankhaje et al., 2017). The sound absorption of concrete is influenced by concrete aggregate texture and porosity. Possession of better sound absorption properties is an important characteristic of LWAC (Khankhaje et al., 2017; Shafigh et al., 2010). Zanariah et al. (2018) reported increase in sound absorption coefficient OPSC determined using impedance tube equipment. Okpala (1990) also reported the reduction in noise coefficient of OPSC. In addition, Khankhaje et al. (2017) reported better sound absorption with higher sound reduction coefficient with low sound transmission class for the pervious concrete produced with OPS as CA compared with NWC.



Fig. 12. Structures built using OPSC (a) A Gazebo (b) Uncompleted building (c) Low-cost house (d) Footbridge.
(Source: Jalam et al. (2016); Gibigaye and Godonou (2018); Teo et al. (2006)).

10. Sustainability aspect

10.1. Carbon footprint

The carbon footprint is a measure of quantity of carbon emitted through fossil fuel combustion and it is expressed as tonnes of carbon emitted per annum (Bhatia, 2016; Mehta, 1999). Estimation of carbon footprint of OPSC is important due to the fact that its knowledge reveals the sustainability of concrete compared with normal weight concrete. Mo et al. (2014) found that the amount of carbon dioxide emission (CO_2) emission of OPSC without GGBS was slightly higher than that of NWC while all other OPSC, containing GGBS from 20 to 70%, showed lower CO_2 compared with NWC. The reduction of CO_2 emission up to 0.39 CO_2-e/m^3 was achieved by Islam *et al.* [192] as the POFA content increased from 0 to 25% in OPSC mix compared with NWC. However, there is higher CO_2 of 0.50 CO_2-e/m^3 than that of the NWC with 0.44 CO_2-e/m^3 emission.

10.2. Efficiency factor

Efficiency factor is referred to the strength to weight ratio of concrete and has influence on the general behaviour of concrete structures [192]. According to Mehta and Monteiro (2006), SLWAC exhibited higher efficiency factor compared with NWC of the same grade. Meanwhile, concrete with higher efficiency factor proffered greater economic advantages when used in multi-storey buildings and bridges (Aslam et al., 2017). Islam (2015) found that the efficiency factor of OPSC increases with addition of 10–25% POFA content compared to that of 5% POFA content and NWC under full water-curing condition. Aslam et al. (2017) investigated the efficiency factor of OPSC containing OPBC of 0–50% with w/b ratio of 0.36 and 30–50% with reduced w/b ratio of 0.295 and reported higher efficiency factor of OPSC containing OPBC compared to control OPSC.

10.3. Cost benefit analysis

It has been shown that the incorporation of OPS in concrete production can help reduce the cost of construction. Olanipekun et al. (2006) revealed the cost savings of 34% and 42% of producing concrete with OPSC with two different mix proportions and different OPS contents ranging from 0 to 100%. Sobuz et al. (2014) found the optimum of 15% OPS content with better strength performance and the cost analysis showed 15%, 12% and 10% reduction on the cost of producing concrete of three mix proportions containing 15% OPS content. Islam (2015) reported the decrease of 14% for the cost of producing OPSC with 25% POFA as replacement for OPC and OPS as CA compared with the OPSC without POFA. Wasiu et al. (2015) revealed the cost reduction of 6.5%, 13% and 19.5% with the use of 10%, 20 and 30% OPS contents. Osei and Jackson (2012) also confirmed similar trend of the cost reduction of

utilising OPSC compared with NWC where the cost saving of 8% and 13% were achieved by utilising OPS with volume-batch and weight batch methods, respectively.

11. Structural applications of OPSC

The available structures constructed all over the world using OPS concrete are shown in Fig. 12(a) to (d). Fig. 12(a) shows a Gazebo structure built with OPSC containing rice husk ash as partial replacement for cement. The building was monitored for 18 months without showing any signs of deterioration, according to Jalam et al. (2016). The columns of a one-storey at Missérété, Republic of Benin shown in Fig. 12(b) was also constructed with OPSC in 2014. According to Gibigaye and Godonou (2018), the columns still maintain good record of service as the supporting elements of the structure to date. Fig. 12(c) shows low-cost house of floor area of about 59 m^2 which was built in 2003 using OPSC. The structure in Fig. 12(d) is the footbridge of about 2 m span built in 2001 with OPSC. According to Teo et al. (2006), the house and footbridge were constructed at the Universiti Malaysia Sabah (UMS) campus and never shows sign of defect after being monitored over a long period though both structures were located closed to coaster area.

12. Conclusions

The growing trend of investigations involving the use of OPS as aggregate is justified by the need to develop sustainable construction materials as well as the fact that previous research on these materials frequently opens doors for future research. The school of thought on the use of OPS as an alternative aggregate in concrete production includes (i) reducing the self-weight of concrete structures (ii) lowering construction costs (iii) providing measures to resolve environmental problems related to agricultural waste disposal (iv) using alternative aggregates due to environmental issues related to the extraction and processing of conventional aggregate and (v) alternative aggregate source to conserve depleting natural resources. This review paper demonstrates that the use of as an alternative aggregate is effective and sustainable, based on the positive results obtained from previous studies using methods, processes, and various additional materials that enable the determination of the optimum content of OPS that enhanced its utilisation for developing SLWAC. Thus, the various methods used to achieve the results recorded in previous studies on the use of OPS as a material for the production of SLWAC should serve as guides and set the standard for its future applications. Based on a review of previous studies, the following conclusions can be drawn:

(i) OPS is dark grey to black in colour with convex and concave shape having relatively smooth to rough surface. It has spiky edges with thickness approximately 0.15 to 8.0 mm and size ranging from 1 to 19 mm and usually hard and porous in nature. OPS can be regarded as LWA with specific gravity ranging from 1.17 to 1.58 and approximately 60% lighter compared with NWA.

(ii) The inclusion of OPS in concrete reduces the workability and the trend increases with increase in OPS content. However, the use of superplasticizer and heat treatment of OPS prior application in OPSC mix can be used to improve the workability of OPSC.

(iii) The saturated surface dry density of OPSC varies between 1735 and 2044 kg/m^3 while oven-dry density varies between 1525 and 1986 kg/m^3 the at 28 days showing that OPSC can be categorised as LWAC. Significant reduction in the density of OPSC could be attained through the addition mineral admixture and fibres.

(iv) The mechanical properties of OPSC such as compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity were lower than that of NWC, and the trend decreased with increasing level of OPS in NWA. When OPS was used as substitute for NWA, the 28-day strength values indicating the suitability of concrete for structural lightweight application were achieved at the optimum level of replacement of NWA with OPS. Using various techniques such as addition of mineral admixture, fibres, superplasticizers, oil-palm-boiler-clinker in OPSC mix or heat treatment of OPS prior application in concrete mix, the strength properties of OPSC was significantly enhanced. Consequently, high strength OPSC with compressive strength ranging from 5.78 to 53.05 N/mm^2, the splitting tensile strength ranging from 0.75 to 5.10 N/mm^2, the flexural strength ranging from 2.27 to 6.04 N/mm^2 were reported by various studies.

(v) General, the incorporation of OPS leads to higher water absorption, permeability and drying shrinkage than that of the NWC. Inclusion of optimum of 50% OPS of the total volume of aggregate is suitable for achieving a good quality concrete with final water absorption less than 5%. Continuous full-water curing is effective in reducing water absorption, permeability and drying shrinkage of OPSC. Also, the addition of mineral admixture to OPSC sample is useful for enhancing the water absorption, permeability and drying shrinkage of OPSC.

(vi) OPSC exhibited lower resistance to chemical attack than NWC, and this was attributed to the weak bond which exist between OPS and cement paste due to the surface texture of OPS. Improvement in the chemical resistance of OPSC could be achieved through the addition mineral admixture.

(vii) OPSC, like other LWAC, outperformed NWC in terms of thermal insulation and acoustic properties. The addition of mineral admixture could improve the thermal and acoustic properties of OPSC even further. Thus, thermal and acoustic performance of OPSC suggests its application for structures in tropical regions characterised with hot weather and as a panel in building where minimum noise level is required.

(viii) The application of OPSC in large-scale testing showed that OPS is viable for structural application considering the structural behaviour of OPSC as a complete structural member (beam, column and slab) in terms of ductility, cracks and bond. The inclusion of fibres in OPSC is effective in enhancing the ductility and energy-absorption capacity of OPSC.

(ix) OPSC is more economical and environment-friendly than NWC. The cost savings of up to 42% could be achieved with OPSC. The addition of mineral admixture is effective in enhancing the efficiency and reducing the carbon footprint of OPSC.

13. recommendations

The gaps in the existing literature expected to provide insight into future studies on OPSC are highlighted below. Based on a review of previous studies, the following areas are recommended in future studies.

(i) Much research has been conducted on the workability and strength properties of PKS concrete. Previous studies, however, determined the strength characteristics of OPSC with and without mineral admixtures at early ages of up to 28 days. Long-term studies on the strength properties of OPSC with mineral admixtures or nano-materials are, thus, required.

(ii) The existing studies on the durability properties of OPSC used mineral admixtures such as palm oil fuel ash, fly ash, and coal bottom ash as mineral admixtures, and the testing ages of the properties considered were no more than 90 days. Long-term durability studies on water absorption, rapid chloride penetration, chloride concentration profile, chemical attack, alkali-aggregate reaction, carbonation, freezing and thawing of OPSC admixed with these and other mineral admixtures or nano-materials are required. Furthermore, more research is needed to develop appropriate prediction models for these durability properties.

(iii) Future research should focus on the effects of age, size, species, climate, source, and origin of OPS on the physico-chemical properties of OPS as well as mechanical and durability OPSC. Only a few studies are available in this area.

(iv) By improving the quality of OPS, mechanical strengths and durability characteristics of OPSC can be enhanced. Other treatment methods, such as polymer impregnation by coating OPS with epoxy resins and coating OPS with nanosilane compound, may be investigated in future studies.

(v) Inclusion of fibres and other LWA, such as POC, in OPSC produced positive results in terms of improving OPSC performance. The types, geometry, and contents of the fibres, on the other hand, have effect on the workability and density of OPSC. The size and quantity of POC also have an impact on the OPSC properties. As a result, further investigations into the fibre and POC selection in OPSC is required.

(vi) At the moment, research into the use of OPS in the development of concrete for structural applications is insufficient. The available research on the applications of OPSC in reinforced concrete members such as beams and slabs has revealed the potential of OPSC as a structural member. Further research into the application of OPSC in full-scale beam, slab, and column under service loads and extreme loading conditions is required. In the future, the use of advanced materials to confine OPSC and structural columns incorporating OPSC should be investigated.

(vii) The use of OPSC in the development of prestressed members is critical for broadening the coverage area of OPSC applications. Finally, future applications of OPSC for protective structures against blast and impact loading are visible.

(viii) Assessment of OPSC in full-scale beam, slab and column under service loads and extreme loading conditions are valuable to the implementation of OPS as a viable structural material. The use of advance materials to confinement OPSC and structural column incorporating OPSC should also be examined in future.

(ix) Application of OPSC in developing pre-stressed members is essential to widen the coverage area of the use of OPS in concrete production. Lastly, the applications of OPSC for protective structure against blast and impact loading are also feasible in the future.

Declaration of Competing Interest

The authors declare there are no conflicts of interest.

References

AASHTO-LRFD, 2004. AASHTO-LRFD Bridge design specifications. America Association of State Highway and Transportation Officials, 3rd ed. Washington, USA.

Abdullah, A.A., 1996. Palm oil shell aggregate for lightweight concrete. In: Chandra, S (Ed.), Waste materials Used in Concrete Manufacturing. Use Concrete Manufacturers, Noyes Publications, New York, New York, pp. 624–636.

ACI 122R-02, 2002. Guide to Thermal Properties of Concrete and Masonry Systems, American Concrete Institute 38800, Country Club Drive. American Concrete Institute, Farmington Hills, MI, 48331, USA.

ACI 209-97, 1997. Prediction of creep, Shrinkage and Temperature Effects in Concrete structures. ACI Manual of Concrete Practice. America Concrete Institute, Farmington Hills, Michigan, USA.

ACI 211.2, 1998. Standard Practice for Selecting Proportions for Structural Lightweight Concrete American Concrete Institute 38800. Country Club Drive, Farmington Hills, MI, 48331, USA.

ACI 212.3R-10, 2010. Report on Chemical Admixtures for Concrete. American Concrete Institute, 38800, Country Club Drive, Farmington Hills, MI, 48331, USA.

ACI 213R-03, 2003. Guide For Structural Lightweight Aggregate Concrete, American Concrete Institute 38800. Country Club Drive, Farmington Hills, MI, USA. Detroit 48331.

ACI Education Bulletin E1, 1999. Aggregates for concrete, Developed by Committee E-701, Materials for Concrete Construction. American Concrete Institute.

Adesanya, D.A., Raheem, A.A., 2010. A study of the permeability and acid attack of corn cob ash blended cements. Constr. Build. Mater. 24, 403–409.

Adesina, A., Awoyera, P., Olalusi, O.B., 2020. Agricultural wastes in concrete: potential of oil palm kernel shell aggregate for lightweight concrete production. J. Solid Waste Technol. Manag. 46, 519–529.

Adeyemi, A.O., Anifowose, M.A., Adebara, S.A., Olawuyi, M.Y., Amototo, I.O., 2017. Effect of palm kernel shell (PKS) as aggregate in concrete with varying water cement ratio. Int. Conf. Sci. Eng. Environ. Technol. 2, 55–62.

Afeti, G., 2016. Value chain analysis of the oil palm sector in Liberia. Assessment of the Skills Needs and Training Providers: Inception Report.

Ahmad, R., Hamidin, N., Ali, U.F.M., Abidin, C.Z.A., 2014. Characterization of bio-oil from palm kernel shell pyrolysis. J. Mechan. Eng. Sci. 7, 1134–1140. doi:10.15282/jmes.7.2014.12.0110.

Aiswarya, R., Jagadesh, K.S., Nithila, S., 2018. Experimental investigation on concrete using oil palm shell. Int. J. Adv. Res. Basic Eng. Sci. Technol. 4, 5–19.

Alengaram, U.J., Jumaat, M.Z., Mahmud, H., 2008. Ductility behaviour of reinforced palm kernel shell concrete beams. Eur. J. Sci. Res. 23, 406–420.

Alengaram, U.J., Jumaat, M.Z., Mahmud, H., Fayyadh, M.M., 2011b. Shear behaviour of reinforced palm kernel shell concrete beams. Constr. Build. Mater. 25, 2918–2927.

Alengaram, U.J., Mahmud, H., Jumaat, M.Z., 2010b. Effect of aggregate size and proportion on strength properties of palm kernel shell concrete. Int. J. Hydrog. Energy 41, 7119–7125.

Alengaram, U.J., Mahmud, H., Jumaat, M.Z., 2010a. Comparison of mechanical and bond properties of oil palm kernel shell concrete with normal weight concrete. Int. J. Physic. Sci. 5, 1231–1239.

Alengaram, U.J., Mahmud, H., Jumaat, M.Z., 2011a. Enhancement and prediction of modulus of elasticity of palm kernel shell concrete. Mater. Des. 32, 2143–2148.

Alengaram, U.J., Mohottige, N.H.W., Wu, C., Jumaat, M.Z., Poh, Y.P., Wang, Z., 2016. Response of oil pal shell concrete slabs subjected to quasi-static and blast loads. Constr. Build. Mater. 116, 391–402.

Alengaram, U.J., Muhit, B.A.A., Jumaat, M.Z., 2013. Utilization of oil palm kernel shell as lightweight aggregate in concrete – a review. Constr. Build. Mater. 38, 161–172.

Alexander, M., Mindess, S., 2010. Aggregates in Concrete S.. Taylor and Francis group, New York.

Ampadu, K.O., Torii, K., 2002. Chloride ingress and steel corrosion in cement mortars incorporating low-quality fly-ash. Cem. Concr. Res. 32, 893–901.

AS3600, 2001. Concrete Structures Standards Australia.

Aslam, M., Shafigh, P., Jumaat, M.Z., 2016b. Drying shrinkage behaviour of structural lightweight aggregate concrete containing blended oil palm bio-products. J. Clean. Prod. doi:10.1016/j.jclepro.2016.03.165.

Aslam, M., Shafigh, P., Jumaat, M.Z., 2017a. High strength lightweight aggregate concrete using blended coarse lightweight aggregate origin from palm oil industry. Sains Malays 46, 667–675. doi:10.17576/jsm-2017-4604-20.

Aslam, M., Shafigh, P., Jumaat, M.Z., 2018. Drying shrinkage strain of palm-oil by-products lightweight concrete: a comparison between experimental and prediction models. KSCE J. Civil Eng. 00, 1–12. doi:10.1007/s12205-017-0630-x.

Aslam, M., Shafigh, P., Jumaat, M.Z., Lachemi, M., 2016a. Benefits of using blended waste coarse lightweight aggregates in structural lightweight aggregate concrete. J. Clean. Prod. 119, 108–117. doi:10.1016/j.jclepro.2016.01.071.

Aslam, M., Shafigh, P., Nomeli, M.A., Jumaat, M.Z., 2017b. Manufacturing of high-strength lightweight aggregate concrete using blended coarse lightweight aggregates. J. Build. Eng. 13, 53–62. doi:10.1016/j.jobe.2017.07.002.

ASTM C 1202, 2000. Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration, 4.02. Annual Book of American Society for Testing Materials, Philadelphia.

ASTM C 33/C 33M, 2013. American Society of Testing and Materials, Standard specification For Concrete Aggregates. ASTM International, West Conshohocken, USA.

ASTM C 330, 2014. American Society of Testing and Materials, Standard specification For Lightweight Aggregates For Structural Concrete. ASTM International, West Conshohocken, USA.

ASTM C1609/C1609M-19, 2019. Standard Test Method For Flexural Performance of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading). ASTM, West Conshohocken, PA, USA.

Aurangzeb, A.Z., Gurmani, S.F., Maqsood, A., 2006. Simultaneous measurement of thermal conductivity, thermal diffusivity and prediction of effective thermal conductivity of porous consolidated igneous rocks at room temperature. J. Phys. D 39, 3876–3881. doi:10.1088/0022-3727/39/17/025.

Bamigboye, G.O., Bassey, D.E., Olukanni, D.O., Ngene, B.U., Adegoke, D., Odetoyan, A.O., Kareem, M.A., Enabulele, D.O., Nworgu, A.T., 2020. Waste materials in highway applications: an overview on generation and utilization implications on sustainability. J. Clean. Prod. 283, 124581. doi:10.1016/j.jclepro.2020.124581.

Basri, H.B., Mannan, M.A., Zain, M.F.M., 1999. Concrete using oil palm shells as aggregate. Cem. Concr. Res. 29, 619–622.

Bazant, Z.P., Baweja, S., 1996. Creep and shrinkage prediction model for analysis and design of concrete structures: model B3. Mater. Struct. 28, 357–365. doi:10.1007/BF02486204.

Bhatia, A., 2016. Greener concrete using coal industrial waste (fly ash): an efficient, cost effective and eco-friendly construction materials for the future. J. Sci. Technol. Adv. 1, 8–14.

Brandt, A.M., 2009. Cement-based composites: materials, Mechanical Properties and Performance. Taylor and Francis, New York.

BS 1881-201, 1986. British Standard Institution, Guide to the Use of Non-Destructive Methods of Test For Hardened Concrete London.

BS 8110-1, 1997. Structural Use of Concrete, Code of Practice For Design and Construction. British Standard Institution, London.

BS 8110-2, 1985b. British Standard Institution, Structural Use of Concrete: Code of Practice for Design and Construction". BSI, London.

BS 8110-2, 1985a. British Standard Institution, Structural Use of Concrete: Code of Practice for Design and Construction". BSI, London.

BS 812: Part 105.1, 1990. British Standards Institution, Testing aggregates-Methods For Determination of Particle Shape –Flakiness Index London UK.

BS 812: Part 105.2, 1990. British Standard Institution, Testing aggregates, Methods For Determination of Particle Shape. Elongation index of Coarse Aggregate London UK.

BS 882, 1992. British Standards Institution, Specification for Aggregates from Natural Sources for Concrete, London.
BS EN 206-1, 2000. Specification, performance, Production and conformity, 389 Chiswick high Road. British Standard Institute, London, W4 4AL.
CEB/FIB90, 2001. CEB Code Final Draft Section 3 Materials prEN 1992-1. Comite Euro-International du Beton (CEB) and Federation Internationale De La Precontrainte (FIP), pp. 25–31.
CEB/FIP manual of design and technology, Lightweight Aggregate Concrete, First Pub. Great Britain, 1997.
Chai, W.W.S., Teo, D.C.L., Ng, C.K., 2014b. Improving the properties of oil palm shell (OPS) concrete using polyvinyl alcohol (PVA) coated aggregates. Adv. Mater. Res. 970, 147–152. doi:10.4028/www.scientific.net/AMR.970.147.
Chai, W.W.S., Teo, D.C.L., Ng, C.K., 2014a. Mechanical properties of concrete produced from waste oil palm shell (OPS) coated with polyvinyl alcohol (PVA) as aggregates. In: Sustainable Engineering Society Conference Sustain. Eng. Soc. Australia, Barton, ACT, 2013, pp. 193–198.
Chia, K.S., Zhang, M.H., 2002. Water permeability and chloride penetrability of high-strength lightweight aggregate concrete. Cem. Concr. Res. 32, 639–645. doi:10.1016/S0008-8846(01)00738-4.
Clarke, J.L., 1993. Structural Lightweight Aggregate Concrete. Blackie Academic & Professional, Glasgow, UK.
Dadzie, D.K., Yankah, J.E., 2015. Palm kernel shells as partial replacement for sand in sandcrete production. Chem. Mater. Res. 7, 61–72.
Daneshmand, S., Saadatian, O., 2011. Influence of oil palm shell on workability and compressive strength of high strength concrete. Ann. Fac. Eng. Hunedoara Int. J. Eng. 2, 51–56.
Das, M.K., Patro, S.K., Rath, A.K., 2016. Sustainable use of industrial-waste as partial replacement of fine aggregate for preparation of concrete - a review. Int. J. Sustain. Built Environ. doi:10.1016/j.ijsbe.2016.04.006.
Deepa, C., Kumari, K.S., Sudha, V.P., 2010. Prediction of the compressive strength of high performance concrete mix using tree based modeling. Int. J. Comput. Appl. 6, 18–24.
Djima, M.O.A., Mang'uriu, G.N., Mwero, J.N., 2018. Experimental investigation of lime treated palm kernel shell and sugarcane bagasse ash as partial replacement of coarse aggregate and cement respectively in concrete. Open J. Civ. Eng. 8, 358–372.
Ekenta, C.M., Ajala, M.K., Akinola, M.O., Oseni, Y., 2017. Abandoned Nigerian economic resources: the case of oil palm. Int. J. Agric. Ext. Rural Dev. Stud. 4, 1–16.
Emiero, C., Oyedepo, O.J., 2012. An investigation on the strength and workability of concrete using palm kernel shell and palm kernel fiber as a coarse aggregate. Int. J. Sci. Eng. Res. 3, 1–5.
EN 1992, 2010. Eurocode 2: Design of Concrete Structures-Part 1-1: General rules and Rules For Buildings. European Committee for Standardization.
EuroLightCon, 2000. Properties of LWC Containing Lytag and Liapor, European Union—BriteEuRamIII DocumentBE96-3942/R8. www.sintef.no/static/BM/projects/EuroLightCon/BE3942R08.pdf, 2020. (accessed 25 July 2020).
Eziefula, U.G., Opara, H.E., Anya, C.U., 2017. Mechanical properties of palm kernel shell concrete in comparison with periwinkle shell concrete. Malays. J. Civ. Eng. 29, 1–14.
Fahrizah, Z., Zailan, S.M., Eravan, S., 2014. The effect of mix design on mechanical and thermal properties oil palm shell (OPS) lightweight concrete. J. Civ. Eng. Res. 4, 203–207.
Fapohunda, C., Ikponmwosa, E., Osekita, I., 2015. Structural behavior of reinforced concrete beams with crushed palm kernel shell as coarse aggregates. Acad. J. Sci. Eng. 9, 15–29.
Farahani, J.N., Shafigh, P., Mahmud, H., 2017. Production of a green lightweight aggregate concrete by incorporating high volume locally available waste materials. Procedia Eng. 184, 778–783.
Foong, K.Y., Alengaram, U.J., Jumaat, M.Z., 2015. Enhancement of the mechanical properties of lightweight oil palm shell concrete using rice husk ash and manufactured sand. J. Zhejiang University-SCIENCE A. 16, 59–69.
Fujiwara, T., 2008. Effect of aggregate on drying shrinkage of concrete. J. Adv. Concr. Technol. 6, 31–44.
Gardner, N.J., Lockman, M.J., 2001. Design provisions for drying shrinkage and creep of normal-strength concrete. ACI Mater. J 98, 156–167. doi:10.14359/10199.
Food and Agricultural Organization (FAO), Records, http://fao.org/faostat/en/#data/QC, 2018 (accessed 3 September 2018).
Gibigaye, M., Godonou, G.F., 2018. Mixture proportion for oil palm kernel shell. In: waisundara, V.Y. (Ed.), Palm oil. Intechopen, pp. 133–146. doi:10.5772/intechopen.75601.
Hamada, H.M., Thomas, B.S., Tayeh, B., Yahya, F.M., Muthusamy, K., Yang, J., 2020. Use of oil palm shell as an aggregate in cement concrete: a review. Constr. Build. Mater. 265, 120357. doi:10.1016/j.conbuildmat.2020.120357.
Incropera, F., DeWitt, D., 1985. Introduction to Heat Transfer. John Wile and Sons, New York.
Islam, M.M.U., 2015. Feasibility Study of Ground Palm Oil Fuel Ash as Partial Cement Replacement Material in Oil Palm Shell Lightweight Concrete. University of Malaysia, Kuala Lumpur Unpublished M.Eng. Thesis.
Islam, M.M.U., Mo, K.H., Alengaram, U.J., Jumaat, M.Z., 2016. Durability properties of sustainable concrete containing high volume palm oil waste materials. J. Clean. Prod. 137, 167–177. doi:10.1016/j.jclepro.2016.07.061.
Jalam, U.A., Jalam, A.A., Sale, I.M., 2016. Cost evaluation of utilizing building materials derived from agricultural waste as sustainable materials for lightweight construction. Econ. Environ. Stud. 16, 673–685.
Jong, L.Y., Teo, D.C.L., 2015. Concrete containing palm oil fuel ash (POFA) and oil palm shell (OPS) subjected to elevated temperatures. UNIMAS e-J. Civ. Eng. 13–17.
JSCE3600, 2007. JSCE Guideline for Concrete No. 15, Standard Specifications For Concrete Structures – Design. Concrete Committee of Japan Society of Civil Engineers, Japan.
Jumaat, M.Z., Alengaram, U.J., Ahmmad, R., Bahri, S., Saiful Islam, A.B.M., 2015b. Characteristics of palm oil clinker as replacement for oil palm shell in lightweight concrete subjected to elevated temperature. Constr. Build. Mater. 101, 942–951.
Jumaat, M.Z., Alengaram, U.J., Ahmmad, R., Bahri, S., Saiful Islam, A.B.M., 2015a. Characteristics of palm oil clinker as replacement for oil palm shell in lightweight concrete subjected to elevated temperature. Constr. Build. Mater. 101, 942–951.
Jumaat, M.Z., Alengaram, U.J., Mahmud, H., 2009. Shear strength of oil palm shell foamed concrete beams. Mater. Des. 30, 2227–2236.
Kareem, M.K., Orogbade, B.O., Ibiwoye, E.O., Nafisat, O.O., 2022. The use of palm oil mill effluent as mixing and curing water in cement-based composite. Silicon 14, 1285–1296. doi:10.1007/s12633-020-00864-w.
Khan, M.I., 2002. Factors affecting the thermal properties of concrete and applicability of its prediction models. Build. Environ. 37, 607–614.
Khan, M.M.H., Guong Wui, L., Deepak, T.J., Nair, S., 2016. Use of oil palm shell as replacement of coarse aggregate for investigating properties of concrete. Int. J. Appl. Eng. Res. 11, 2379–2383.
Khankhaje, E., Salim, M.R., Mirza, J., Hussin, M.W., Rafieizonooz, M., 2016. Properties of sustainable lightweight pervious concrete containing oil palm kernel shell as coarse aggregate. Constr. Build. Mater. 126, 1054–1065.
Khankhaje, E., Salim, M.R., Razman, M., Mirza, J., Hussin, M.W., Khan, R., Rafieizonooz, M., 2017. Properties of quiet pervious concrete containing oil palm kernel shell and cockleshell. Appl. Acoust. 122, 113–120.
Khatib, J.M., Mangat, P.S., 1995. Absorption characteristics of concrete as a function of location relative to casting position. Cem. Concr. Res. 25, 999–1010. doi:10.1016/0008-8846(95)00095-T.
Kodur, V.K.R., Sultan, M.A., 2003. Effect of temperature on thermal properties of high- strength concrete. J. Mater. Civ. Eng. 15, 101–107 10.1061/(ASCE)0899-1561(2003)15:2(101).
Kosmatka, S.H., Wilson, M.L., 2011. Design and Control of Concrete Mixtures, EB001, 15th ed. PCA, Skokie, Illinois USA.
Krishnamurthy, M., Vandanapu, S.N., 2019. Micro-structural and interfacial transition zone investigation on oil palm shell lightweight concrete. Int. J. Microstruct. Mater. Prop. 14, 448–461.
Kupaei, R.H., Alengaram, U.J., Jumaat, M.Z., 2014. The effect of different parameters on the development of compressive strength of oil palm shell geopolymer concrete. Sci. World J. 898536, 1–16. doi:10.1155/2014/898536.
Lee, S.K. Handika, N., Tjahjono, E., Arijoeni, E., Study on the effect of pretreatment of oil palm shell (OPS) as coarse aggregate using hot water 50 °C and room temperature water 28 °C to lightweight concrete strength. Proceedings of the MATEC Web of Conferences 276, 01023, pp. 1–9, 2019. https://doi.org/10.1051/matecconf/201927601023.
Maghfouri, M., Shafigh, P., Alimohammadi, V., 2019. Drying shrinkage strain development of agro-waste oil palm shell lightweight aggregate concrete by using the experimental result, ACI and Eurocode prediction models. Int. J. Integr. Eng. 11, 255–263.
Maghfouri, M., Shafigh, P., Alimohammadi, V., Doroudi, Y., Aslam, M., 2020. Appropriate drying shrinkage prediction models for lightweight concrete containing coarse agro-waste aggregate. J. Build. Eng. doi:10.1016/j.jobe.2019.1011648.
Maghfouri, M., Shafigh, P., Aslam, M., 2018. Optimum oil palm shell content as coarse aggregate in concrete based on mechanical and durability properties. Adv. Mater. Sci. Eng. 4271497, 1–14. doi:10.1155/2018/4271497.
Mahmud, H., Jumaat, M.Z., Alengaram, U.J., 2009. Influence of sand/cement ratio on mechanical properties of Palm kernel shell concrete. J. Appl. Sci. 9, 1764–1769.
Mannan, M.A., Alexandra, J., Ganapathy, C., Teo, D.C.L., 2006. Quality improvement of oil palm shell (OPS) as coarse aggregate in lightweight concrete. Build. Environ. 41, 1239–1242.
Mannan, M.A., Ganapathy, C., 2001. Mix design for oil palm shell concrete. Cem. Concr. Res. 31, 1323–1325.
Mannan, M.A., Ganapathy, C., 2002. Engineering properties of concrete with oil palm shell as coarse aggregate. Constr. Build. Mater. 16, 29–34.
Mannan, M.A., Ganapathy, C., 2004. Concrete from an agricultural waste-oil palm shell (OPS). Build. Environ. 39, 441–448.
McNeil, K., Kang, T.H.-K., 2013. Recycled concrete aggregates: a review. Int. J. Concr. Struct. Mater. 7, 61–69. doi:10.1007/s40069-013-0032-5.
Mehta, P.K., 1999. Concrete technology for sustainable development. Concr. Int. 21, 47–52.
Mehta, P.K., Monteiro, P.J.M., 2006. Concrete, Microstructure, Properties and Materials. McGraw-Hill, New York Third ed.
Mindess, S., Young, J.F., Darwin, D., 2003. Concrete, 2nd ed. Prentice Hall, New Jersey, USA.
Mo, K.H., Alengaram, U.J., Jumaat, M.Z., 2014c. A review on the use of agriculture waste material as lightweight aggregate for reinforced concrete structural members. Adv. Mater. Sci. Eng. 365197, 1–9. doi:10.1155/2014/365197.
Mo, K.H., Alengaram, U.J., Jumaat, M.Z., 2014b. Utilization of ground granulated blast furnace slag as partial replacement in lightweight oil palm shell concrete. Mater. Struct. doi:10.1617/s11527-014-0336-1.
Mo, K.H., Alengaram, U.J., Jumaat, M.Z., Jing Lin, M.Y., Lim, J., 2015a. Assessing some durability properties of sustainable lightweight oil palm shell concrete incorporating slag and manufactured sand. J. Clean. Prod. doi:10.1016/j.jclepro.2015.06.122.
Mo, K.H., Alengaram, U.J., Jumaat, M.Z., Liu, M.Y.J., 2015b. Contribution of acrylic fibre addition and ground granulated blast furnace slag on the properties of lightweight concrete. Constr. Build. Mater. 95, 686–695.

Mo, K.H., Alengaram, U.J., Jumaat, M.Z., Liu, M.Y.J., 2017b. Contribution of acrylic fibre addition and ground granulated blast furnace slag on the properties of lightweight concrete. Constr. Build. Mater. 95, 686–695.
Mo, K.H., Goh, S.H., Alengaram, U.J., Visintin, P., Jumaat, M.Z., 2017a. Mechanical, toughness, bond and durability-related properties of lightweight concrete reinforced with steel fibres. Mater. Struct. 50, 1–14. doi:10.1617/s11527-016-0934-1.
Mo, K.H., Yap, S.P., Alengaram, U.J., Jumaat, M.Z., Bu, C.H., 2014a. Impact of hybrid fibre-reinforced oil palm shell concrete. Constr. Build. Mater. 30, 499–507.
Mo, K.M., Alengaram, U.J., Jumaat, M.Z., 2016. Bond properties of lightweight concrete-a review. Constr. Build. Mater. 112, 478–496.
Muthusamy, K., Fadzi, M.Y., Muhammad, A.Z., Akmal, N., Ahmad, S.W., Azzimah, Z.N., Hanafi, H.M., Hafizuddin, R.M., 2018. Effect of fly ash content towards sulphate resistance of oil palm shell lightweight aggregate concrete. IOP Conf. Ser. Mater. Sci. Eng. 342, 012105. doi:10.1088/1757-899X/342/1/012105.
Muthusamy, K., Rasid, M.H., Isa, N.N., Hamdan, N.H., Jamil, N.A.S., Budiea, A.M.A., Ahmad, S.W., 2021. Mechanical properties and acid resistance of oil palm shell lightweight aggregate concrete containing coal bottom ash. Mater. Today Proc. 41, 47–50.
Muthusamy, K., Zamri, N.A., 2015. Short term investigation on sulphate resistance of oil palm shell lightweight aggregate concrete containing palm oil fuel ash as partial cement replacement. Res. J. Appl. Sci. Eng. Technol. 10, 91–94.
Ndoke, P.N., 2006. Performance of palm kernel shells as a partial replacement for coarse aggregate in asphalt concrete. Leonardo Electron. J. Pract. Technol. 5, 145–152.
Nemati, K.M., 2020. Aggregates For Concrete. Civil Engineering Chapter 5 -.
Neville, A.M., 2008. Properties of Concrete, 14th ed. Prentice Hall, New Jersey, USA.
Neville, A.M., Brook, J.J., 2010. Concrete Technology, 2nd ed. Prentice Hall, England.
Newman, J.B., 1993. Chapter 2: properties of structural lightweight aggregate concrete. Structural Lightweight Aggregate Concrete. Chapman and Hall.
Nizamuddin, S., Shrestha, S., Athar, S., Ali, B.S., Siddiqui, M.A., 2016. A critical analysis on palm kernel shell from oil palm industry as a feedstock for solid char production. DE GRUTER Rev. Chem. Eng. doi:10.1515/revce-2015-0062.
Obeng, K., Ocran, K.A.G., Anaba, D., 1997. Palm kernel shell as fuel for burning bricks. Build. Res. Inf. 25, 131–136.
Odeyemi, S.O., Abdulwahab, R., Abdulsalam, A.A., Anifowose, M.A., 2019. Bond and flexural characteristics of partially replaced self-compacting palm kernel shell concrete. Malays. J. Civ. Eng. 31, 1–7.
Okafor, F.O., 1988. Palm kernel shell as a lightweight aggregate for concrete. Cem. Concr. Res. 18, 901–910.
Okafor, F.O., 1991. An investigation of the use of superplasticizer in palm kernel shell aggregate concrete cement. Cem. Concr. Res. 21, 551–557.
Okoroigwe, E., Saffron, C.M., Kamdem, P.K., 2014. Characterization of palm kernel shell for materials reinforcement and water treatment. J. Chem. Eng. Mater. Sci. 5, 1–6.
Okpala, D.C., 1990. Palm kernel shell as lightweight aggregate in concrete. Build. Environ. 25, 291–296.
Oktay, H., Yanruta, S.R., Akpolat, A., 2015. Mechanical and thermophysical properties of lightweight aggregate concretes. Constr. Build. Mater. 96, 217–225.
Olanipekun, E.A., Olusola, K.O., Ata, O., 2006. A comparative study of concrete properties using coconut shell and palm kernel shell as coarse aggregates. Build. Environ. 41, 297. doi:10.1016/j.buildenv.2005.01.029, -30.
Olaoye, R.A., Ajamu, S.O., Oluremi, J.R., 2011. Structural behaviour of palm kernel shell concrete at elevated temperature. Webs J. Epistem. Sci. Eng. Technol. 1, 95–101.
Olayinka, A.A., Ewaen, I.E., 2020. Shrinkage and creep characteristics of palm kernel shell concrete. J. Eng. Stud. Res. 26, 47–56.
Olusola, K.O., Babafemi, A.J., 2013. Effect of coarse aggregate sizes and replacement levels on the strength of palm kernel shell (PKS) Concrete. Civ. Eng. Dimens. 15, 43–50. doi:10.9744/CED.15.1.43-50.
Oriola, K.O., Raheem, A.A., Kareem, M.A., Abdulwahab, R., 2021. Assessment of Workability and Compressive Strength of Rice Husk Ash-Blended Palm Kernel Shell Concrete. LAUTECH J. Civ. Environ. Stud. 7, 100–115.
Osei, D.Y., Jackson, E.N., 2012. Experimental study on palm kernel shells as coarse aggregates in concrete. Int. J. Sci. Eng. Res. Civ. Eng. 5, 56–67.
Oti, J.E., Kinuthia, J.M., Robinson, R., Deries, P., 2015. The use of palm kernel shells and ash for concrete production. World Academy of Sci. Eng. Technol. Int. J. Civ. Environ. Eng. 9, 87–91.
Oti, O.P., Nwaigwe, K.N., Okereke, N.A.A., 2017. Assessment of palm kernel shell as a composite aggregate in concrete. AgricEconInt:CIGR J. 19, 34–41.
Owen, P.L., Newman, J.B., 2003. Newman, Lightweight aggregate manufacture. In: Newman, J., Choo, B.S. (Eds.), Advanced Concrete Technology- Concrete Properties, Elsevier Linacre House. Jordan Hill, Oxford OX2 8DP, Burlington.
Oyejobi, D.O., Abdulkadir, T.S., Yusuf, I.T., Badiru, M.J., 2012. Effects of palm kernel shells sizes and mix ratios on lightweight concrete. USEP J. Res. Inf. Civ. Eng. 9, 21–27.
Perrie, 1994. Flakiness Index. Commentary On SABS 1083. Cement and Concrete Institute, Midrand.
Poku, K., 2002. Small-scale Palm Oil Processing in Africa, FAO Agricultural services Bulletin, 148 Rome.
Prusty, J.K., Patro, S.K., 2015. Properties of fresh and hardened concrete using agro waste as partial replacement for coarse aggregate- a review. Constr. Build. Mater. 82, 101–113.
Raharinaivo, A., Pierre, B., Gerard, P., Georges, G., 1986. The Influence of concrete deterioration on reinforcement rusting. Corros. Prev. Control 83–87.
Raheem, A.A., Nwakanma, E.O., Ogunleye, K.O., 2008. Engineering properties of concrete with palm kernel shell as fine and coarse aggregates. USEP: J. Res. Civ. Eng. 5, 56–67.
Raheem, A.A., Oriola, K.O., Kareem, M.A., Abdulwahab, R., 2021. Investigation on thermal properties of rice husk ash-blended palm kernel shell concrete. Environ. Chall. 5, 1–16.
Ramasamy, P., Asrah, H., Mannan, M.A., Teo, D.C.L., Neglo, K., 2008. Performance of oil palm shell (OPS) and OPS concrete under aggressive conditions. In: Proceedings of the 2nd Engineering Conference (EnCon), 18-19 December, Kuching, Sarawak, Malaysia, pp. 93–98.
Ritchie, H., Roser, M., 2021. Forests and Deforestation.
Sakata, K., Tsubaki, T., Inoue, S., Ayano, T., 2001. Prediction equations of creep and drying shrinkage for-wide ranges strength concrete. In: In creep, drying shrinkage and durability of concrete and other Quasi-brittle Materials. Proceedings of the Sixth International Conference, 69, Cambridge (MA), pp. 1–19. doi:10.2208/jscej.2001.690-1.
Salvato, J.A., Nemerow, N.L., Agardy, F.J., 2003. Environmental Engineering, 5th ed. John Wiley & Sons, Inc., Hoboken, New Jersey.
Samouh, H., Rozière a, E., Loukilia, A., 2017. The differential drying shrinkage effect on the concrete surface damage: experimental and numerical study. Cem. Concr. Res. doi:10.1016/j.cemconres.2017.09.016.
Saranya, S., Kavitha, S., Dethan, P., 2018. Experimental study on durability characteristics of Poly- vinyl alcohol treated oil palm shell concrete. Int. Res. J. Eng. Technol. 5, 1908–1911.
Sengul, O., Azizi, S., Karaosmanoglu, F., Tasdemira, M., 2011. Effect of expanded perlite on the mechanical properties and thermal conductivity of lightweight concrete. Energy Build. 43, 671–676.
Serri, E., Mydin, Md.A.Othuman, Suleiman, Md.Z., 2014a. Thermal properties of oil palm shell lightweight concrete with different mix design. J. Teknologi. 70, 155–159.
Serri, E., Suleiman, M.Z., Mydin, Md.A.Othman, 2015. Durability performance of oil palm shell lightweight concrete as insulation concrete. Appl. Mech. Mater. 747, 217–220. doi:10.4028/www.scientific.net/AMM.747.217.
Serri, E., Suleiman, Md.Z., Mydin, Md.A.Othuman, 2014b. The effects of oil palm shell aggregate shape on the thermal properties and density of concrete. Adv. Mater. Res. 935, 172–175.
Shafigh, P., Alengaram, U.J., Mahmud, H.B., Jumaat, M.Z., 2013b. Engineering properties of oil palm shell lightweight concrete containing fly ash. Mater. Des. 49, 613–621.
Shafigh, P., Jumaat, M.Z., Mahmud, H., 2010. Mix design and mechanical properties of oil palm shell lightweight aggregate concrete: a review. Int. J. Phys. Sci. 5, 2127–2134.
Shafigh, P., Jumaat, M.Z., Mahmud, H., 2011b. Oil palm shell as a lightweight aggregate for production high strength lightweight concrete. Constr. Build. Mater. 25, 1848–1853.
Shafigh, P., Jumaat, M.Z., Mahmud, H., Alengaram, U.J., 2011a. A new method of producing high strength oil palm shell lightweight concrete. Mater. Des. 32, 4839–4843.
Shafigh, P., Jumaat, M.Z., Mahmud, H., Alengaram, U.J., 2013a. Oil palm shell lightweight concrete containing high volume ground granulated blast furnace slag. Constr. Build. Mater. 40, 231–238.
Shafigh, P., Jumaat, M.Z., Mahmud, H.B., 2012a. Effect of replacement of normal weight coarse aggregate with oil palm shell on properties of concrete. Arab J. Sci. Eng. 37, 955–964.
Shafigh, P., Jumaat, M.Z., Mahmud, H.B., Norjidah, H.A., 2012b. Lightweight concrete made from crushed oil palm shell: tensile strength and effect of initial curing on compressive strength. Constr. Build. Mater. 1, 252–258.
Shafigh, P., Nomeli, M.A., Alengaram, U.J., Mahmud, H.B., Jumaat, M.Z., 2016b. Engineering properties of lightweight aggregate concrete containing limestone powder and high volume fly ash. J. Clean. Prod. 135, 148–157.
Shafigh, P., Salleh, S., Ghafari, H., Mahmud, H.B., 2016a. Oil palm shell as an agricultural solid waste in artificial lightweight aggregate concrete. Eur. J. Environ. Civ. Eng. doi:10.1080/19648189.2016.1182084.
Shetty, M.S., 2005. Concrete Technology, (Revised Edition). S. Chand, Ram Nagar, New Delhi.
Singh, G., 2012. Strength and Durability of Concrete Containing Waste Foundry Sand, pp. 1–153 Ph.D. Thesis ThaUniversityPatiala-147004 Punjab, India.
Singh, N., Singh, S.P., 2016. Carbonation and electrical resistance of self-compacting concrete made with recycled concrete aggregates and metakaolin. Constr. Build. Mater. 121, 400–409.
Sobuz, H.R., Hasan, N.Md.S., Tamanna, N., Islam, Md.S., 2014. Structural lightweight concrete production by using oil palm shell. J. Mater. 870247, 1–6. doi:10.1155/2014/870247.
Sofyani, F.D., Handika, N., Tjahjono, E., Arijoeni, E., 2018. Flexural behaviour of reinforced lightweight concrete beam using hot water pre-treated oil palm shell coarse aggregate. MATEC Web of Conferences 276. ICAnCEE 1–7. doi:10.1051/matecconf/201927601032.
Sulymon, N.A., 2005. Palm-kernel shell concrete for structural use – a preliminary investigation. Glob. J. Environ. Sci. 4, 87–91.
Teo, D.C.L., Mannan, M.A., Kurian, V.J., 2006. Structural concrete using oil palm shell (OPS) as lightweight aggregate. Turk. J. Eng. Environ. Sci. 30, 251–257.
Teo, D.C.L., Mannan, M.A., Kurian, V.J., 2010. Durability of lightweight OPS concrete under different curing conditions. Mater. Struct. 43, 1–13. doi:10.1617/s11527-008-9466-7.
Teo, D.C.L., Mannan, M.A., Kurian, V.J., Ganapathy, C., 2007. Lightweight concrete made from oil palm shell (OPS): structural bond and durability properties. Build. Environ. 42, 2614–2621. doi:10.1016/j.buildenv.2006.06.013.
Thong, C.C., Teo, D.C.L., Ng, C.K., 2015. The effect of polyvinyl alcohol (PVA) on the mix proportion of oil palm shell (OPS) concrete. Appl. Mech. Mater. 695, 297–300.
Thong, C.C., Teo, D.C.L., Ng, C.K., 2017. Durability characteristics of polyvinyl alcohol–treated oil palm shell concrete. J. Mater. Civ. Eng. 29, 1–9.
Traore, Y.B., Messan, A., Hannawi, K., Gerard, J., Prince-Agbodjan, W., Tsobnang, F., 2017. Experimental investigations on the physical and mechanical properties of lightweight concrete using oil palm shell as coarse aggregate. J. Mater. Sci. Eng. A 7, 157–168.

Traore, Y.B., Messan, A., Hannawi, K., Gerard, J., Prince-Agbodjan, W., Tsobnang, F., 2018. Effect of oil palm shell treatment on the physical and mechanical properties of lightweight concrete. Constr. Build. Mater. 161, 452–460.

Umasabor,R.I., Okovido,J.O., Fire resistance evaluation of rice husk ash concrete. Heliyon. 4 (2018) 1–14. e01035. doi:10.1016/j.heliyon.e01035.

Vakhshouri, B., Nejadi, S., 2017. Review on the mixture design and mechanical properties of the lightweight concrete containing expanded polystyrene beads. Aust. J. Struct. Eng. doi:10.1080/13287982.2017.1353330.

Wasiu, J., Salami, V., Awolusi, T.F., 2015. Oil palm fiber as partial replacement aggregates for normal concrete. Int. J. Eng. Res. 4, 487–491.

Whitehurst, E.A., 1986. Evaluation of concrete properties from sonic test. ACI Monograph 2, 73.

Williams, F.N., Ijigah, E.A., Anum, I., Isa, R.B., Obanibi, A.O., 2014. Suitability of palm kernel shell as coarse aggregate in lightweight concrete production. Civ. Environ. Res. 6, 55–59.

Yap, S.P., Alengaram, U.J., Jumaat, M.Z., 2013. Enhancement of mechanical properties in polypropylene- and nylon-fiber reinforced oil palm shell concrete. Mater. Des. 49, 1034–1041.

Yap, S.P., Alengaram, U.J., Mo, K.H., Jumaat, M.Z., 2017b. High strength oil palm shell concrete beams reinforced with steel fibres. Mater. Constr. 67, e142. doi:10.3989/mc.2017.11616.

Yap, S.P., Alengaram, U.J., Mo, K.H., Jumaat, M.Z., 2017a. Ductility behaviour of oil palm shell steel fibre-reinforced concrete beams under flexural loading. Eur. J. Environ. Civil Eng. 23, 866–878. doi:10.1080/19648189.2017.1320234.

Yew, M.K., Bin Mahmud, H., Ang, B.C., 2015a. Influence of different types of polypropylene fibre on the mechanical properties of high-strength oil palm shell lightweight concrete. Constr. Build. Mater. 90, 36–43.

Yew, M.K., Mahmud, H.B., Ang, B.C., Yew, M.C., 2014b. Effects of oil palm shell coarse aggregate species on high strength lightweight concrete. Adv. Mater. Sci. Eng. 387647, 1–12. doi:10.1155/2014/-387647.

Yew, M.K., Mahmud, H.B., Ang, B.C., Yew, M.C., 2014a. Effects of heat treatment on oil palm shell coarse aggregate for high strength lightweight concrete. Mater. Des. 54, 702–707.

Yew, M.K., Mahmud, H.B., Ang, B.C., Yew, M.C., 2015b. Effects of low volume fraction of polyvinyl alcohol fibers on the mechanical properties of oil palm shell lightweight concrete. Adv. Mater. Sci. Eng. 425236, 1–11. doi:10.1155/2015/425236.

Yew, M.K., Yew, M.C., Saw, L.H., Ang, B.C., Lee, M.L., Lim, S.K., Lim, J.H., 2017. Enhancement of durability properties of heat-treated oil palm shell species lightweight concrete. AIP Conf. Proc. 1828, 020012. doi:10.1063/1.4979383.

Yusuf, I.T., Babatunde, Y.O., Abdullah, A., 2018. Investigation on the flexural strength of palm kernel shell concrete for structural applications. Malaysia J. Civ. Eng. 30, 269–281.

Zanariah, J., Zaiton, H., Nizam, Y.M., Khairulzan, Y., Dianah, M., Nadirah, D., O.M, Hanifi, 2018. Preliminary investigation of acoustical properties of concrete containing oil palm shell as an aggregate replacement. In: E3S Web of Conferences 3401015, pp. 1–8. doi:10.1051/e3sconf/2018340101.