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Palm oil industry's bi-products as coarse aggregate in structural lightweight concrete

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Abstract. Recent trend is to use the lightweight concrete in the construction industry because it has several advantages over normal weight concrete. The Lightweight concrete can be produced from the industrial waste materials. In South East Asian region, researchers are very keen to use the waste materials such as oil palm shell (OPS) and palm oil clinker (POC) from the palm oil producing industries. Extensive research has been done on lightweight concrete using OPS or POC over the last three decades. In this paper the aggregate properties of OPS and POC are plotted in conjunction with mechanical and structural behavior of OPS concrete (OPSC) and POC concrete (POCC). Recent investigation on the use of crushed OPS shows that OPSC can be produced to medium and high strength concrete. The density of OPSC and POCC is around 20-25% lower than normal weight concrete. Generally, mechanical properties of OPSC and POCC are comparable with other types of lightweight aggregate concrete. It can be concluded from the previous study that OPSC and POCC have the noteworthy potential as a structural lightweight concrete.

Keywords: agricultural waste materials; oil palm shell (OPS); palm oil clinker (POC); coarse aggregate; mechanical properties; structural behavior

1. Introduction

Nowadays, lightweight concrete is a popular choice in the construction sector. The use of lightweight concrete (LWC) has many advantages over normal weight concrete. Structural lightweight concrete allows Engineers to use smaller structural elements due to reduction of self-weight. Building can be taller using the same foundation and concrete beams can go longer due to greater span-depth ratio (Chandra and Berntsson 2002, Shannag 2000). As lightweight aggregate concrete (LWAC) reduces the amount of dead load and construction cost noticeably, it is fair to claim that it has a significant advantage over normal weight concrete (Lopez *et al.* 2006). And because of this reason, production of structural lightweight concrete is becoming popular every day in construction industry. Lightweight concrete generally has the density of less than 2000 kg/m^3. The lightweight concrete having compressive strength of more than 20 MPa is known as structural lightweight concrete (BS8110 1997).

Lightweight concrete, especially which are made from lightweight aggregates are most commonly used for structural purpose and has found applications in a variety of constructions worldwide such as bridges, precast members, buildings and also offshore structures construction (Chandra and Berntsson 2002, Raithby and Lydon 1981). In general these lightweight concretes made from expanded clay, shale, pumice are mostly utilized in the western countries and are not extensively used in developing countries, which may due to the limited supply and high production cost of the aggregates.

Malaysia is one of the largest palm oil producing countries in the world. Over 4 (four) million tons of OPS is being produced throughout the country annually as a waste materials (Jumaat *et al.* 2015, Teo *et al.* 2006c). However, these OPS were of no economical values and were mostly left to decay (Okpala 1990). In recent years, it is being used as raw burning materials for power production in the palm oil producing factories (Choong 2012). And the residue from the burning materials is known as POC. Now-a-days, the use of OPS and POC as coarse aggregate in concrete has become popular in research owing to its environmental and economic benefits (Alengaram *et al.* 2008b, Basri *et al.* 1999, Mannan and Ganapathy 2001b, Okafor 1988, Okpala 1990, Shafigh *et al.* 2011b). Concrete which has employed OPS and POC has been termed as oil palm shell concrete (OPSC) and palm oil clinker concrete (POCC) respectively (Ahmmad *et al.* 2014, Huda *et al.* 2016, Mohammed *et al.* 2014).

Three singly and three doubly reinforced beams were investigated with different reinforcement ratios in the study of Teo *et al.* (2006b). Final failure happened because of crushing of the compression concrete showing ample amount of ultimate deflection. Yielding of the tensile reinforcement occurred before crushing of the concrete cover in the pure bending zone. The failure stage experienced significant deflection. Experimental ultimate

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moments (M_{ult}) and theoretical design moments (M_{des}) showed a closer correlation for doubly reinforced beams than singly reinforced beams (Teo *et al.* 2006b). For beams with reinforcement ratios of 3.14% or less, the ultimate moment found from the experiment was about 4-35% higher than the predicted values. They concluded that for OPS concrete beams, BS8110 (1997) could be used to calculate ultimate moment capacity and deflection for reinforcement ratios up to 3.14%. Flexural performance of reinforced oil palm kernel shell concrete (OPKSC) beams was published by Alengaram *et al.* (2008a) showing more ductile behavior than normal weight concrete beams. Mohammed *et al.* (2014) reported the flexural performance of POC concrete beam considering identical specification as the study of Teo *et al.* (2006b). Even though POCC had a lower value of modulus of elasticity, the deflection of reinforced POCC beams, with reinforcement ratio less than 0.5 under the design service load satisfied BS 8110 (BS8110 1997) code.

A considerable amount of research have been carried out to aid the understanding of the introduction of OPSC and POCC concrete mixture designs separately and its material properties. The OPSC or POCC constitutes of cement, sand, OPS/POC and water. It is fascinating that both the OPS and POC have low bulk density. Lightweight concrete can be produced by using OPS and POC as coarse aggregate. Hence, it is of utmost interest to know the behavior of an innovative lightweight concrete employing both OPS and POC as coarse aggregate.

In this study a summary of aggregate properties of OPS and POC are shown along with mechanical and structural behavior of OPS concrete (OPSC) and POC concrete (POCC). Recent investigation on the use of crushed OPS shows that OPSC can be produced to medium and high strength concrete. The density of OPSC and POCC is around 20-25% lower than normal weight concrete. As the mechanical properties of OPSC and POCC are similar to the existing type of lightweight aggregate concrete, OPSC and POCC might achieve noteworthy successes.

2. Lightweight concrete

The density is the main parameter to define the concrete as a lightweight concrete. Usually density of lightweight concrete is lower than the normal weight concretes. According to the application of lightweight concrete, it can also be ordered in three categories (Neville 2008):

1. Structural lightweight concrete (ASTM C 330-89): The density of this concrete is between 1350 to 2000 kg/m^3 and 28-day compressive strength should be greater than or equal of 17 MPa. This concrete is considered for structural purpose.

2. Lightweight concrete for masonry units (ASTM C 331-89): The usual density of this concrete is between 500 to 800 kg/m^3 and 28-day compressive strength should be in between 7 to 17 MPa.

3. Low-density or insulation concrete (ASTM C 332-87): The usual density of this concrete is between 300 to 800 kg/m^3 and 28-day compressive strength should be in-between 0.7 to 17 MPa. Furthermore, thermal conductivity coefficient of this concrete should be below 0.3 J/m2s0C/m.

Fig. 1 Mass storage of oil palm shell (OPS)

In the point of view of lightweight concrete's production method, lightweight concrete can be classified into three categories (Neville and Brooks 2008):

1. Lightweight concrete made from the aggregate which are porous in nature with low specific gravity is known as lightweight aggregate concrete.

2. If the air void is introduced in the cement paste to produce the lightweight concrete, this type of lightweight concrete is known as aerated, foam or gas concrete.

3. Lightweight concrete can also be made by avoiding the fine aggregate between the coarse aggregate particles. This concrete is widely termed as no-fine concrete.

Generally, it can be said that lightweight concrete should have the oven-dry density of about 300 to 2000 kg/m^3, with 28 day compressive strengths of 1 to over 17 MPa and the coefficient of thermal conductivities of 0.2 to 1.0 W/mk (Newman and Owens 2003). Properties of structural lightweight concrete is very similar to other lightweight concrete except that it has a lower density and higher 28 days compressive strength. Typical density of structural lightweight concrete ranges from 1400 to 2000 kg/m^3 (Shannag 2011). Typical compressive strength of structural lightweight concrete ranges from 20 to 35 MPa (Kosmatka *et al.* 2002). High strength lightweight concrete can also be produced from the lightweight aggregate. Various pozzolans such as fly ash, silica fume, metakaolin, calcined clays and shales can be used to produce high strength (35-70 MPa) lightweight aggregate concrete with a maximum water to cement material ratio of 0.45 (Holm and Bremner 2000). Usually, the compressive strength can be increased by reducing the size of coarse aggregate and/or partial replacement of lightweight fine aggregate with a good quality normal weight sand at a given cement and water content (Mehta and Monteiro 2006).

3. OPS and POC as lightweight aggregate

Yielding more than half of the world's palm oil every year, Malaysia is the second largest source of palm oil in the world (Teo *et al.* 2006c). At the same time, a huge quantity of solid waste comes from these palm oil factories.

Fig. 2 Storage of palm oil clinker (POC)

Fig. 3 OPS aggregates: (a) original size, (b) original small size and (c) crushed from original size

The residue of palm oil industries includes OPS and POC (Figs. 1 and 2). Recently these waste materials are being used in land filling and production of charcoal. This not only causes soil pollution but also affects the ground water supply source. Therefore, using them as a building construction material is turning waste into resources, a very efficient waste management option as well as a very useful structural design option. This will also help prevent the depletion of natural resources and maintain ecological balance.

The use of OPS as a lightweight aggregate in producing the lightweight concrete was started in early 1985 (Salam *et al.* 1985). Continuing research revealed that OPS and POC can be utilized as a lightweight aggregate to produce the structural lightweight concrete. (Abdullah 1996, Basri *et al.* 1999, Mannan and Ganapathy 2001b, Teo *et al.* 2007).

4. Properties of OPS aggregate

4.1 Shape, thickness, texture

Palm oil processing system is divided into six primary stapes: sterilization, threshing, pressing, depericarping, separation of palm kernel and palm shell, and clarification (Abdullah 1996). Oil palm shells is one of the byproduct of this process. The color for oil palm shells is dark grey to black. The shells are found in different shapes depending on the breaking pattern of the nut. OPS has the concave and convex faces. The surfaces of the concave and convex faces are fairly smooth. However, the broken edge is rough and spiky. The thickness of the OPS varies depending on the type of palm tree from which the nuts are obtained. Generally it ranges from 0.15-8 mm (Basri *et al.* 1999, Okpala 1990). It is worth mentioning that Shafigh *et al.* (2011a) have reported that OPS aggregate from crushing the larger original OPS aggregate can be an appropriate method to enhance the compressive strength of lightweight OPS concrete (Fig. 3). After collection of OPS, it has been washed and crushed using a stone-crushing machine in the laboratory.

Table 1 Chemical composition of OPS aggregate (Teo *et al.* 2007)

Elements	Results (%)
Ash	1.53
Nitrogen (as N)	0.41
Sulphur (as S)	0.000783
Calcium (as CaO)	0.0765
Magnesium (as MgO)	0.0352
Sodium (as Na_2O)	0.00156
Potassium (as K2O)	0.00042
Aluminum (as Al_2O_3)	0.130
Iron (as Fe_2O_3)	0.0333
Silica (as SiO_2)	0.0146
Chloride ((as Cl^-)	0.00072
Loss on Ignition	98.5

4.2 Water absorption

The 24 hour water absorption capacity of OPS is in the range of 21-33%. This value indicates that the OPS has the high level of water absorption capacity compared to the normal weight aggregates that usually have the water absorption capacity less than 2 percent (Neville 2008). It was being reported that the porosity of the shell is about 37% (Okpala 1990). As OPS is a highly porous materials, it can absorb more water than relatively nonporous materials like gravel. Mannan *et al.* (2006) reported that 20% poly vinyl alcohol solution as a pre-treatment methods can improve the quality of OPS. This decreased the water absorption of OPS significantly from 23.3% to 4.2%.

4.3 Bulk density and specific gravity

Due to the higher porosity of OPS than normal weight aggregates, loose and compacted bulk densities varies in the range of 500-600 kg/m^3 and 590- 620 kg/m^3 respectively. The specific gravity of OPS varies in the range of 1.14-1.37 respectively. The densities of OPS are nearly 60% lighter than normal weight coarse aggregates. Thus it falls in the range of light weight aggregate and concrete using OPS aggregate exhibits lightweight concrete (Okafor 1988, Okpala 1990).

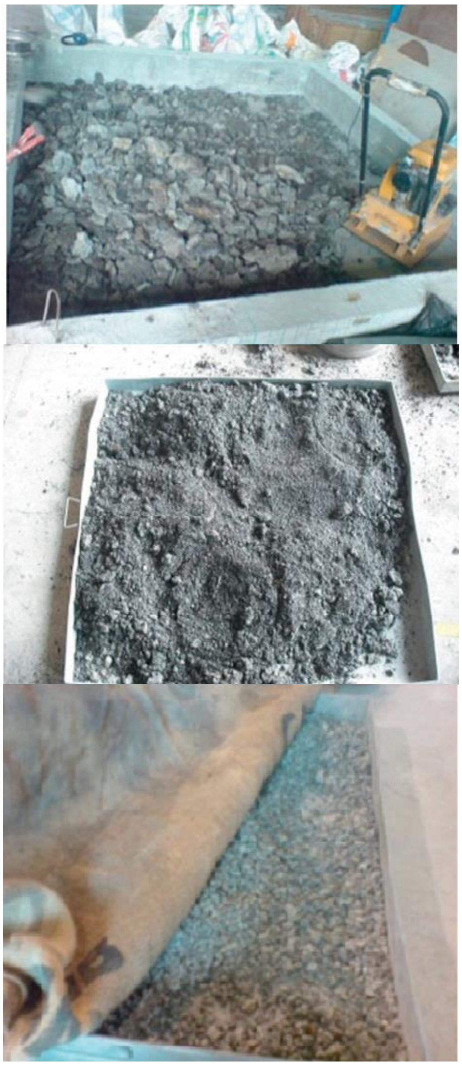

Fig. 4 A process flow of POC aggregate

4.4 Compressive and impact value

The OPS is hard and does not erode easily. Basri *et al.* (1999) reported that the Los Angeles abrasion value of the OPS and crushed stone is 4.8% and 24%, respectively. This values indicates that it is much lower than conventional coarse aggregates and has a good resistance to wear. Furthermore, (Teo *et al.* 2007) reported that the aggregate impact value and the aggregate crushing value of OPS aggregates were much lower than conventional crushed coarse aggregates. This shows that the aggregate has a good absorbance to shock. Koya and Fono (2009) demonstrated that because these shells are subjected to hard and variable braking forces particles they can be effectively used in brake lining formulations when properly combined with other additives. There is only one report concerning the compressive strength of OPS aggregate. Okpala (1990) stated that the indirect compressive strength test of OPS aggregate was 12.10 MPa with a standard deviation of about 2 MPa. Table 1 shows the chemical composition of OPS aggregate. From the table, it can be observed that the loss on ignition of OPS is about 100%. This percentage was reported by Mannan and Ganapathy (2002).

5. Properties of POC aggregate

5.1 Shape and texture

Malaysian palm oil industries burn the palm oil waste to yield steam needed for the milling process. The bi product of this burning process is palm oil clinker (POC) (Mohammed *et al.* 2011). Their color ranges from gray to black. After processing this raw POC, it is being used to produce lightweight concrete. A process flow of POC aggregate is shown in the Fig. 4. The raw POC was collected from the palm oil processing mill then crushing and sieving were performed to get the expected particle sizes (Mohammed *et al.* 2013). The POC aggregates can be found in different shape like angular, polygonal etc., subjected to the breaking pattern of the raw POC. The faces of the POC are very rough and porous. However, the broken edge is spiky. Usually particles less than 5 mm are considered as fine aggregate and particles in the range of 5-14 mm are considered as coarse aggregate. The pore space of the POC coarse aggregate will be occupied by the fine aggregate and cement paste and in turn the pore space of the fine aggregate will be packed by cement paste creating a strong matrix in concrete.

5.2 Water absorption

The 24 hour water absorption capacity of POC is 4.35%. This value indicates that the POC has the high level of water absorption capacity compared to the normal weight aggregates that usually have the water absorption capacity less than 2 percent (Neville 2008). In general, lightweight aggregate have higher water absorption values compared to normal weight aggregate. The water absorption values indicated that POC has the lower water absorption capacity among the lightweight aggregates (Huda *et al.* 2016). Higher water absorption were stated for OPS and pumice aggregate which have a value of about 37% (Hossain 2004). Lightweight aggregate concrete has an internal water supply stored in the porous lightweight aggregate due to this water lightweight concrete is less sensitive to the poor concrete at their early ages compared to the normal weight concrete (Al-Khaiat and Haque 1998).

5.3 Bulk density and specific gravity

POC aggregates are porous in nature. Therefore, low bulk density and high water absorption were expected. The specific gravity of POC varies in the range of 1.7-1.82. POC coarse aggregate has a unit weight of 781 kg/m^3. This is approximately 48% lighter than the crashed granite stone (Teo *et al.* 2006c). Thus it falls in the range of light weight aggregate and concrete using POC aggregate exhibits lightweight concrete (Okafor 1988, Okpala 1990).

5.4 Compressive and impact value

Los Angeles abrasion value of the POC is 27%. This value indicates the similar results to normal weight aggregate. Higher aggregate impact value (AIV) and aggregate crushing value (ACV) of POC aggregates have

Table 2 Chemical composition of POC aggregate (Ahmmad *et al.* 2014)

Elements	Results (%)
Silica (as SiO_2)	59.63
Potassium (as K_2O)	11.66
Calcium (as CaO)	8.16
Phosphorus (as P_2O_5)	5.37
Magnesium (as MgO)	5.01
Iron (as Fe_2O_3)	4.62
Aluminum (as Al_2O_3)	3.7
Sulfur (as SO_3)	0.73
Sodium (as Na_2O)	0.32
Titanium (as TiO_2)	0.22
Others	0.58

Table 3 Acceptable mix proportion of OPS concrete

Mix design of OPS concrete	Mix proportion Cement:sand:LWA:water	Remarks
Teo *et al.* (2006b) Teo *et al.* (2006c) Teo *et al.* (2006a)	1:1.66:0.60:0.38	Cement content fixed at 510 kg/m^3
Alengaram *et al.* (2008a)	1:1.20:0.80:0.40	Cement content fixed at 480 kg/m^3 5% fly ash added 10% silica fume added 1.0% superplasticizer added
Alengaram *et al.* (2011)	1:1.20:0.80:0.40	Cement content fixed at 500 kg/m^3 5% fly ash added 10% silica fume added 1.0% superplasticizer added
Jumaat *et al.* (2009)	1:1.20:0.80:0.40	Cement content fixed at 420 kg/m^3 6.7 kg/m^3 foam content used 5% fly ash added 10% silica fume added 0.5% superplasticizer added
Ahmed and Sobuz (2011)	1:1.71:0.39:0.41 1:1.65:0.25:0.45 1:1.65:0.37:0.45	50% OPS+50% granite 10% OPS+90% granite 15% OPS+85% granite
Muda *et al.* (2012)	1:1.5:0.45:0.40	5% silica fume added 2.0% superplasticizer added

been reported compared to the normal weight aggregates (Teo *et al.* 2006b). More precisely the AIV and ACV were about 34% and 30% higher than the normal weight aggregate, respectively. The higher ACV value for the POC aggregate might be caused by the particle shape of POC used in this study which is porous and angular. The aggregate with such shape and condition have the possibility to be crushed when load is applied on them. Table 2 shows the chemical composition of POC aggregate.

6. Concrete with OPS aggregate

6.1 Mix design

For a particular compressive strength, cement content is fairly constant in well-proportioned concrete mixtures. Hence, several trial mixtures with varying cement contents are prerequisite to produce a range of compressive strengths (Kosmatka *et al.* 2002). The oil palm shells tend to segregate in wet concrete mixes due to its lighter weight in the cement matrix. A good mix design can only be found through the trial mixes (Abdullah 1996). Mix design methods for normal weight concrete are not compatible with the lightweight aggregate concrete (Huda *et al.* 2015, Mannan and Ganapathy 2001b, Shetty 2005). Furthermore, they followed the mix design method for lightweight aggregate such as Leca, fumed slag, Aglite and Lytag.

Table 4 Approximate relationships between average compressive strength and cement content of structural lightweight concrete

Compressive strength (MPa)	Cement content (kg/m^3)	
	All-lightweight	Sanded-lightweight
17	240-305	240-305
21	260-335	250-335
28	320-395	290-395
34	375-450	360-450
41	440-500	420-500

However, these methods were not suitable for OPS concrete. They explained that the OPS aggregate is a natural organic material with a smooth texture and different shapes. According to ACI-213R, for structural lightweight concrete (compressive strength ranges from 17 to 41 MPa) the cement content is in the range of 240-500 kg/m^3 (Mehta and Monteiro 2006). Table 3 summarizes the mix designs of OPS concrete used for the investigation of reinforced OPS concrete beam in the past researches. This guideline could be used for future investigations since the resulting reinforced concrete beams were performed satisfactorily.

6.2 Slump

To check the uniformity of concrete mix of given proportions, Slump is very useful (Neville 1995). Slump test is the standard test to understand the workability of concrete. It measures the consistency of concrete according to ACI 116R. It is reported that with the increase in water cement ratio, the slump value increases. (Mannan and Ganapathy 2001b, Okafor 1988, Okpala 1990) found the slump to be very low (0-4 mm) indicating a very low workability (Neville 1995). At the earlier age of research with OPS, Abdullah (1996) achieved 15MPa compressive strength with slump values in the range of 0-260 mm. However, High slump value (105 mm) can be achieved by incorporating a small percentage of superplasticizer (Alengaram *et al.* 2010).

6.3 Density

The density of lightweight concrete is the most important factor for the structural applications (Rossignolo *et al.* 2003). The typical density of lightweight concrete ranges from 1400 to 2000 kg/m^3. Whereas normal weight concrete has the density of 2400 kg/m^3 (Chen and Liu 2005). Okafor (1988) reported that the production of concrete with a density of approximately 1758 kg/m^3 using this agricultural solid waste (OPS) is possible. According to Basri *et al.* (1999) investigation, OPS concrete has 19-20% lower air-dry densities than normal weight concrete. Other studies show that OPS concrete is 22% (Mannan and Ganapathy 2004) and 24% (Alengaram *et al.* 2008b) lower than the normal weight concrete. Furthermore, it was reported that OPS concrete having 10% and 15% fly ash are

2% and 3% lower than OPS concrete without fly ash content (Mannan and Ganapathy 2004).

6.4 Compressive strength

To define the excellence of concrete in practice, the most commonly used parameter is the compressive strength (Wiegrink *et al.* 1996). The 28-day concrete compressive strength should not be less than 17 MPa for structural purpose (Neville and Brooks 2008). As per ACI Committee 211.2 (1998), the projected relationship between average compressive strength and cement content of structural lightweight concrete is shown in Table 4.

Okafor (1988) reported that the maximum 28 day compressive strength of lightweight concrete produced from OPS is about 25 to 35 MPa. This range is within the typical compressive strength for structural lightweight concrete of 20-35 MPa (Kosmatka *et al.* 2002). The 28-day compressive strength of OPS concrete was found as 20 and 24 MPa by using 480 kg/m^3 cement, water to cement ratio of 0.41 and mix proportion of 1:1.71:0.77 by weight of cement, sand and OPS aggregate (Mannan and Ganapathy 2001b). The highest 28-day compressive strength, of about 36 MPa, was achieved by using fly ash and silica fume, a sand to cement ratio of 1.6, and water to binder ratio of 0.35, as reported by Alengaram *et al.* (2008b). Okafor (1991) investigated the performance of a super plasticizer in PKS lightweight concrete. He concluded that the compressive strength of PKS lightweight concrete for water to cement ratios of 0.45 and 0.50 increases with the increase in dosage level of the super plasticizer from 0 to 2.5% of cement weight. This is due to the greater dispersion of cement particles. However, with a water to cement ratio of 0.60 and level of dosage of 2.5%, due to bleeding and segregation in the concrete, the compressive strength at all ages is lower than that of the corresponding mix with an admixture dosage of 2%.

Mannan *et al.* (2006) showed that with an improvement in quality of OPS aggregates, it is possible to decrease the water absorption of this aggregate to about 82% (from 23.3% to 4.2%) and achieving better adhesion between the OPS and cement paste. This improved the compressive strength by 35.3%, 38.8% and 39.2% at 3, 7 and 28 days, respectively. These highest compressive strengths at early and later ages were obtained using OPS pre-treated with 20% poly vinyl alcohol as a PVA solution.

Basri *et al.* (1999) reported that the compressive strength of OPS concrete is approximately 50% lower than that of ordinary concrete. On the basis of Okafor's investigation (Okafor 1988), OPS performs satisfactorily as a lightweight concrete in middle and low strength concrete. A recent study has revealed that OPS can be used as a lightweight aggregate for producing high strength lightweight concrete (Shafigh *et al.* 2011a). In this study normal weight aggregate is being used as a partial replacement of OPS aggregate and 28-day compressive strength has been found in the range of 41-43 MPa (Shafigh *et al.* 2011a).

6.5 Splitting tensile strength

In designing of structural element, the compressive strength of concrete is commonly considered as main property. However, for some special purposes, such as the design of highway and airfield slabs, the shear strength, resistance to cracking; the tensile strength is of interest (Neville 2008). A maximum splitting tensile strength of 2.0 MPa is a prerequisite for structural lightweight aggregate concrete (Holm and Bremner 2000). Several studies (Abdullah 1996, Alengaram *et al.* 2008b, Mannan and Ganapathy 2002, Teo *et al.* 2006c) show that the splitting tensile strength of continuously water cured OPS concrete at 28-day varied from about 1.1 to 2.4 MPa. This is about 6-10% of the corresponding cube compressive strength. For cold-bonded fly ash aggregates, this percentage is about 8-10% with the compressive strength ranging from 21 to 47 MPa (Gesoğlu *et al.* 2004). The ratio of split-tensile strength to a corresponding compressive strength of about 21-24% was reported for crushed basaltic-pumice lightweight concrete with a compressive strength ranging from 28 to 38.9 MPa at 28 days of age (Kılıç *et al.* 2003). In most cases, the splitting tensile strength for lightweight concrete for cube compressive strengths of 20, 30, 40 and 50 MPa is in the range of 1.4-2, 1.8- 2.7, 2.2-3.3 and 2.5-3.8 MPa, respectively (CEB/FIP 1977).

Tensile strength of the concrete is related to shear resistance, torsion, anchorage and bond strength, and crack resistance, which can be calculated from its relationship with compressive strength. The best fit overall for OPS concrete is given by the expression

$$f_r = 0.57\sqrt{f_c} - 1.17 \ (R^2 = 0.88) \quad (1)$$

Or

$$f_r = 0.20\sqrt[3]{f_c} \ (R^2 = 0.84) \quad (2)$$

Where f_r is the splitting strength and f_c is the compressive strength of cubes, both in MPa.

For cold-bonded fly ash lightweight aggregates concrete there is a relation between splitting tensile and cube compressive strength for compressive strength ranging from 20.8 to 47.3 MPa, as given in Eq. (3) (Gesoğlu *et al.* 2004)

$$f_r = 0.27\sqrt[3]{f_c^2} \quad (3)$$

The relation reported by (Neville 2008) is given in Eq. (4) for palletized blast furnace slag lightweight aggregate concrete for a compressive strength of between 10 and 65 MPa

$$f_r = 0.23\sqrt[3]{f_c^2} \quad (4)$$

The tensile strength of structural lightweight concrete is less than the tensile strength of the similar strength grade normal weight concrete (Al-Khaiat and Haque 1998). Mannan and Ganapathy (2002) concluded that the tensile strength for OPS concrete is nearly 10% of the 28-day compressive strength. They also concluded that the behavior of OPS concrete in this respect is very similar to that of control normal weight concrete.

6.6 Flexural tensile strength

Flexural tensile strength of lightweight concrete is greatly influenced by the curing method than the normal weight concrete (CEB/FIP 1977). According to the test results, flexural specimens showed that dried specimens are extremely sensitive to moisture (Mehta and Monteiro 2006).

For continuously moist cured concrete, the flexural strength of lightweight aggregate concrete is 9 to 11 percent of the compressive strength but in air-drying regimes, the flexural strength is normally less than 4% of the compressive strength. Furthermore, in this regime flexural strength is 60% to 70% of the splitting tensile strength. But in moist cured condition, the flexural strength is usually 50% greater than the splitting tensile strength (Holm and Bremner 2000).

They are also, compared to the lightweight concrete based on expanded clay lightweight aggregates as reported by Lo *et al.* (2004). The best fit equations for the flexural tensile strength (f_T) of OPS concrete are calculated based on Eq. (5)

$$f_T = 0.58\sqrt{f_c}\ (R^2 = 0.84) \quad (5)$$

Or

$$f_T = 0.33\sqrt[3]{f_c}\ (R^2 = 0.87) \quad (6)$$

Where f_T is flexural tensile strength and f_c is cube compressive strength in MPa.

Lo *et al.* (2004) reported that the relationship between the flexural and cube compressive strength of expanded clay aggregate concrete at 28 days can be represented by Eq. (7). Using this equation, it was determined that their measured flexural strength is marginally lower than the past research findings for concrete mixes of similar compressive strength.

$$f_T = 0.69\sqrt{f_c} \quad (7)$$

For cube strengths ranging from 20 to 60 MPa, another relationship between the compressive strength and the flexural tensile strength of moist cured, lightweight concrete was made using expanded shale and clay aggregates. This is provided by Eq. (8) (CEB/FIP 1977)

$$f_r = 0.46\sqrt[3]{f_c^2} \quad (8)$$

This shows that, in general, the flexural strength of OPS lightweight concrete is lower than the lightweight concrete made with artificial lightweight aggregates.

6.7 Modulus of elasticity (E)

The most important mechanical properties of concrete.in designing of structural elements is modulus of elasticity (Young's modulus). In the prediction of the deformation of reinforced concrete structures, modulus of elasticity is a key influencing factor. The modulus of elasticity of concrete is governed by the moduli of elasticity of its components. It depends upon the modulus of elasticity of the matrix, type of aggregates, the effective water-to binder ratio, and the volume of the cement (Chandra and Berntsson 2002).

The modulus of elasticity of OPS concrete is in the range of about 5-11 GPa for a compressive strength range of 24-37 MPa (Alengaram *et al.* 2008a, Mannan and Ganapathy 2002, Teo *et al.* 2006b, Teo *et al.* 2006c). For the same strength, the modulus of elasticity of lightweight aggregate concretes is 25-50% lower than normal weight concrete (Neville and Brooks 2008). The elastic modulus of normal weight concrete is higher because the modulus of the normal weight aggregate particles are greater than the modulus of the lightweight aggregate particles (Holm and Bremner 2000). For example, the modulus of elasticity of expanded clay and shale aggregates is between 5 to 15 GPa, however, this value for dense natural aggregates such as quartz, limestone and basalt is about 60, 80 and 100 GPa, respectively (CEB/FIP 1977). Wilson and Malhotra (1988) reported that the modulus of elasticity of lightweight concrete made with expanded shale lightweight aggregate ranges from 23.8 to 27 GPa, for compressive strength range of 33.6-60.8 MPa. Rossignolo *et al.* (2003) reported that at the age of 7 days the modulus of elasticity and compressive strength of the Brazilian lightweight aggregate (expanded clay) concrete varied from 12 to 15.2 GPa and 39.7 to 51.9 MPa, respectively. The modulus of elasticity of structural lightweight concrete ranges between 10 and 24 GPa, which is generally much less than that of normal aggregate concrete (CEB/FIP 1977). The lower modulus of elasticity of lightweight aggregate concrete allows the development of a higher ultimate strain, compared with normal weight concrete of the same strength (Neville 2008).

These values show that the modulus of elasticity of OPS lightweight concrete is very much lower than that of normal weight concrete and lower than other types of lightweight aggregate concrete. A low modulus of elasticity affects the prestress losses as well as the member deflections. Kılıç *et al.* (2003) reported that the E of Pumice structural lightweight aggregate concrete with a 28-day compressive strength (for standard cylindrical samples) of about 21 MPa is about 9.3 GPa. They concluded that the disadvantage of possible excessive deformation in such elements as slabs and beams due to this low elasticity modulus can be compensated for by keeping the span lengths as small as possible and by keeping the slab depths just a little greater than customary values. The example given by Sylva *et al.* (2004) shows that because of the lower E in LWC compared to NWC and, hence higher prestress loss in LWC, a girder designed with lightweight concrete would require approximately 8 additional strands to maintain the same effective prestress force as a normal weight girder. A previous study by (Teo *et al.* 2006b) showed that the deflection of a beam made with OPS concrete (cube compressive strength of 26.3 MPa and modulus of elasticity of 5.28 GPa) with a reinforcement ratio of 1.13% exceeded the maximum value as provided by BS8110 (1997). They recommended that when OPS concrete beams are required for higher load bearing purposes, larger beam cross-sections should be considered to satisfy the deflection criteria.

6.8 Flexural behavior of OPSC beam

Flexural behavior of reinforced beams was reported by Teo *et al.* (2006b) and Alengaram *et al.* (2008a). Six beams, three each of singly and doubly reinforced were tested with different reinforcement ratios (Teo *et al.* 2006b). Vertical flexural cracks were observed in the constant-moment region and final failure occurred due to crushing of the compression concrete with significant amount of ultimate deflection. Since all beams were under-reinforced, yielding

Table 5 Acceptable mix proportion of POC concrete

Mix design	Mix proportion Cement:sand:LWA	Water cement ratio
Omar and Mohamed (2002)	1 : 0.95 : 1.26	0.40
Mohammed *et al.* (2011) Hussein *et al.* (2012)	1 : 1.48 : 0.69	0.44
Mohammed *et al.* (2013)	1 : 0.95 : 0.31	0.20
	1 : 0.95 : 0.31	0.40
	1 : 0.95 : 0.31	0.60

of the tensile reinforcement occurred before crushing of the concrete cover in the pure bending zone. Eventually, crushing of the concrete cover occurred during failure, with a significant amount of deflection. A comparison between the experimental ultimate moments (M_{ult}) and the theoretical design moments show a closer relationship for doubly reinforced beams than singly reinforced ones (Teo *et al.* 2006b). The theoretical design moment (M_{des}) of the beams was predicted using the rectangular stress block analysis as recommended by BS8110 (1997). For beams with reinforcement ratios of 3.14% or less, the ultimate moment obtained from the experiment was approximately 4-35% higher compared to the predicted values. They concluded that for OPKSC beams, BS8110 (1997) can be used to obtain both a conservative estimate of the ultimate moment capacity and adequate load factor against failure for reinforcement ratios up to 3.14%. The beam with the highest reinforcement ratio of 3.14% showed slightly higher mid-span deflection than the other two beams which indicates more ductile behavior. They also concluded that the ductility and moment curvature for OPKSC beams follows the same trend as those of the NWC beams (Teo *et al.* 2006b).

7. Concrete with POC aggregate

7.1 Mix design

The mix proportioning can be carried out with trial mixes or according to the requirements of ACI Committee 211.2 (1998). There are some evidence for mix design of POCC can be found from the previous research work (Kanadasan and Razak 2014). Omar and Mohamed (2002) used the mix proportion of cement, sand and LWA as 1: 0.95: 1.26. The water cement ratio was 0.40. They used 500 kg/m^3 cement content with this mix proportion to get the lightweight concrete having the compressive strength of 35 MPa. According to ACI Committee 211.2 (1998), Mohammed *et al.* (2013) carried out a study with water-cement ratio of 0.40-0.46 and cement content of 480-520 kg/m^3.

Five mixing proportions were taken to justify the mechanical properties of POCC. In their study, the coarse aggregates were taken in dry condition as POC drops moisture easily to the air. Due to the high water absorption of POC, the aggregates were pre-soaked for 24 h in water before mixing. This is expected to prevent further absorption during mixing. The saturated surface dry (SSD) state of POC was achieved. Two stages mixing approach was employed to allow the cement paste to coat the aggregate permitting the absorbed water to be retained and preventing any water absorption or penetration of cement paste into the aggregate. Table 5 summarizes the mix designs of POC concrete used for the investigation of reinforced POCC beam in the past researches. This guideline could be used for future investigations since the resulting reinforced concrete beams were performed satisfactorily.

7.2 Slump

The standard examination for the workability of concrete is Slump test. The consistency of concrete can be measured by the slump test (ACI116R 2000). It is very useful in calculating the variations in the uniformity of mix of given proportions (Neville 1995). It is seen that the slump value is increased when the water cement ratio is increased as with the normal concrete. Hilton *et al.* (2007) achieved 105-125 mm slump by susing 0.55 w/c ratio. Mannan and Neglo (2010) achieved 40-70 mm slump by using 0.48-0.57 w/c with incorporating a small percentage of superplasticizer. Ahmmad *et al.* (2014) found 124 mm slump with 0.33 w/c incorporating 1.6% superplasticizer. High range water reducing admixtures (Superplasticizer or SP) are capable of dispersing cement grains which are directed towards high slump value resulting in high workability.

7.3 Density

The density of normal weight concrete is 2400 kg/m^3 Whereas LWC has the typical density ranging from 1400 to 2000 kg/m^3 (Chen and Liu 2005). Hilton *et al.* (2007) found the density of saturated surface dry condition falls within the limit of the ranges of lightweight concrete. In their study, series using only POC as coarse aggregates and natural sand offered the density around 2000 kg/m^3 and series using POC as coarse and fine aggregates presented the density around 1850 kg/m^3. This values are 19% and 26% lower than the normal weight concrete respectively. Mannan and Neglo (2010) reported the concrete with POC aggregate exhibits the mean density below 2000 kg/m^3. Mohammed *et al.* (2011) reported the density of POC concrete about 1769 kg/m^3. From the above discussion it can be concluded that the concrete from the POC aggregates produce lighter structures.

7.4 Compressive strength

As the compressive strength is the most important to describe the excellence of concrete, ASTM C 330-89 has recommended the minimum value for the 28- day concrete compressive strength as 17 MPa (Neville and Brooks 2008). As per ACI Committee 213 (1987), the projected relationship between average compressive strength and cement content of structural lightweight concrete is shown in Table 2.4.

Mohammed *et al.* (2011) has exposed that the maximum compressive strength of lightweight concrete produced using this POC is approximately 30.9 MPa. This is within the typical compressive strength for structural lightweight concrete of 20-35 MPa (Kosmatka *et al.* 2002). Mohammed *et al.* (2013) exhibited that by using 480 kg/m^3 cement, a free water to cement ratio of 0.40 and POC aggregate, the 28-day compressive strength of OPS concrete is between 25.5 to 42.56 MPa. Hilton *et al.* (2007) found the 28-day compressive strength, of about 33.7 MPa, was achieved by using 420 kg/m^3 cement and water to cement ratio of 0.35. They also tried to use the fly ash with cement to produce lightweight concrete. In his study he used 90% cement and 10% fly ash. Ahmmad *et al.* (2014) used 482 kg/m^3 cement content with W/C 0.33 to produce LWC. He concluded that the compressive strength of POC lightweight concrete as 44.89 MPa. So far this strength was the maximum. However, it can be concluded that cement (450-480 kg/m^3) with a water to cement ratio of 0.32-0.42, the 28 days compressive strength can be found 35-45 Mpa.

7.5 Splitting tensile strength

In designing of structural element, the compressive strength of concrete is commonly considered as main property. However, for some special purposes, such as the design of highway and airfield slabs, the shear strength, resistance to cracking; the tensile strength is of interest (Neville 2008). According to ASTM C 330, a maximum splitting tensile strength of 2.0 MPa is a requirement for structural lightweight aggregate concrete (Holm and Bremner 2000). Several studies (Hilton *et al.* 2007, Mohammed *et al.* 2011, Mohammed *et al.* 2013) show that the splitting tensile strength of continuously water cured POC concrete at 28-day varied from about 2.1 to 4.2 MPa. This is about 6-12% of the corresponding cube compressive strength.

The ratio of split-tensile strength to a corresponding compressive strength of about 21-24% was reported for crushed basaltic-pumice (scoria) lightweight concrete with a compressive strength ranging from 28 to 38.9 MPa at 28 days of age (Kılıç *et al.* 2003). In most cases, the splitting tensile strength for lightweight concrete for cube compressive strengths of 20, 30, 40 and 50 MPa is in the range of 1.4-2, 1.8- 2.7, 2.2-3.3 and 2.5-3.8 MPa, respectively (CEB/FIP 1977).

7.6 Flexural tensile strength

Flexural tensile strength of lightweight concrete is greatly influenced by the curing method than the normal weight concrete (CEB/FIP 1977). According to the test results, flexural specimens showed that dried specimens are extremely sensitive to moisture (Mehta and Monteiro 2006). For continuously moist cured concrete, the flexural strength of lightweight aggregate concrete is 9 to 11 percent of the compressive strength but in air-drying regimes, the flexural strength is generally less than 4 percent of the compressive strength. Furthermore, in this regime flexural strength is 60 to 70 percent of the splitting tensile strength. But in moist cured, the flexural strength is generally 50 percent greater than the splitting tensile strength (Holm and Bremner 2000). Hilton *et al.* (2007) reported the flexural strength about 6.2 MPa. Mohammed *et al.* (2011) claims the flexural strength is about 4.2 MPa from his study.

7.7 Modulus of elasticity (E)

Young's modulus or E-value of concrete is it is one of the most important parameters in the design of structural members. However, this is one of the least researched areas in POCC. The young's modulus of concrete is greatly governed by the moduli of elasticity of its components. It depends upon the modulus of elasticity of the matrix, type of aggregates, the effective water-to binder ratio, and the volume of the cement (Chandra and Berntsson 2002). The modulus of elasticity of POC concrete is in the range of about 16-22 GPa for a compressive strength range of 31-44 MPa (Ahmmad *et al.* 2014, Mohammed *et al.* 2011). For the same strength, the modulus of elasticity of lightweight aggregate concretes is 6-20% lower than normal weight concrete (Neville and Brooks 2008). The elastic modulus of normal weight concrete is higher because the modulus of the normal weight aggregate particles are greater than the modulus of the lightweight aggregate particles (Holm and Bremner 2000). Wilson and Malhotra (1988) reported that the modulus of elasticity of lightweight concrete made with expanded shale lightweight aggregate ranges from 23.8 to 27 GPa, for compressive strength range of 33.6-60.8 MPa. Rossignolo *et al.* (2003) reported that at the age of 7 days the modulus of elasticity and compressive strength of the Brazilian lightweight aggregate (expanded clay) concrete varied from 12 to 15.2 GPa and 39.7 to 51.9 MPa, respectively. The modulus of elasticity of structural lightweight concrete ranges between 10 and 24 GPa, which is generally much less than that of normal aggregate concrete (CEB/FIP 1977). Values shows that modulus of elasticity of POCC is much better than the OPSC.

7.8 Flexural behavior of POCC beam

In the research involving reinforced POC beam subjected to flexural loading, Mohammed *et al.* (2014) investigated the effect of varying tension reinforcement ratios of the reinforced POC beams, ranging from 0.35% to 2.23%. All the reinforced POC beams exhibited typical flexural failure, which suggested the use of POC did not bring upon detrimental effect on the flexural behavior of reinforced concrete beam. The authors also found that the experimental value of the moment capacity of the reinforced POC beams was close to the prediction using BS 8110 design method, as only 1-7% difference was observed. However, the experimental serviceability deflection values were about 10-45% lower compared to BS 8110. Despite this, the authors felt that the serviceability deflection for the singly reinforced POC beams was acceptable since it adhered to the limit stated in BS 8110. In the case of the doubly reinforced POC beams, similar to the finding by Teo *et al.* (2006b), it was recommended that larger beam depths should be used to ensure that the span-deflection ratio limit is satisfied. Apart from that, it was found that ACI 318 and BS 8110 gave reasonable crack width prediction at service loads for the reinforced POC beams. In addition, the crack widths at service loads obtained from the study were below the maximum permissible limit stipulated in ACI 318 and BS 8110.

Based on the research carried out by Mohammed *et al.* (2014), it could be summarized that the use of POC in reinforced concrete beam was suitable for structural application since most of the behavior conformed to design codes and also comparable to other types of reinforced LWC beams which were done previously. Mohammed *et al.* (2013) also carried out research on the shear behavior of reinforced POC beams with varying tension reinforcement ratios, shear span to effective depth ratio, and compressive strength of POC. In general, the shear failure cracking observed for the reinforced POC beams was similar to that of conventional reinforced NWC beams. The increase in tension reinforcement ratio and compressive strength led to the increase in the shear strength of the reinforced POC beams while the effect of shear span to effective depth ratio on the reinforced POC beams was similar to that for conventional reinforced NWC beams. It is noteworthy that the shear strength prediction based on BS 8110, ACI, and EC2 overestimated the shear capacity of the reinforced POC beams and safety precaution should be taken to avoid under design of the shear capacity for reinforced POC beam. This study showed that reinforced POC beam exhibited similar shear failure as what would be expected of conventional reinforced concrete beam and this further justifies the usage of POC in reinforced concrete beam, bearing in mind that adequate safety factor should be applied when considering the ultimate shear capacity.

8. Summary

Previous researchers have produced lightweight concrete using OPS with 28-day cube compressive strength of 35 MPa or less (Alengaram *et al.* 2008b, Basri *et al.* 1999, Mannan and Ganapathy 2001b, Okafor 1988, Shafigh *et al.* 2011b). Mannan and Ganapathy (2001a) found 28-day compressive strength of OPSC in between 20 and 24 MPa depending on the curing conditions by using 480 kg/m^3 ordinary Portland cement with w/c ratio of 0.41. The highest 28-days compressive strength has been reported by Mannan *et al.* (2006) is about 33 MPa with slump value of 95 mm. Furthermore, the 28-day compressive strengths of the concrete are in the range of 26-36 MPa and slump value was in the range of 0-160 mm. They have used cement content in the range of 440-530 kg/m^3 with 5% fly ash as cement replacement and 10% silica fume as additional cementing material (Alengaram *et al.* 2008b). A recent study has revealed that OPS can be used as a lightweight aggregate for producing high strength lightweight concrete (Shafigh *et al.* 2011a). In their study normal weight aggregate is being used as a partial replacement of OPS aggregate and 28-day compressive strength has been found in the range of 41-43 MPa (Shafigh *et al.* 2011a).

Existing literatures show that the test results for compressive strength of POC concrete range from 25.5 to 42.56 MPa. It is higher than the minimum required strength of 17 MPa for structural lightweight concrete (Mohammed *et al.* 2014). Maximum 28 days compressive strength of POC concrete has been achieved as 44.89 MPa (Ahmmad *et al.* 2014).

9. Problem statement

The limitation of OPS concrete is that it shows less compressive strength but ductile failure (Ahmmad *et al.* 2014). Hence, it is being attempted to use POC aggregate for producing light weight concrete with consistent and high compressive strength. POC concrete poses the consistent and high compressive strength but its failure mode is brittle (Ahmmad *et al.* 2014). Mo *et al.* (2014) has used steel fiber to improve the flexural toughness and others mechanical properties.

From the above discussion, it is clear that both OPS concrete and POC concrete has their own advantages and disadvantages. But a few attempts have been carried out to combine the OPS and POC for production of consistent and improved structural lightweight aggregate concrete. The structural behavior of this concrete has not yet been studied. The study will include the workability and density, compressive strength, flexural strength and splitting tensile strength, modulus of elasticity and the stress-strain behavior. Hereafter, this structural grade lightweight aggregate concrete will be termed as palm shell and clinker concrete (PSCC). And then, for structural applications, the flexural behavior of singly reinforced PSCC beams is being examined and clearly established.

The current design procedures by BS8110 (1997) for flexural strength of both the Lightweight Aggregate Concrete and the Normal Weight Concrete are derived from the understanding of concrete cast using normal aggregates. Hence, it is apparent that, the current design procedures by BS8110 (1997) may not be suitable to predict the ultimate flexure resistance of the PSCC beams. Since no guidance has been given from the current codes of practice (BS8110 1997), it is therefore essential that a research investigation to be carried out to aid the current understanding on flexure strength of PSCC beams.

10. Conclusions

1. The OPS are found in different shapes depending on the breaking pattern of the nut. OPS has the concave and convex faces. The thickness of the OPS varies depending on the type of palm tree from which the nuts are obtained. Generally it ranges from 0.15-8 mm. OPS can be termed as LWA as it has low specific gravity in the range of 1.17-1.6. On the other hand, the POC aggregates can be found in different shape like angular, polygonal etc., subjected to the breaking pattern of the raw POC. The faces of the POC are very rough and porous. However, the broken edge is spiky. The specific gravity of POC varies in the range of 1.7-1.82.

2. OPS has the loose and compacted bulk densities in the range of 500-600 kg/m^3 and 600-620 kg/m^3, respectively. POC coarse aggregate has a unit weight of 781 kg/m^3. The existence of numerous pores in the OPS and POC are responsible for high water absorption in the range of 21-33% and 4.35% respectively.

3. The abrasion value of OPS and conventional crushed coarse aggregates are 4.8 and 24.0 respectively. From this it’s very clear that OPS has the lower abrasion value than conventional coarse aggregate. But the abrasion value of POC aggregates is 27.0 which is very similar to the conventional crushed aggregates.

4. At earlier research, OPSC and POCC are stated to have low workability due to low slump values. But, the

limitation related with low slump value can be resolved using uperplasticizer.

5. The density of OPSC and POCC are found in the range of 1650-1980 kg/m^3 which confirms the requirements of lightweight concrete. There are many factors such as w/c ratio, usage of fine aggregate, water absorption and grain size of OPS and POC etc. affect the density.

6. At earlier research, the compressive strength of OPSC was reported as 13-22 MPa. After that it was found that the compressive strength of OPSC can raise up to 43 MPa with crushed OPS aggregate. Other mechanical properties such as splitting tensile strength and flexural tensile strength are reported to be 6-10% and 8-14% respectively of the compressive strength. The maximum modulus of elasticity OPSC was reported as 16 GPa.

7. The compressive strength of POCC was reported as 30-45 MPa. Splitting tensile strength and flexural tensile strength are reported to be 6-12% and 10-18% respectively of the compressive strength. The modulus of elasticity OPSC was reported in the range of 16-22 GPa.

8. According to existing study, OPSC and POCC beams exhibited pure flexural behavior. Moment capacity and deflections can be predicted with existing code for both beam produced from OPSC and POCC.

11. Future recommendations

1. In order to enable the universal equation to predict the splitting tensile strength, flexural strength, and modulus of elasticity, regression model can be done by incorporating vast amount of published or experimental data for the future study.

2. Further investigation is recommended to visualize the precise PSCC behavior in several environmental and structural conditions.

3. Shear and torsional behavior of PSCC and POCC beam need to be studied.

4. Long term behavior such as creep, temperature shrinkage are needed to be studied for PSCC and POCC beam.

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