Review

Mix design and mechanical properties of oil palm shell lightweight aggregate concrete: A review

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To build environmentally sustainable structures, especially in developing countries, the possibility of using some agricultural wastes and industrial by-products from different industries as construction materials will be highly desirable and has several practical and economic advantages. Oil palm shell (OPS) is a form of agricultural solid waste in the tropical regimes. Research over the last two decades shows that OPS can be used as a lightweight aggregate for producing structural lightweight aggregate concrete. The density of OPS concrete is around 20 - 25% lower than normal weight concrete. Generally, mechanical properties of OPS concrete are slightly lower than the other types of lightweight aggregate concrete. It seems that from the summary and analysis of the existing information concerning OPS concrete and comparing it with other lightweight aggregate concrete it appears that significant achievements can be attained.

Key words: Lightweight aggregate concrete, agricultural solid waste, mix design, mechanical properties, oil palm shell (OPS).

INTRODUCTION

Concrete is a widely used construction material in civil engineering projects throughout the world for the following reasons: It has excellent resistance to water, structural concrete elements can be formed into a variety of shapes and sizes and it is usually the cheapest and most readily available material for the job (Mehta and Monteiro, 2006). From the various kinds of concrete, lightweight concrete (LWC) is one of the most interesting subjects for researchers because of its advantages such as the savings on reinforcement, formwork and scaffolding , foundation costs as well as the savings derived from the reduced cost of transport and erection. Furthermore, better fire resistance, heat insulation, sound absorption, frost resistance, superior anti-condensation properties and increased damping are other advantages of lightweight concrete (CEB/FIP, 1977). The most popular way of achieving LWC production is by using

lightweight aggregate (LWA) (Polat et al., 2010). Lightweight aggregate concrete (LWAC) is not a new invention in concrete technology; it has been used since ancient times. The fact that some of these structures are still in good condition validates the durability of concrete (Chandra and Berntsson, 2002). LWA may be subdivided into two groups: Those that occur naturally and those that are manufactured. The main natural LWAs are diatomite, pumice, scoria, volcanic cinders and tuff (Neville and Brooks, 2008). Manufactured aggregates can be divided into two groups. Naturally occurring materials that require further processing (produced by the application of heat) such as expanded clay, shale, slate, perlite and vermiculite and materials that occur as industrial by-products such as sintered pulverized-fuel ash (fly ash), sintered slate and colliery waste, foamed or expanded blast-furnace slag (CEB/FIP, 1977).

An alternative LWA in tropical regimes and countries that have a palm oil industry is Oil Palm Shells (OPS), sometimes called Palm Kernel Shells (PKS). The use of OPS as a lightweight aggregate or porous aggregate in producing lightweight concrete was researched early in

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Figure 1. The great mass of oil palm shells (OPS) in the palm oil mill area.
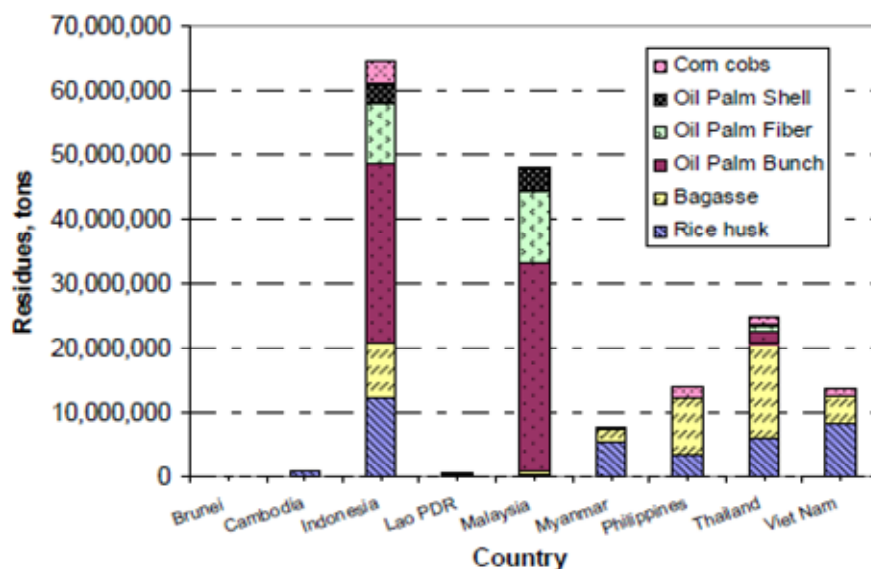
Figure 2. Estimates of agricultural residues in South-East Asia, (2005) (ESCAP, 2007).

1985 by Salam and Abdullah (1985) in Malaysia. The oil palm industry is important in many countries such as Malaysia, Indonesia and Nigeria. Malaysia is one of the world leaders in the production and export of palm oil (Subramanian et al., 2008) and contributes about 57.6% of the total supply of palm oil in the world (Ahmad et al., 2010). This industry is one of the main pillars of the country's economy contributing some RM 28.60 billion in export earnings from palm oil and oil palm products in 2006 (MPOB, 2006). Oil palm shells are produced in large quantities by the oil mills (Figure 1). For instance, in Malaysia and Nigeria it was estimated that over 4 (Teo et al., 2006) and 1.5 (Ndoke, 2006) million tonnes of oil palm shell (OPS) solid waste is produced annually and only a fraction is used for fuel (traditionally used as solid

fuels for steam boilers at palm oil mills) and other applications such as a palliative for un-tarred roads and for producing activated carbon. For comparison, Figure 2 (ESCAP, 2007) shows the estimates of several types of agricultural residues in South-East Asia, from which it can be seen that there are large amounts of agricultural residues in some countries.

Research shows that OPS can be used as a lightweight aggregate for producing structural lightweight aggregate concrete (Teo et al., 2007; Abdullah, 1996; Teo et al., 2006; Basri et al., 1999; Mannan and Ganapathy, 2001; Mannan and Ganapathy, 2004). Furthermore, it was found that OPS structural lightweight concrete is a good thermal performance material for low cost housing (Harimi et al., 2007). The utilization of this agricultural

solid waste as a lightweight aggregate in the construction industry not only reduces the cost of construction materials but also resolves the problem concerning the disposal of waste products generated at the palm oil mills.

The authors believe that from the summary and analysis of the existing information pertaining to OPS concrete and by comparing it with other lightweight aggregate concrete significant achievements can be attained. Furthermore, new subjects for research will be identified for researchers to explore innovative lightweight concrete based on the financial and environmental design factors.

PROPERTIES OF OIL PALM SHELL (OPS)

Palm oil processing is separated into six stages: Sterilization, threshing, pressing, depericarping, separation of kernel and shell and clarification (Abdullah, 1996). Shells are one of the wastes produced during this process. Their colour ranges from dark grey to black. The shells are of different shapes, such as angular, polygonal etc., depending on the breaking pattern of the nut. The surfaces of the shells are fairly smooth for both concave and convex faces. However, the broken edge is rough and spiky. The thickness varies and depends on the species of palm tree from which the palm nut is obtained and ranges from 0.15 - 8 mm (Basri et al., 1999, Okpala, 1990).

The shell has a 24 h water absorption capacity range of 21 - 33%. This value implies that the OPS have high water absorption compared to conventional gravel aggregates that usually have water absorption of less than 2% (Neville, 2008). This high water absorption could be due to the high pore content. It was reported that the porosity of the shell is 37% (Okpala, 1990). Mannan et al. (2006) reported an improvement in the quality of OPS by using pre-treatment methods such as 20% poly vinyl alcohol as a PVA solution. This decreased the water absorption of OPS significantly from 23.3 to 4.2%.

Because of the higher porosity of OPS than conventional aggregates, loose and compacted bulk densities and the specific gravity range from about 500-550, 590 - 620 kg/m^3 and 1.14 - 1.37, respectively. These ranges of densities show that OPS are approximately 60% lighter than conventional coarse aggregates. The densities of the shell are within the range of most typical lightweight aggregates (Okpala, 1990; Okafor, 1988). The shell is hard and does not easily suffer deterioration. The Los Angeles abrasion value of the OPS and crushed stone was reported as (Basri et al., 1999) 4.8 and 24% respectively. This shows that it is much lower than conventional coarse aggregates and has a good resistance to wear. Furthermore, the aggregate impact value and aggregate crushing value of OPS aggregates were much lower compared to conventional crushed stone aggregates. This shows that the aggregate has a good absorbance to shock (Teo et al., 2007). 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. Okpalan (1990) reported 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 elsewhere (Mannan and Ganapathy, 2002).

OPS LIGHTWEIGHT AGGREGATE CONCRETE

Mix design

In well-proportioned mixtures, the cement content and strength relationship is fairly constant for a particular source or one type to another. Therefore, trial mixtures with varying cement contents are required to develop a range of compressive strengths, including the strength specified (Kosmatka et al., 2002). Because the oil palm shells are lighter than the cement matrix, the shells tend to segregate in wet concrete mixes. Abdullah (1996) suggested that trial mixes are necessary to achieve a good mix design. Lightweight concrete mix design is usually established by trial mixes. Mix design methods that apply to normal weight concrete are generally difficult to use with lightweight aggregate concrete (Shetty, 2005). A study for finding a mix design method for OPS lightweight concrete was conducted by Mannan and Ganapathy (2001). They found that the 28-day compressive strength of OPS concrete, designed according to the America concrete institute (ACI) method for conventional concrete, is not suitable for OPS lightweight concrete because the strength is very much less than the targeted design strength. Even with this method and the use of superplasticizer, the strength could not be increased. Furthermore, they followed the mix design method for lightweight aggregate such as Leca, Fumed slag, Aglite and Lytag. 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. Finally, they suggested six acceptable mix proportions for OPS concrete with different ingredients, as shown in Table 2.

Olanipekun et al. (2006) investigated the effect of crushed, granular coconut and palm kernel shells as substitutes for conventional coarse aggregate in two mix ratios of 1:1:2 and 1:2:4 with a water to cement ratio of 0.75 and 0.50 and a 28-day compressive strength of 35 and 27.5 MPa respectively. They concluded that by using

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 K_2O)	0.00042
Aluminium (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

Table 2. Acceptable mix proportion of OPS concrete reported by (Mannan and Ganapathy, 2001).

Mix code	Proportions by weight of cement (cement = 480 kg/m^3), w/c = 0.41					Demoulded density (kg/m^3)	Fresh Property (Slump, mm)	28-day compressive strength (N/mm^2)
	Cement	Fly ash	CaCl$_2$	Sand	OPS			
E1	1.00	0.00	0.00	1.71	0.77	1890-1905	7	24.20
E2	0.90	0.10	0.00	1.71	0.77		8	22.60
E3	0.85	0.15	0.00	1.71	0.77		9	19.50
E4	1.00	0.00	0.5%	1.71	0.77		6	23.45
E5	1.00	0.00	1.0%	1.71	0.77		7	29.40
E6	1.00	0.00	1.5%	1.71	0.77		8	24.50

these lightweight aggregates, grades 20 and 15 lightweight concrete can be obtained if the percentage replacement levels of the conventional coarse aggregate with both lightweight aggregates do not exceed 25 and 50% respectively, for both mix ratios tested.

Irrespective of other mix proportions of OPS structural lightweight concrete, the OPS content in 1 m^3 for achieving the compressive strength for grades of 20 - 35, ranged from 290 - 450 kg. (Teo et al., 2007; Teo et al.,2006; Mannan and Ganapathy, 2004; Mannan and Ganapathy, 2002; Mannan and Ganapathy, 2001; Mannan et al., 2002; Alengaram et al., 2008). In these researches, the cement content was in the range of 400 - 600 kg/m^3. It should be noted that, generally, the cement content in lightweight aggregate concrete varies from the same as normal weight aggregate to 70% more for the same strength of concrete (Neville and Brooks, 2008). 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).

Density

For structural applications of lightweight concrete, the density is often more important than the strength (Rossignolo et al., 2003). The density of LWC typically ranges from 1400 to 2000 kg/m^3 compared with that of 2400 kg/m^3 for normal-weight concrete (NWC) (Chen and Liub, 2005). Okafor (1988) reported that the production of concrete with a density of approximately 1758 kg/m^3 using this agricultural solid waste is possible. According to Basri et al.(1999) investigation, the 28-day air-dry densities of OPS concrete were 19 - 20% lower than ordinary crushed stone concrete. Other studies show that OPS concrete is 22% (Mannan and Ganapathy, 2004) and 24% (Alengaram et al., 2008) lower than the normal weight concrete. Furthermore, it was reported (Mannan and Ganapathy, 2004) that OPS concrete containing 10 and 15% fly ash are 2 and 3% lower than OPS concrete without fly ash content.

MECHANICAL PROPERTIES

Compressive strength

The compressive strength is the most commonly used parameter to describe the quality of concrete in practice (Wiegrink et al., 1996). According to ASTM C 330-89, the 28-day cylinder compressive strength should not be less

than 17 MPa (Neville and Brooks, 2008). Okafor (1988) reported that the maximum compressive strength of lightweight concrete produced using this agricultural shell is approximately 25 to 35 MPa. This range is within the typical compressive strength for structural lightweight concrete (20 - 35 MPa) (Kosmatka et al., 2002). Mannan and Ganapathy (2001) showed that by using 480 kg/m^3 cement, a free water to cement ratio of 0.41 and mix proportion of 1:1.71:0.77 by weight of cement, sand and OPS aggregate, the 28-day compressive strength of OPS concrete is between 20 and 24 MPa depending on the curing.

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 a water to binder (SF+FA) ratio of 0.35 was reported elsewhere (Alengaram et al., 2008). Okafor (1991) investigated the performance of a superplasticizer in PKS lightweight concrete. He concluded that the compressive strength of PKS lightweight concrete in water to cement ratios of 0.45 and 0.50 increases with the increase in dosage level of the superplasticizer 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%, to bleeding and segregation in the concrete, the compressive strength at all ages is lower than that those 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 to 35.3, 38.8 and 39.2% for 3, 7 and 28-day 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.

Splitting tensile strength

The compressive strength of concrete is the property commonly considered in structural design, however, for some purposes, such as the design of highway and airfield slabs, the shear strength, resistance to cracking; the tensile strength is of interest (Neville, 2008). The studies (Teo et al., 2006; Abdullah, 1996; Mannan and Ganapathy, 2002; Alengaram et al., 2008) showed that the splitting tensile strength of the continuously water cured OPS concrete at 28-day varied from about 1.1 to

2.4 MPa. That is about 6 - 10% of the corresponding cube compressive strength. For cold-bonded fly ash aggregates, this percentage is about 8 to 10% with the compressive strength ranging from 21 to 47 MPa (Gesoglu et al., 2004). The ratio of split-tensile strength to a corresponding compressive strength of about 21 - 24% was reported (Kilic et al., 2003) for crushed basaltic-pumice (scoria) lightweight concrete with a compressive strength ranging from 28 to 38.9 MPa at 28 days of age. In most cases, the splitting lightweight concrete in cube compressive strength 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).

The best fit overall for OPS concrete is given by the expression:

$$f_t = 0.57\sqrt{f_{cu}} - 1.17 \quad (R^2 = 0.88) \qquad \text{(Equation1)}$$

or

$$f_t = 0.20\sqrt[3]{f_{cu}^2} \quad (R^2 = 0.84) \qquad \text{(Equation 2)}$$

Where f_t is the splitting strength and f_{cu} 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 Equation 5 (Gesoglu et al., 2004):

$$f_t = 0.27\sqrt[3]{f_{cu}^2} \qquad \text{(Equation 3)}$$

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

$$f_t = 0.23\sqrt[3]{f_{cu}^2} \qquad \text{(Equation 4)}$$

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) reported that the tensile strength for OPS concrete is nearly 10% of the 28-day compressive strength. They concluded that the behaviour of OPS concrete in this respect is very similar to the control normal weight concrete.

Flexural tensile strength

Figure 3 shows the relationship between the flexural and compressive strength at 28 days for OPS concrete specimens that were stored under water. There were also compared to the lightweight concrete based on expanded clay lightweight aggregates reported by Lo et al. (2004).
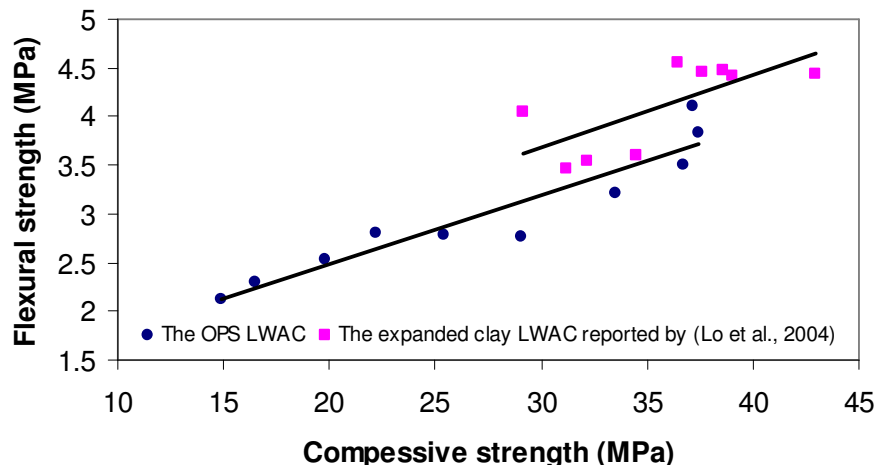
Figure 3. Relationship between 28-day flexural and compressive strength.

The best fit equations for the flexural tensile strength (f_r) of OPS concrete are calculated based on Figure 3:

$$f_r = 0.58\sqrt{f_{cu}} \qquad (R^2 = 0.84) \qquad \text{(Equation 5)}$$

or

$$f_r = 0.33\sqrt[3]{f_{cu}^2} \qquad (R^2 = 0.87) \qquad \text{(Equation 6)}$$

Where f_r is flexural strength and f_{cu} is cube compressive strength in MPa.

Lo et al. (2004) reported that the relationship between the flexural and cube compressive strength of expanded clay lightweight aggregate concrete at 28 days can be represented by Equation 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

$$f_r = 0.69\sqrt{f_{cu}} \qquad \text{(Equation 7)}$$

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 Equation 8 (CEB/FIP, 1977):

$$f_r = 0.46\sqrt[3]{f_{cu}^2} \qquad \text{(Equation 8)}$$

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

Modulus of elasticity (E)

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 (Teo et al., 2006; Teo et al., 2006; Mannan and Ganapathy, 2002; Alengaram et al., 2008; Alengaram et al., 2008). In general, the modulus of elasticity of concrete is primarily affected by the stiffness and volume of components (Gao et al., 1997). 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 mainly from 5 to 15 GPa, however, the but 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).

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. Haktanir and Altun (2002) reported that the modulus of elasticity (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 in Sylva et al. (2002) shows that because of the lower E in LWC compared to NWC, hence the 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. (2006) 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 BS 8110. 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.

CONCLUSION

Oil palm shells are an agricultural solid waste in palm oil industry and can be an alternative material for production LWAC and in the building environmentally sustainable structures. Results obtained from last researches concerning the use of oil palm shells for the production of lightweight aggregate concrete and the analysis and comparison between this agricultural solid waste lightweight aggregate concrete and other types of LWAC, it can be concluded that:

1. The specific gravity of OPS range from about 1.14-1.37; that shows OPS are approximately 60% lighter than conventional coarse aggregates. The 24 h water absorption capacity is much higher than conventional gravel aggregates. It can be used as lightweight aggregates for the production of structural lightweight concrete.
2. The physical and mechanical characteristics of OPS are different from the other types of lightweight aggregates. For this reason the mix design is different and trial mixes are necessary to achieve a good mix design.
3. The 28-day compressive strength of OPS concrete is in the range of the typical compressive strength for structural lightweight concrete with a density of around 20 - 25% lower than normal weight concrete.
4. The splitting tensile strength of OPS concrete is slightly lower than the lightweight concrete made with cold-bonded fly ash and palletized blast furnace slag

lightweight aggregate.
5. The flexural tensile strength of OPS concrete is lower than the lightweight concrete was made using expanded clay and shale aggregates.
6. The modulus of elasticity of OPS concrete is lower than the other types of lightweight aggregate concrete. For this reason, for higher load bearing purposes, larger cross-sections should be considered to satisfy the deflection criteria.

REFERENCES

Abdullah AAA (1996). Palm oil shell aggregate for lightweight concrete. Waste material used in concrete manufacturing, 624-636.

Ahmad Z, Ibrahim A, Tahir P (2010). Drying shrinkage characteristics of concrete reinforced with oil palm trunk fiber. Int. J. Eng. Sci. Technol., 2(5): 1441-1450.

Alengaram UJ, Jumaat MZ, Mahmud H (2008). Ductility Behaviour of Reinforced Palm Kernel Shell Concrete Beams. Eur. J. Sci. Res., 23(3): 406-620.

Alengaram UJ, Jumaat MZ, Mahmud H (2008). Influence of sand content and silica fume on mechanical properties of palm kernel shell concrete. International conference on construction and building technology ICCBT, 251-262.

Al-Khaiat H, Haque MN (1998). Effect of internal curing on early strength and physical properties of a lightweight concrete. Cem. Con. Res., 28(6): 859-866.

Basri HB, Mannan MA, Zain MFM (1999). Concrete using waste oil palm shells as aggregate. Cem. Con. Res., 29: 619-622.

CEB/FIP Manual of Design and Technology (1977). Lightweight Aggregate Concrete. First pub. Great Britain.

Chandra S, Berntsson L (2002). Lightweight aggregate concrete: Science, Technology, and Applications. United States: Noyes/William A Pub.

Chen B, Liub J (2005). Contribution of hybrid fibers on the properties of the high-strength lightweight concrete having good workability. Cem. Con. Res., 35: 913-917.

ESCAP Report (2007): Biomass Increasingly Important in Indonesia and Thailand. E news Environ. Sustain. Dev., 7(2): 5.

Gao J, Sun W, Morino K (1997). Mechanical Properties of Steel Fiber-reinforced, High-strength, Lightweight Concrete. Cem. Con. Comp., 19: 307-313.

Gesoglu M, Ozturan T, Guneyisi E (2004). Shrinkage cracking of lightweight concrete made with cold-bonded fly ash aggregates. Cem. Con. Res., 34: 1121-1130.

Haktanir T, Altun F (2002). Structural lightweight concrete with pumice aggregates of erciyes region. Challenges conc. Const., 4: 587-596.

Harimi M, Hrimi D, Kurian VJ, Nurmin B (2007). Evaluation of the thermal performance of metal roofing under tropical climatic performance of metal roofing under topical climatic conditions. Malaysian Cons. Res. J. (MCRJ), 1(1): 72-80.

Holm TA, Bremner TW (2000). State of the art report on high strength, high durability structural low-density concrete for applications in severe marine environments. US Army Corps of Engineers, Engineering Research and Development Center, ERDC/SL, TR-00-3.

Kilic A, Atis CD, Yasar E, Ozcan F (2003). High-strength lightweight concrete made with scoria aggregate containing mineral admixtures. Cem. Con. Res., 33: 1595-1599.

Kosmatka SH, Kerkhoff B, Panarese WC (2002). Design and control of concrete mixtures. 14rd ed. USA: Portland cem. assoti.

Koya OA, Fono TR (2009). Palm Kernel Shell in the Manufacture of Automotive Brake Pad. Technoexpo.

Lo TY, Cui HZ, Li ZG (2004). Influence of aggregate pre-wetting and fly ash on mechanical properties of lightweight concrete. Waste Manage., 24: 333-338.

Mannan MA, Alexander J, Ganapathy C, Teo DCL (2006). Quality improvement of oil palm shell (OPS) as coarse aggregate in lightweight concrete. Build. Environ., 41: 1239-1242.

Mannan MA, Basri HB, Zain MFM, Islam MN (2002). Effect of curing conditions on the properties of OPS-concrete. Build. Environ., 37: 1167-1171.

Mannan MA, Ganapathy C (2004). Concrete from an agricultural waste-oil palm shell (OPS). Build. Environ., 39: 441-448.

Mannan MA, Ganapathy C (2002). Engineering properties of concrete with oil palm shell as coarse aggregate. Cons. Build. Mat., 16: 29-34.

Mannan MA, Ganapathy C (2001). Long-term strengths of concrete with oil palm shell as coarse aggregate. Cem. Con. Res. 31: 1319–1321.

Mannan MA, Ganapathy C (2001). Mix design for oil palm shell concrete. Cem. Con. Res., 31: 1323-1325.

Mehta PK, Monteiro PJM (2006). Concrete: microstructure, properties, and materials. 3rd ed. New York: McGraw-Hill.

MPOB, Malaysia Palm Oil Board (2006). Higher value products from oil palm biomass. Website: http://mpob.gov.my.

Ndoke PN (2006). Performance of Palm Kernel Shells as a Partial replacement for Coarse Aggregate in Asphalt Concrete. Leonardo Elec. J. Prac. Tec., 9: 145-152.

Neville AM, Brooks JJ (2008). Concrete technology. Malaysia: Prentice Hall.

Neville AM (2008). Properties of concrete. 14th ed., Prentice Hall, Malaysia.

Okafor FO (1991). An investigation on the use of superplasticizer in palm kernel shell aggregate concrete. Cem. Con. Res., 21: 551-557.

Okafor FO (1988). Palm Kernel Shell as a Lightweight Aggregate for Concrete. Cem. Con. Res., 18: 901-910.

Okpala DC (1990). Palm kernel shell as a lightweight aggregate in concrete. Build. Environ., 25: 291-296.

Olanipekun EA, Olusola, KO, Ata, O (2006). A comparative study of concrete properties using coconut shell and palm kernel shell as coarse aggregates. Buil. Environ., 41: 297-301.

Polat R, Demirboğa R, Karakoç MB, Türkmen I (2010). The influence of lightweight aggregate on the physico-mechanical properties of concrete exposed to freeze–thaw cycles. Cold Reg. Sci. Tech., 60: 51-56.

Rossignolo JA, Agnesini MVC, Morais JA (2003). Properties of high-performance LWAC for precast structures with Brazilian lightweight aggregates. Cem. Con. Compo., 25: 77-82.

Salam SA, Abdullah AAA (1985). Lightweight concrete using oil palm shells as aggregates. National symposium on oil palm by-products for agro-based industries. Kuala Lumpur.

Shetty MS (2005). Concrete technology theory and practice. 1rd Multicolor illustrative revised ed. India.

Subramaniam V, Ngan MA, May CY, Sulaiman NMN (2008). Environmental performance of the milling process of Malaysian Palm Oil using the life cycle assessment approach. Am. J. Environ. Sci., 4(4): 310-315.

Sylva GS, Burns NH, Breen JE (2002). Composite bridge systems with high-Performance lightweight concrete. ACI symposium, High-Performance structural lightweight concrete, pp. 91-100.

Teo DCL, Mannan MA, Kurian VJ (2006). Flexural Behaviour of Reinforced Lightweight Concrete Beams Made with Oil Palm Shell (OPS). J. Adv. Conc. Tech., 4(3): 459-468.

Teo DCL, Mannan MA, Kurian VJ, Ganapathy C (2007). Lightweight concrete made from oil palm shell (OPS): Structural bond and durability properties. Buil. Environ., 42: 2614-2621.

Teo DCL, Mannan MA, Kurian VJ (2006) . Structural Concrete Using Oil Palm Shell (OPS) as Lightweight Aggregate. Turk. J. Eng. Env. Sci., 30: 251-257.

Teo DCL, Mannan MA, Kurian VJ, Zakaria I (2006). Flexural Behaviour of Reinforced Lightweight OPS Concrete Beams. 9th International conference on concrete engineering and technology, Malaysia, pp. 244-252.

Wiegrink K, Marikunte S, Shah SP (1996). Shrinkage cracking of high-strength concrete. ACI Mat. J., 93(5): 409-415.

Wilson HS, Malhotra VM (1988). Development of high strength lightweight concrete for structural applications. Int. J. Cem. Compo. LWC, 10(2): 79-90.