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ENGINEERING PROPERTIES OF LIGHTWEIGHT GEOPOLYMER CONCRETE USING PALM OIL CLINKER AGGREGATE

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ABSTRACT: The palm oil industry generates a significant amount of wastes which their managing has been a major environmental concern in producing countries. The utilization of these wastes as an aggregate source for concrete production will help to sanitize the environment and provides a cheaper and renewable aggregates source for construction industries. This paper presents the results of the experimental program conducted on fly-ash based geopolymer concrete containing Palm Oil Clinker Aggregate (POCA). Several geopolymer concrete mixes were prepared in which POC was used as a replacement to both fine and coarse aggregates at different percentages starting from 25% to 100%. Mix proportioning was done in accordance with ACI 211.1-91. Geopolymer concrete specimens were cast, cured at ambient conditions and tested for the slump, density, water absorption and compressive, shear and flexural strengths. Overall, the use of fly ash-based geopolymer binder and POCA can enhance the sustainability aspects in concrete production as well as produce a high strength concrete. A concrete mixture containing 100% POCA can produce a structural lightweight concrete having a compressive strength of more than 30 MPa and a density of 1821 kg/m^3. The use of a geopolymer binder promotes the workability and strength of POCA concrete and reduces its water absorbability. Incorporation of POCA up to 75% did not much change the structural efficiency of the produced concrete, while it was reduced by 32% when the POCA fully replaced the natural aggregate. Nevertheless, the benefits in terms of cost, energy, and environmental savings cannot be overlooked.

Keywords: Geopolymer, Palm oil clinker, Lightweight concrete, Fly ash, Structural efficiency

1. INTRODUCTION

High amounts of agricultural and industrial waste are generated worldwide. The increasing demands for palm oil have increased the amount of generated wastes, which their management is a major concern to the producing countries. Malaysia and Indonesia are the world's largest producers of palm oil and huge amounts of wastes are generated in the milling process every year [1, 2]. These wastes are usually disposed in landfills generating environmental hazards and wasting the available land resources which would have been put into beneficial alternative uses [3].

Considerable efforts have been made to utilize such wastes in concrete including the oil palm shell (OPS), palm oil clinker (POC) and palm oil fuel ash (POFA), and promising results were obtained [2, 4-6]. To date, POC and POFA have been used to produce a high-strength concrete with a compressive strength of more than 80 MPa [7]. POCA has been successfully used in lightweight concrete production [8, 9]. It is reported that concrete with a density in the range of 1770 kg/m^3 to 2050 kg/m^3 and compressive strength of 25 MPa can be produced using POCA [8]. This is higher than the minimum strength required for structural lightweight concrete applications. On the other hand, using POCA is reported to increase the ductility of concrete. Incorporation of 70% POCA found to increase the concrete ductility by 2.8 times over the normal aggregate concrete [10]. The improved ductility side to side with the reduced weight promotes the use of POCA concrete for the enhancement of the earthquake’s structural resistance. The use of OPS as a replacement to aggregate has been also investigated by many researchers [11, 12]. Due to its organic matter content, OPS is known to increase the water absorption of concrete when used in its raw form. OPSs have a uniform particle gradation and 60% to 90% of the shells are in the range of 5 mm to 13 mm in size [13]. The high absorption of the OPS will adversely affect the mechanical properties of concrete due to the voids which are created at the paste-aggregate interfacial zone. This besides the smooth surface of OPS will reduce the bond strength between the cement paste and OPS [14].

Geopolymers are innovative binders that can utilize many types of waste materials to produce a green construction material [3]. Geopolymers are aluminosilicate molecular units that can be produced by the geopolymerization processes. Geopolymerization represents the processes of the chemical integration of materials having rich content of silicon and aluminum atoms (such as: fly ash, granulated blast furnace slag, red mud, rice husk ash, and volcanic ash) and an alkaline solution (such as sodium hydroxide and sodium silicate). These atoms are combined by the process to produce the building units of geopolymer binders which are analogous to those binding the natural rocks [15]. Geopolymer binders can be used as an alternative to the Ordinary Portland Cement (OPC) in concrete production. Even they are known to provide superior properties [16]. Properties of geopolymer binders are mainly a function of the source material and alkaline solution properties [15, 17-19]. The use of a geopolymer binder and POCA will help to produce a concrete that its main constituents are waste materials. This will promote a new generation of green construction materials and save the environment where the cement industry is considered as the second larger producer of CO_2 emissions [3]. At the same time, quarrying of aggregate to supply the increasing demand for construction materials is another originator to environmental degradation. Researchers have explored the utilization of POCA in OPC concrete. However, limited research is available on the incorporation of POCA in the production of lightweight geopolymer concrete. Yet, many researchers considered the use of POFA as source material to produce the geopolymer binder itself [20].

In view of bringing POCA and fly ash-based geopolymer binder together as ingredients in concrete production, from being waste materials and polluting to the environment to a wealth-creating element, the current study investigates the properties of this sustainable green construction material. The utilization of both POCA and Fly ash wastes as ingredients in concrete manufacturing is one of the many alternatives that could push down disposed wastes. The present work studies the production of high-strength lightweight concrete using POC as aggregates and fly ash-based geopolymer as a binding material.

2. MATERIALS AND METHODS

The geopolymer binder was produced using fly ash as source material, and a mixture of sodium silicate and sodium hydroxide solutions for the activating solution choice. The chemical composition of the used fly ash is shown in Table 1. The used fly ash can be classified as Type-F fly ash but with high calcium content. The high calcium content can be beneficial in producing a geopolymer binder that can be cured at ambient conditions [17]. The concentration of the used sodium hydroxide solution was 14 M. The used sodium silicate solution composed of 29.43%, 14.26%, and 56.31% of SiO_2, Na_2O, and H_2O, respectively. The sodium hydroxide solution to sodium silicate mixing ratio was 1:2 as a weight ratio. Two types of aggregate were used; the first was crushed granite having a 14 mm maximum aggregate size for the coarse aggregate and natural river sand for the fine aggregate. The second was the POCA for both coarse and fine aggregates. POC was collected from the clinker mill, after which it was crushed and sieved to the desired particle sizes. The properties of POCA used are given in Table 2.

Table 1: Chemical composition of fly ash (% by weight)

Composition	%	Composition	%
Fe_2O_3	29.32	P_2O_5	1.11
SiO_2	28.52	SO_3	0.73
CaO	17.91	MnO	0.3
Al_2O_3	12.34	TiO_2	1.06
K_2O	1.81	ZnO	0.13
MgO	1.78	L.O.I.	3.62

Table 2: Properties of POC aggregates

Properties	Fine	Coarse
Size of aggregate	<5 mm	5-14 mm
Bulk dry density	1096 kg/m^3	823 kg/m^3
Bulk specific gravity (SSD)	1.87	1.62
Water absorption (24 hours)	14.65%	4.43%
Abrasion value (%)	-	26.21%
Aggregate crushing value	-	18.04%

The experimental program involved the mix design, casting and curing, and determination of fresh and hardened properties of concrete mixtures. Proportioning of the mix ingredients was done in accordance with ACI 211.1-91 [21]. The aggregates were used in dry condition. Five mixes were prepared by maintaining a constant fly ash content of 480 kg/m^3, and alkaline solution to fly ash ratio (Alk/FA) of 0.50. The details of the mix proportions are given in Table 3. Mix designations POCC-0, POCC-25, POCC-50, POCC-75, and POCC-100 represents the geopolymer concrete mix containing 0%, 25%, 50%, 75% and 100% of POCA, respectively as volume percentages.

The available standards for mixing, casting, and testing of OPC concrete were also adopted here for geopolymer concrete mixing, casting, and testing as possible. For each mix, cylindrical specimens of 150 mm diameter were prepared in accordance with ASTM C192 [22]. The slump of the fresh concrete was measured in accordance

Table 3: Details of geopolymer concrete mixtures in kg/m^3

Mix Designation	Fly Ash	Fine Aggregate		Coarse Aggregate	
		Sand	Clinker	Granite	Clinker
POCC-0	480	620	0	1050	0
POCC-25	480	465	121.8	787.5	164.6
POCC-50	480	310	243.7	525	329.1
POCC-75	480	155	365.5	262.5	493.7
POCC-100	480	0	487.3	0	658.3

with ASTM C143 [23]. The geopolymer concrete specimens were cured at ambient conditions at a temperature of 23±2℃ and relative humidity 80 ±5%. The compressive strength of concrete was measured at the age of 1, 3, 7, 28, and 90 days in accordance with ASTM C39 [24]. The density and water absorption were measured after 28 days in accordance with ASTM C642 [25]. To determine the flexural and shear strength of the geopolymer concrete mixtures, prisms of 150x150x500 mm were cast and tested at the age of 28 days. The flexural strength was obtained using the third-point loading test in accordance with ASTM C78 [26]. The shear strength was obtained by the direct shear test in accordance with the Japan Society of Civil Engineers (JSCE) test procedures [27] with some modifications. Fig. 1 shows the setup used for the shear test.

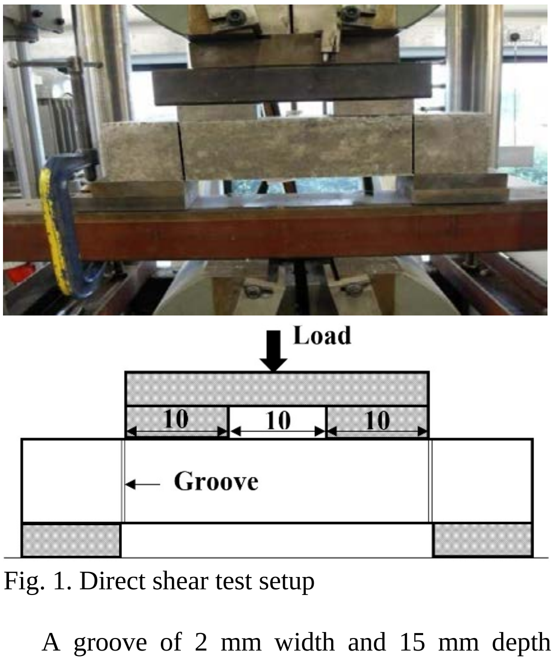

Fig. 1. Direct shear test setup

A groove of 2 mm width and 15 mm depth were sawn all-around faces of the specimens in the narrow gap of 2.5 mm between the rigid supporting edges and loading blocks as shown in the schematic setup in Fig. 1. This was done to get a predefined crack plane and guarantee that the failure will due to the direct shear mode of failure [28]. For all tests, three specimens were tested, and the average value was recorded. The scanning electron microscope (SEM) was used to explore the specimens' microstructure at 5000x magnification.

3. RESULTS AND DISCUSSIONS

3.1 Slump

The results of the slump test are displayed in Fig. 2. The results revealed a reduction in the slump value with the increment of the aggregate replacement ratio. This can be attributed to the fact that POCA got a higher water absorption as compared to the granite aggregate. The 5 minutes absorption of POC coarse aggregate was 2.83% compared to 0.04% for the granite aggregate. This means that POCA will absorb higher amounts of the alkaline solution during the mixing processes. In turn, this will reduce the amount of the solution available for fly ash and a drier paste will be produced. The paste works as a lubricant to the aggregate. On the other hand, POCA is lighter than the used natural aggregates.

The higher the POCA content the lower the fresh unit weight of the produced concrete. Since the slump is a measure of the displacement of the fresh concrete mass from its original position under gravity without any disturbing force, its magnitude will be reduced as the overall weight of the fresh content decreases. Additionally, the rough and spiky surface of POCA will reduce the mixture workability. The slump value decreased almost in a linear fashion (21% reduction for each 25% POCA increment) to reach a 30 mm for POCC-100 mix. Such a slump value in the case of conventional concrete mixtures is known to produce a stiff concrete mixture. However, the workability of this mix was acceptable and not as expected for such low slump value. This can be attributed to the fact that fly ash is a very fine material and it has the filler action, this besides the high viscosity of the alkaline solution (compared to water) will produce a mix of high consistency. Yet, in terms of slump value, a concrete mixture of medium workability can still be produced when the aggregate replacement percentage is in the range 25 to 75%. In addition, no segregation or floating was observed for all mixtures. Using of POCA with OPC concrete is reported to provide almost a similar range of slump. Most of the published work reported the use of superplasticizers to maintain workability [29], while when it was not utilized a zero-slump vale was reported [29].

In this research, superplasticizers were not utilized; yet, higher workability was obtained. The use of the alkaline solution in geopolymers instead of water in OPC concrete helps to increase the workability in the case of POCA. Smaller amounts of the alkaline solution were absorbed by the POCA because of its higher viscosity as compared to water. The 5 minutes alkaline solution absorption of the coarse POCA was 1.76% which is lower by almost 38% than its water absorption value. It's worth mentioning that in the case of geopolymer binders, the use of superplasticizers does not have a significant effect the same as in OPC concrete, the alkaline solution tends to degrade the superplasticizer and wastes its functionality [30].

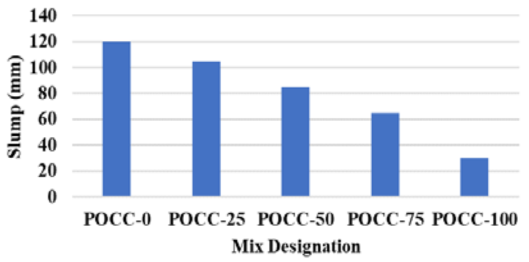

Fig. 2. The slump of geopolymer concrete mixtures at different POCA percentages

3.2 Air Dry Density

The density test results given in Table 4 show that the concrete density reduced with the increment of POCA percentage. The unit weight of POCA, being a lighter material, is lower than the unit weight of natural aggregates mainly from rock fragments. The dry bulk density of fine and coarse POCA was 1096 kg/m^3 and 823 kg/m^3, respectively. While it was 1645 kg/m^3 and 1560 kg/m^3 for the coarse granite aggregate and natural river sand, respectively. In this wise, as POCA content increases the overall density of the concrete reduces. The weight loss value was increasing nearly in a linear fashion where for each 25% increment of POCA the weight reduced by almost 5.5%. For the mixture at which only POCA was used (POCC-100), the average density was 1821 kg/m^3. According to the American concrete institute, the density range for structural lightweight concrete is from 1440 kg/m^3 to 1850 kg/m^3 [31]. The density of 1821 kg/m^3 recorded for full replacement fall within the range for structural lightweight concrete and suggests that POCA concrete can be used as structural lightweight concrete. According to Eurocode 2, all the produced mixes incorporating POCA can be classified as a lightweight concrete where the density was less than 2200 kg/m^3 [32].

Table 4: Density of concrete mixtures

Mix Designation	Density (kg/m^3)	The average reduction in density (%)
POCC-0	2345	-
POCC-25	2165	7.7
POCC-50	2079	11.3
POCC-75	1942	17.2
POCC-100	1821	22.3

3.3 Absorption

Fig. 3 displays the water absorption of geopolymer concrete mixes incorporating various percentages of POCA. For all specimens, the water absorption value was lower than 3.2%. All mixtures produced high-quality concrete specimens as the water absorption percentage was less than 10% as recommended by Neville [33]. Concrete produced using POCA is known to have a high water absorption value. This is true when OPC is used as a binding material [34]; however, in this study, the use of geopolymer binder resulted in a much lower water absorption value. This can be attributed to the fact that fly ash particles used in geopolymer binder production are finer in size than cement binder particles [35]; hence, besides its being the source materials, it will also work as a filler [15].

It will react inside the pores of POCA resulting in a refinement of voids and reduces POCA's absorption of water. Moreover, fly ash geopolymerization processes produce a dense microstructure as appears from the micrographs shown in Fig. 7 and affirmed by the low absorption value measured for the reference specimen (POCC-0). It's worth to note that the increment in the water absorption percentage was increasing in an exponential manner. This can be referred to the added porosity due to the POCA incorporation side by side to the reduced workability that makes the concrete difficult to be compacted. The higher percentages of POCA will increase the interconnectivity of pores and creates internal networks or pathways that allow the flow of water into the concrete and increase the absorption value.

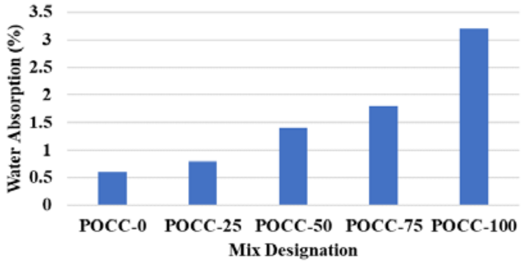

Fig. 3. Water absorption of geopolymer concrete mixtures at different POCA percentages

3.4 Compressive Strength

The compressive strength (f_c') results of geopolymer concrete mixtures at various POCA percentages and different ages up to 90 days are depicted in Fig. 4. Replacement of natural aggregate with POCA reduced the compressive strength for all mixtures. This can primarily be related to the lower strength of POCA as compared to the granite aggregate. The measured aggregate crushing value of POCA was around 19% higher as compared to the granite aggregate. Hence, the aggregate crushing value will control the concrete strength. This was noticed from the failure surface of the tested specimens where most of the aggregate crushed in the case of POCA, while many of them remained uncrushed in the case of granite aggregate specimens. Also, the compressive strength of POCC-0, POCC-25, and POCC-50 at 1-day age was almost the same (20 MPa).

At early ages, the failure occurred mainly due to the geopolymer binder-aggregate bond failure, where the binder yet to develop its full strength. Therefore, the concrete strength was not dependent on the aggregate strength. For POCC-75 and POC-100 mixtures the strength dropped even at the 1-day age. This can be ascribed to the loss of workability at the higher aggregate replacement percentages. At the age of 90 days, the compressive strength reduced in an increasing fashion at higher replacement percentages as depicted in Fig. 5. At this age, the higher replacement percentage will result in a higher content of the weaker POCA and a stiffer mix. Stiffer mixtures have lower workability; hence, more air vides will be contained within the concrete texture in the bulk of the geopolymer binder and at the transition zone between the binder and aggregate. This will be more significant in the case of geopolymer concrete since the geopolymer binder has a higher viscosity and more air bubbles will be entrapped. The entrapped air voids varied in size between 0.5 mm to 6 mm as can be seen from the fractured surface of the POCC-100 specimen shown in Fig. 6.

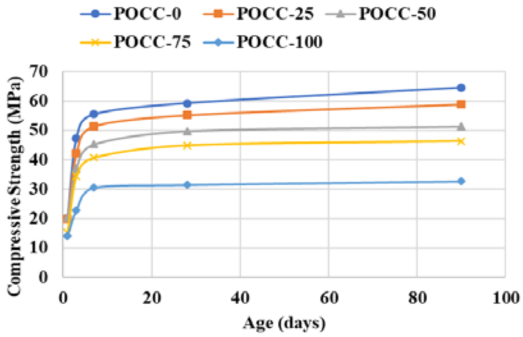

Fig. 4. Compressive strength vs age at different POCA percentages

POCA content also affected the rate of strength development of the geopolymer binder. Fig. 4 shows that at a higher replacement percentage, the increment in the compressive strength at later ages was lower. For POCC-0 specimens, the strength remained to increase until 90 days, at 7 days about 85.9% of the 90 days strength was achieved, while it was 93.3% for POCC-100. Generally, geopolymerization is a fast reaction process when compared to the ordinary cement hydration reactions [15], and most of the strength will be achieved at an early age as can be seen in Fig. 4. At a higher replacement percentage, the POCA will absorb a higher amount of the alkaline solution, and fewer solutions will be available for fly ash fast geopolymerization process. The geopolymerization processes will be stopped at an early age, and more fly ash particles will remain unreacted as can be seen in Fig. 7 for POCC-0 and POCC-100 SEM micrographs.

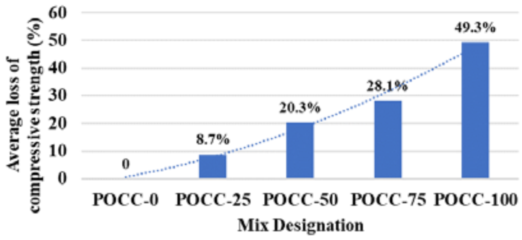

Fig. 5. Average compressive strength loss at the age of 90 days of different mixtures

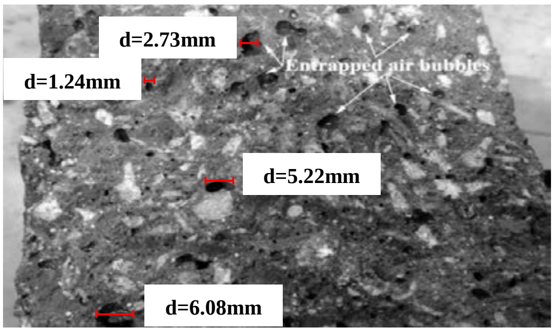

Fig. 6. The fractured surface of POCC-100 mixture specimen

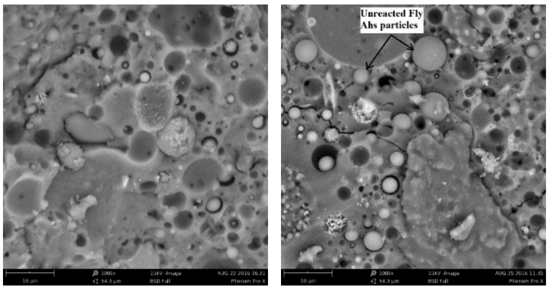

Fig. 7. SEM micrographs of POCC-0 (left) and POCC-100 (right) cracked specimens

To compare the structural performance of POCA and non-POCA (reference) specimens, the structural efficiency concept can be introduced. Structural efficiency can be expressed as the compressive strength to density ratio [36]. The structural efficiency (MPa / kg/m^3) of POCC-0, POCC-25, POCC-50, and POCC-100 was 0.025, 0.025, 0.024, 0.023, and 0.017, respectively. Incorporation of POCA up to 75% did not much change the structural efficiency of the developed concrete. While it was reduced by 32% when POCA fully replaced the aggregate. Nevertheless, the benefits in terms of cost, energy, and environmental savings cannot be overlooked.

In summary, POCC-100 mix in which POCA fully replaced the aggregate can be used as a structural lightweight concrete as its density and compressive strength at 28 days was about 1821 kg/m^3 and 31 MPa, respectively. The use of fly ash-based geopolymer binder promotes the strength of the produced concrete. POCA has a porous structure, and fly ash particles are very fine particles working as a micro-filler [37]. These particles enter inside the POCA pores and react with the alkaline solution which has been absorbed by the aggregate. This will increase the bond between the geopolymer binder and aggregate resulting in an improvement in the concrete overall strength. This can also be noticed from the low absorption results, where for such porous aggregate a higher absorption value should be recorded.

3.5 Shear Strength

Table 5 shows the results of the shear strength test. For all tested specimens, the mode of failure was the ideal shear mode, which occurred at both predefined planes coinciding with the grooves. The shear strength (τ) was computed by assuming an elastic behavior using the following formula $\tau=P/A_{eff}$, where P is the ultimate load on one plane of the tested specimen, and A_{eff} is the effective cross-section area equals to 12x12=144 cm^2. The results showed that increasing the POCA content proportionally decreased the measured shear strength. Regression analysis revealed a strong correlation between shear and compressive strengths, and they can be related using $\tau = 0.8 f_c'^{0.59}$ with a coefficient of determination (R^2) of 0.92. Reduction in the shear strength with the increment of POCA content was lower than the reduction in its compressive strength. At full aggregate replacement, the compressive strength reduced by 49.3% compared to 31.7% for shear strength. This may due to the good POCA interlock.

For concrete of compressive strength of less than 60 MPa, the shear transfer mechanism is dominated by the binder-aggregate interlock at the shearing plane [38]. In such concrete, the aggregate strength and stiffness are higher than it for the binder, the binder will be crushed at the shearing plan. This is true in the case of OPC normal-weight concrete; however, for lightweight aggregate which usually has a lower strength and stiffness, the shearing mechanism will be different [39]. For the specimens with POCA, it was noted that many of the POCA was crushed at the shearing plane. This may happen not only because of the weaker POCA but also due to the stronger geopolymer binder-aggregate transition zone since geopolymer binders have a high adhering capability. The presence of voids within the POCA porous structure allows for the fast propagation of cracks and hastens the failure under applied load [37]. Accordingly, in POCA concrete, the weakest plane is the POC coarse aggregate. For geopolymer POCA concrete, the shear strength comes mainly from the binder-aggregate transition zone adhesion, in addition to the binder-aggregate interlock along with the sheared plans.

Table 5: The mechanical properties of the tested specimens measured at 28 days

Mix Designation	Compressive Strength (MPa)	Shear Strength (MPa)	Flexural Strength (MPa)
POCC-0	64.51	9.41	6.31
POCC-25	58.94	9.04	6.02
POCC-50	51.40	7.94	5.56
POCC-75	46.44	7.09	5.10
POCC-100	32.72	6.42	4.78

3.6. Flexural Strength

Table 5 shows the results of the flexural strength tests (also known as rupture modulus (f_r)). The effect of POCA content on flexural strength was like its effect on the previously measured strengths. Higher POCA content reduced the measured flexural strength. At full aggregate replacement, the reduction was about 49%. The specimens were exposed to bending during the flexural strength test. Bending will develop tension and compression stresses within the bottom and top fiber of specimen cross-section, respectively. The compression zone is reported to have an insignificant role in failure [39]. The tensile zone will play the main role in the development of flexural strength. Therefore, the low crushing value of the POCA did not greatly affect the flexural strength results. Generally, tension failure happens due to binder-aggregate bond breakdown or rupture of the binder matrix itself rather than aggregate fracture. Yet, it was noticed that some of the aggregates were fractured at the failure surface. This attributed to the presence of voids within the aggregate matrix which contributed to the concentration of stresses and hastened the propagation of cracks, and to the high adhering capability of geopolymer binders [15, 16]. The ratio of the flexural strength to the compressive strength did not vary significantly when the POCA content increased up to 75%, and it ranged from 9.7% to 11%. While it was dropped to 14.6 % at full replacement. Regression analysis showed that the flexural and compressive strengths are strongly correlated with R^2 of 0.96 and can be best related by $f_r = 3.47e^{0.0091f_c'}$. The use of the ACI 363R-92 [40] recommended equation ($f_r = 0.94\sqrt{f_c'}$) for predation of the rupture modulus of high strength concrete in the range $21 < f_c' < 83$ will overestimate the results with an estimation error ranged from 12% to 26%. On the other hand, the use of ACI 318M-14 [41] equation for normal strength concrete ($f_r = 0.62\lambda\sqrt{f_c'}$) will underestimate the results with an error ranged from 20% to 45%.

4. CONCLUSIONS

The outcome of this work revealed that the fly ash-based geopolymer binder and POCA can effectively be used to produce a green sustainable structural lightweight concrete. All POCA mixtures produced a concrete having a compressive strength of more than 30 MPa. However, only a full aggregate replacement can satisfy the ACI definition of structural lightweight concrete since its density is less than 1850 kg/m^3. The use of a geopolymer binder promotes the fresh and hardened properties of POCA concrete as compared to POCA with OPC concrete. Geopolymer binder produced consistent mixes which have acceptable workability even at low slump values and without the addition of superplasticizers. In designing POCA mixtures, the high-water adsorption should be taken seriously. However, the use of a geopolymer binder reduced the water absorption and produced high-quality concrete. In terms of compressive, shear and flexural strengths, and structural efficiency, the use of 75% POCA content in designing the geopolymer concrete mixtures found to be the most efficient content.

5. REFERENCES

[1] Mekhilef S., Siga S., and Saidur R., A review on palm oil biodiesel as a source of renewable fuel, Renew. Sust. Energ. Rev., vol. 15, Issue 4, 2011, pp. 1937-1949.

[2] Mannan M., and Ganapathy C., Concrete from an agricultural waste-oil palm shell (OPS), Build. Environ., vol. 39, Issue 4, 2004, pp. 41-48.

[3] Malkawi A. B., Al-Mattarneh H., Achara B. E., Muhammed B. S., and Nuruddin M. F., Dielectric properties for characterization of fly ash-based geopolymer binders, Const. Build. Mat, vol. 189, 2018, pp. 19-32.

[4] Abutaha F., Razak H. A., and Kanadasan J., Effect of palm oil clinker (POC) aggregates on fresh and hardened properties of concrete, Const. Build. Mat, vol. 112, 2016, pp. 416-423.

[5] Ibrahim H. A., and Razak H. A., Effect of palm oil clinker incorporation on properties of pervious concrete, Const. Build. Mat, vol. 115, 2016, pp. 70-77.

[6] Alhasanat M. B., Al Qadi A. N., Haddad M., and Al-Mattarneh H., Effect of Aggregate Size on the Engineering Properties of Palm Oil Clinker Concrete, GSTF Journal of Engineering Technology (JET), vol. 3, Issue 4, 2017.

[7] Muthusamy K., Properties of high strength palm oil clinker lightweight concrete containing palm oil fuel ash in tropical climate, Const. Build. Mat, vol. 199, 2019, pp. 163-177.

[8] Alengaram U. J., Jumaat M. Z., and Mahmud H., Ductility behaviour of reinforced palm kernel shell concrete beams, Eur. J. Sci. Res., vol. 23, Issue 3, 2008, pp. 406-420.

[9] Oyejobi D. O., Jameel M., Sulong N., Raji S. A., and Ibrahim H. A., Prediction of optimum compressive strength of light-weight concrete containing Nigerian palm kernel shells, J. King Saud Univ., in-press, 2019.

[10] Ahmmad R., Jumaat M. Z., Bahri S., and Islam A. B. M. S., Ductility performance of lightweight concrete element containing massive palm shell clinker, Const. Build. Mat, vol. 63, 2014, pp. 234-241.

[11] Olanipekun E., Olusola K., and Ata O., A comparative study of concrete properties using coconut shell and palm kernel shell as coarse aggregates, Build. Environ., vol. 41, Issue 3, 2006, pp. 297-301.

[12] TEO D. C. L., Mannan M. A., and Kurian V. J., Structural concrete using oil palm shell (OPS) as lightweight aggregate, Turkish J. Eng. Env. Sci., vol. 30, Issue 4, 2006, pp. 251-257.

[13] Malkawi A. B, Aladwan J., and Al-Salaheen M., Agricultural Palm Oil Wastes for Development of Structural Lightweight Concrete, International Journal of Civil Engineering and Technology, vol. 10, Issue 7, 2019.

[14] Okpala D., Palm kernel shell as a lightweight aggregate in concrete, Build. Environ., vol. 25, Issue 4, 1990, pp. 291-296.

[15] Nuruddin M. F., Malkawi A. B., Fauzi A., Mohammed B. S., and Almattarneh H. M., Evolution of geopolymer binders: a review, in IOP Conf. Series: Materials Science and Engineering, vol. 133, 2016.

[16] Nuruddin M. F., Malkawi A. B., Fauzi A., Mohammed B. S., and Almattarneh H. M., Geopolymer concrete for structural use: Recent findings and limitations, in IOP Conf. Series: Materials Science and Engineering, vol. 133, 2016.

[17] Malkawi A. B., Nuruddin M. F., Fauzi A., Almattarneh H., and Mohammed B. S., Effects of Alkaline Solution on Properties of the HCFA

Geopolymer Mortars, Procedia Eng., vol. 148, 2016, pp. 710-717.

[18] Nuruddin M., Malkawi A., Fauzi A., Mohammed B., and Al-Mattarneh H., Effects of alkaline solution on the microstructure of HCFA geopolymers, in Engineering Challenges for Sustainable Future, vol. 501 Issue 505): ROUTLEDGE in association with GSE Research, 2016, pp. 501-505.

[19] Fauzi A., Nuruddin M. F., Malkawi A. B., Abdullah B., Al M. M., and Mohammed B. S., Effect of Alkaline Solution to Fly Ash Ratio on Geopolymer Mortar Properties, Key Engineering Materials, vol. 733, 2017.

[20] Salih M. A., Ali A. A. A., and Farzadnia N., Characterization of mechanical and microstructural properties of palm oil fuel ash geopolymer cement paste, Const. Build. Mat, vol. 65, 2014, pp. 592-603.

[21] ACI-Committee-211, Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete. ACI, 2009.

[22] ASTM C192 / C192M-16a, Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory, ASTM International, West Conshohocken, PA, 2016.

[23] Olivia M., Durability related properties of low calcium fly ash based geopolymer concrete, Doctor of Philosophy, Department of Civil Engineering, Curtin University , 2011.

[24] Lamond J. F., Guide for Use of Normal Weight and Heavyweight Aggregates in Concrete, American Concrete Institute, 2001.

[25] Testing of Concrete. Non-Destructive tests on hardened concrete: ISO 1920-7, 2004.

[26] ASTM C78/ C78M-18, Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading), 2018.

[27] Japan-Society-of-Civil-Engineers, Method of test for shear strength of steel fiber reinforced concrete (SFRC), JSCE-SF6, 1990, pp. 67-69.

[28] Soetens T., and Matthys S., Shear-stress transfer across a crack in steel fibre-reinforced concrete, Cem. Concr. Compos., vol. 82, 2017, pp. 1-13.

[29] Aslam M., Shafigh P., and Jumaat M. Z., Oil-palm by-products as lightweight aggregate in concrete mixture: a review, Journal of cleaner production, vol. 126, 2016, pp. 56-73.

[30] Malkawi A. B., Nuruddin M. F., Fauzi A., Al-Mattarneh H., and Mohammed B. S., Effect of Plasticizers and Water on Properties of HCFA Geopolymers, Key Engineering Materials, vol. 733, 2017, pp. 76-79.

[31] ACI-Committee-213, Guide for Structural Lightweight-Aggregate Concrete, American Concrete Insttitute, 2014, pp. 53-59.

[32] P. Code, Eurocode 2: Design Of Concrete Structures-Part 1-1: General Rules and Rules For Buildings, 2005.

[33] Neville A. M., Properties of Concrete, 5th ed. Harlow, England: Prentice Hall Pearson, 2011.

[34] Abutaha F., Abdul Razak H., and Ibrahim H., Effect of coating palm oil clinker aggregate on the engineering properties of normal grade concrete, Coatings, vol. 7, Issue 10, 2017, pp. 175.

[35] Fauzi A., Nuruddin M. F., Malkawi A. B., and Abdullah M. M. A. B., Study of Fly Ash Characterization as a Cementitious Material, Procedia Eng., vol. 148, 2016, pp. 487-493.

[36] Kanadasan J., and Abdul Razak H., Utilization of palm oil clinker as cement replacement material, Materials, vol. 8, 2015, pp. 817-838.

[37] Abutaha F., Razak H. A., Ibrahim H. A., and Ghayeb H. H., Adopting particle-packing method to develop high strength palm oil clinker concrete, Resources, Conservation and Recycling, vol. 131, 2018, pp. 247-258.

[38] Wong R., Ma S., Wong R., and Chau K., Shear strength components of concrete under direct shearing, Cem. Concr. Res., vol. 37, Issue 8, 2007, pp. 1248-1256.

[39] Al-Akhras N. M., Jamal Shannag M., and Malkawi A. B., Evaluation of shear-deficient lightweight RC beams retrofitted with adhesively bonded CFRP sheets, Eur. J. Environ. Civ. En., 2015, pp. 1-15.

[40] ACI-363R, State of the Art Report on High-Strength Concrete, Journal Proceedings, vol. 81, Issue 4, 1997.

[41] ACI-318-Committee, Building Code Requirements for Structural Concrete and Commentary, Farmington Hills: American Concrete Institute, 2014.