

# Properties of fresh and hardened sustainable concrete due to the use of palm oil fuel ash as cement replacement

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**Abstract:** Palm oil fuel ash (POFA) is a by-product resulting from the combustion of palm oil waste such as palm oil shell and empty fruit bunches to generate electricity in the palm oil mills. Considerable quantities of POFA thus generated, accumulate in the open fields and landfills, which causes atmospheric pollution in the form of generating toxic gases. Firstly, to protect the environment; and secondly, having excellent properties for this purpose; POFA can be and has been used as partial cement replacement in concrete preparation. Therefore, this paper compiles the results obtained from previous studies that address the properties of concrete containing POFA as cement replacement in fresh and hardened states. The results indicate that there is a great potential to using POFA as cement replacement because of its ability to improve compressive strength, reduce hydration heat of cement mortar and positively affect other fresh and hardened concrete properties. The paper recommends that conducting further studies to exploit high volume of POFA along with other additives as cement replacement while maintaining high quality of concrete can help minimize CO<sub>2</sub> emissions due to concrete.

## 1. Introduction and background

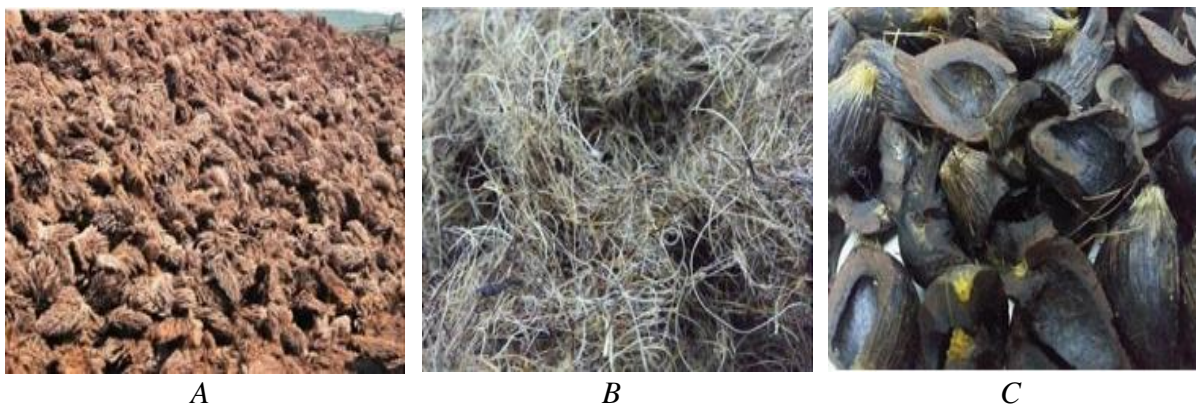
In recent years, the world has witnessed a high demand on the energy sources. The industrial development worldwide has led to the consumption of large quantities of resources such as coal, natural gas, and petrochemicals. In addition to their limited availability and considerably high production costs, these fuels are the main contributors to the global warming and environmental pollution. Furthermore, these resources are non-renewable. This situation has led scientists and academics to focus their efforts towards researching the potential of using alternative and renewable materials. The ideal attributes sought in these alternatives are that these should be easily available, easy to use without any barriers, and friendly towards the environment. Palm oil waste materials are such renewable sources, which can be used in various industries because of the chemical composition being rich in silica and alumina.

On the other hand, there is a growing demand to produce cement to meet construction requirements. The production of cement worldwide is currently 2.9 billion tons a year; this quantity is expected to rise to



4 billion tons in the next ten years [1]. In order to produce one ton of Ordinary Portland Cement (OPC), about one ton of CO<sub>2</sub> is released into the atmosphere causing pollution. A study on the causes of air pollution reported that the CO<sub>2</sub> emission generated from cement manufacture constituted 7% of total CO<sub>2</sub> generated worldwide. This contributes to the climate change that has implications on the quality of future human life [1-3]. Therefore, there is an urgent need to use alternative materials that have high pozzolanic activity, which makes these materials suitable as replacement of cement in the preparation of concrete. The use of these materials can partially help solve the problems associated with cement production such as high production cost, energy consumption, and pollution. This will also mitigate the dumping of these waste materials into landfills.

Malaysia is considered the main contributor in the palm oil industry and this production continues to increase with time due to expansion in the plantation of palm oil trees. It is the first country in terms of export of palm oil products [4]. Approximately 90% of the palm oil is used in food, while 10% is used to produce soap [5]. The increasing demand of the palm oil products has led to the plantation of palm oil increase considerably, from 400 ha in 1920 to more than 4.5 million ha in 2008 [6]. During the production of palm oil, large quantities of waste materials are generated such as palm oil shell, palm oil clinker, and empty fruit, as shown in Figure 1. These wastes can be used as biomass fuel to generate electricity in the palm oil mills. Each palm oil tree consists of 14-15% fibre, 23% empty fruits, 6-7% palm oil shells, 6-7% palm kernel, and only 21% palm oil [7]. It means that for producing one kg of palm oil, there is 5kg dry biomass generated [6]. The palm oil waste has become one of the challenges facing palm oil industry due to accumulation of these wastes in huge amounts beside palm oil mills and in the landfills. The palm oil waste causes generation of undesirable toxic gases such as CO<sub>2</sub>, thus contributing to environmental pollution.



**Figure 1.** Biomass wastes from palm oil mills. (A) Empty fruit bunches (EFB), (B) Mesocarp fibre and (C) Palm kernel shells.

However, few of the studies mentioned above have taken into consideration the utilization of POFA in various concrete forms such as foamed concrete, self-compaction concrete, and other types to achieve the desired benefits from it in concrete production. Therefore, large quantities of POFA are still disposed into open fields and landfills, which causes environmental pollution. Many methods have been employed by the palm oil mills to dispose palm oil waste. These trial measures have resulted in two more challenges, which include the contamination of ground water levels [8] and spreading of these wastes away easily by wind, which causes smog [9]. In connection with the efforts to effectively dispose palm oil waste and reduce environmental pollution due to cement production, this study is aimed at compiling the research on the properties of fresh and hardened concrete containing POFA as reported by previous studies to demonstrate the potential of POFA to be used as cement replacement during concrete production.

## 2. POFA Properties

This section presents the chemical composition and physical properties of POFA, both the unground and ground types.

### 2.1 Chemical Composition

Many researchers have examined the chemical composition of POFA [10, 11]. It has been reported that the differences in the chemical composition of POFA as in Table 1 is due to many factors such as variety of waste material sources and temperature of burning waste. Silica makes the most proportion in the POFA composition; it is responsible for pozzolanic activity. The highest content of silica from among palm tree parts results from burning kernel [12, 13].

**Table 1.** Chemical composition of POFA as reported in literature.

Ref.	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	MgO	Na <sub>2</sub> O	K <sub>2</sub> O	SO <sub>3</sub>	SiO <sub>2</sub> + Al <sub>2</sub> O <sub>3</sub> + Fe <sub>2</sub> O <sub>3</sub>	LOI
[11]	57.71	4.56	3.30	6.55	4.23	0.50	8.27	0.25	65.57	10.52
[14]	67.09	6.12	5.92	5.58	3.06	0.11	5.45		79.13	2.20
[15]	55.5	9.2	5.6	12.4	4.6	0.0	0.0	2.3	70.3	7.9
[16]	60.42	4.26	3.34	11.00	5.31	0.18	5.03	0.45	68.02	2.55
[17]	67.72	3.71	4.71	5.57	4.04	0.16	7.67	1.07	76.14	6.20
[18]	54.0	0.9	2.0	12.9	4.9	1.0	13.5	4.0	56.9	3.7
[19]	53.5	1.9	1.1	8.3	4.1	---	6.5	2.36	56.5	20.9
[1]	47.22	2.24	2.65	6.48	5.86	1.22	11.86	9.19	52.11	5.42
[20]	53.5	1.9	1.1	8.3	4.1	1.3	6.5	--	56.5	18.0
[12]	51.18	4.61	3.42	6.93	4.02	0.06	5.52	0.36	59.21	21.6
[21]	63.41	5.55	4.19	4.34	3.74	0.16	6.33	0.91	73.15	6.20
[22]	54.80	7.40	4.47	14.00	4.14	---	---	0.71	66.67	9.3
[23]	43.60	11.40	4.70	8.40	4.80	0.39	3.50	2.80	59.7	18.00
[24]	65.3	2.5	1.9	6.4	3.0	0.3	5.7	0.4	69.7	10.0
[25]	59.62	2.54	5.02	4.92	4.52	0.76	7.52	1.28	67.18	8.25
[26]	57.8	4.6	3.3	6.6	4.2	0.5	8.3	0.3	65.7	10.1
[27]	60.42	4.26	3.34	11	5.31	0.18	5.03	0.45	68.02	2.55

The silica content ranges between 43.6% and 67.72% of the total components in POFA. Silica content contributes mainly to the pozzolanic reaction and is considered a suitable partial replacement of cement. Whereas, the (SiO<sub>2</sub> + Al<sub>2</sub>O<sub>3</sub> + Fe<sub>2</sub>O<sub>3</sub>) ranges between 52.11 % and 79.13 % of the total components of POFA, which is responsible for formation of additional calcium hydro silicate C-H-S gels in concrete mixtures [28-30].

### 2.2 Physical Properties

Physical properties of POFA as presented in Table 2 also differ greatly as reported by several researchers due to the variety of conditions. High burning temperature changes the colour of particles from dark black to grey. Due to the carbon burning in the POFA particles, pozzolanic activity of POFA increases because of reduction in carbon and increased fineness of POFA. In terms of shape, POFA particles have spherical shape and the specific gravity is less than that of cement [31]. The surface area of POFA particles increases when fineness of the particles is increased by grinding mill. In contrast to Unground POFA (UGPOFA), the ground POFA (GPOFA) has the ability to resist high thermal deterioration due to the fineness of the particles, which act as micro-fillers successfully to avoid concrete degradation [32]. The particle size of GPOFA is smaller than that of OPC, while particle size of OPC is smaller than that of UGPOFA. The unburnt carbon causes absorption of high quantity of water and superplasticizer and thus minimizes the concrete workability. In order to remove the carbon particles, GPOFA should be heated at high temperature of up to 500 °C for one hour [12, 14]. Average particle size can be achieved when POFA particles are collected in a 45 µm sieve. In order to get high fineness POFA, it should be ground to increase the surface

area and reduce the particle size to obtain GPOFA. Many researchers have classified the POFA particle size into three, large, medium, and small depending on the particle size resulting from grinding process. The grinding process increases pozzolanic activity due the increased specific gravity and fineness of particles [33].

**Table 2.** Physical properties of POFA as reported in literature.

Ref.	Specific gravity	Blain fineness (m <sup>2</sup> /kg)	Retained on 45 µm sieve (%)	Median particle size d <sub>50</sub> µm
[34]	2.42	493	4.98	14.58
[35]	2.15	750	15.00	20.00
[10]	2.33	1244	1.50	10.10
[15]	2.53	---	1.70	10.70
[36]	2.25	1180	1.00–3.00	7.20
[37]	2.39	1228	4.30	12.30
[12]	2.42	435	---	15.76
[14]	2.56	450	---	22.53
[16]	2.6	---	---	1.069
[17]	2.2	1720	---	18.46
[18]	2.42	4930 cm <sup>3</sup> /gm	33	---
[19]	2.42	4935 cm <sup>3</sup> /gm	4.98	14.58
[1]	2.31	458.2	---	16.08

The specific gravity of POFA is less than that of cement, and ranges between 2.15 and 2.6 as presented in Table 2. Whereas, the median particle size of POFA varies due to the difference in the grinding process and machine used for this purpose; it ranges between 1.069 µm and 22.53 µm.

### 3. Properties of Fresh Concrete Containing POFA

The properties of fresh concrete, containing GPOFA and UGPOFA, such as workability and heat of hydration are discussed in detail in the following sub-sections.

#### 3.1 Workability

Workability is one of the main properties of fresh concrete, which can be determined by conducting a slump test. Many studies have been conducted to find out the impact of POFA on the workability of fresh concrete. Most of these studies have reported that increasing POFA content leads to decrease in concrete workability. Tay et al. [38] showed that reduction of concrete workability is due to increased quantity of POFA in concrete production. Also, reduction of segregation in concrete occurs and the compacting factor improves, ranging between 0.93 and 0.97. Awal et al. [25] used high volume GPOFA to replace cement by 50%, 60% and 70%; and the slump value was reported as 160, 115, 90, and 80 mm, respectively. Increasing GPOFA resulted in decreasing slump in concrete. Some researchers have used Nano silica in concrete containing UGPOFA in order to reduce utilization of superplasticizer to achieve a required workability [39]. Aldahdooh et al. [40] reported that using GPOFA in concrete as cement replacement increases the concrete workability. Therefore, increase of workability is associated with minimizing carbon content and reducing loss of ignition (LOI) in the GPOFA. On the other hand, Rangbar et al. [41] reported that GPOFA cannot be used as a replacement of cement in self-compacted concrete by more than 20%, and if used it may have a negative impact on other properties such as workability and segregation. A reduction in concrete workability value occurs when more quantity of POFA is added to the cement paste and concrete mortar [42]. In order to get acceptable values of workability, chemical admixtures should be added to achieve the required slump, similar to slump in OPC [43–45].

Due to the coarse pozzolan of the POFA particles, demand of water also reduces, which causes decrease of workability. Crushed and agglomerated POFA particle shapes require higher quantity of water than the natural mix in order to decrease inter particle friction and thus increase the concrete workability

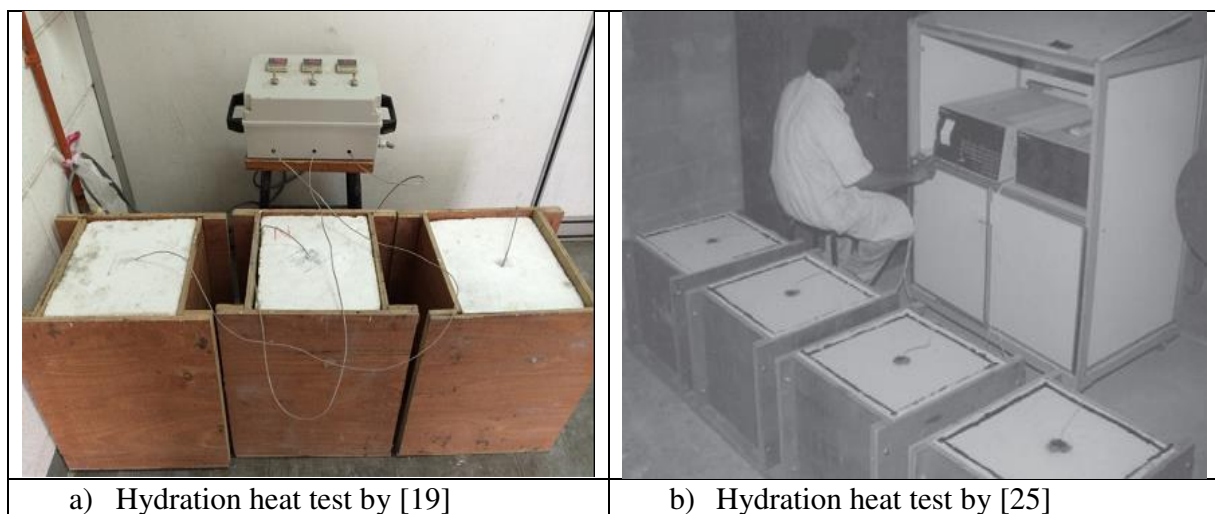
[45]. There was a reduction in the concrete workability due to addition of Nano silica which results in high water demand [46]. Farzadnia et al. [47] used workability of concrete as indicator to water consumed by using Nano silica and/or POFA as cement replacement; the water demand increased when more than 30% of POFA was added to the mix; workability decreased from 115.5mm to 112mm. Many studies have been conducted on the replacement of cement by POFA and it has been reported that adding further quantity of POFA contributes to decrease in the workability value of fresh concrete [14, 48]. Addition of high amounts of POFA causes reduction in the compressive strength of the concrete samples in addition to reducing the workability [47]. Yusuf et al. [27] reported that the workability of concrete can be enhanced by adding  $H_2O/Na_2O$  to the concrete mix but it reduces the compressive strength.

### 3.2 Heat of Hydration

The hydration temperature of a concrete sample describes its chemical characteristics [19]. Concrete hydration heat is basically one of the concrete hardening properties and is measured through a test as shown in Figure 2. Rising heat of hydration usually causes undesirable problems in the concrete mass and adversely affects durability performance [23]. Adding POFA to concrete causes decrease in hydration heat of the mixture [25, 43]. Reduction in the hydration heat of concrete containing POFA is an important advantage to the areas with hot climates such as Malaysia, Indonesia, and Thailand; where the temperatures may exceed 40°C. Lim et al. [19] studied the effect of replacement of cement by high volume of Nano POFA on the hydration heat and microstructure. The authors noted that there is increase in the hydration heat during the initial reading and for the both of GPOFA and UPOFA concretes, while significantly different hydration heat was recorded in the control sample. Generally, in comparison to the control sample, adding POFA, regardless the size, to the concrete mix has potential to reduce the hydration heat successfully; even though the fineness of the binder has a notable impact on the hydration heat of cement mortar [25, 49].

GPOFA and UPOFA play a significant role not only in reducing hydration heat, but also delaying the peak temperature when mixed with concrete mortar [25]. Cubical plywood with the side dimension of 500 mm was internally insulated with 76 mm thick expanded polystyrene acting as the insulator as shown in Figure 2. Four concrete mixes were prepared, one with 100% OPC and the others with 50%, 60% and 70% POFA as cement replacement of the total weight. The concrete was cast into the cubical plywood in order to test heat of hydration. Sata et al. [10] reported that concrete containing 80% POFA has the ability to decrease hydration temperature by 30% if compared with control cement mortar sample. The hydration heat of concrete containing POFA depends mainly on the calcium hydroxide  $Ca(OH)_2$  generated during cement hydration process. Cement hydration heat is affected chemically and physically by adding some pozzolanic materials, which have the ability to decrease and delay the hydration heat [50-52].





**Figure 2.** Hydration heat of concrete.

#### 4. Properties of Hardened Concrete Containing POFA

##### 4.1 Compressive Strength

Many studies have been undertaken to identify the compressive strength of concrete incorporating POFA as partial cement replacement. Researchers have utilized POFA as cement replacement in various quantities due to the high silica content in it, which makes a good pozzolanic activity, which is considered favourable in concrete mixtures, as presented in Table 3. Unground POFA has coarse particles, whereas fine POFA called ground POFA has better characteristics. However, compressive strength is usually affected by increased POFA content in the concrete composites. Show [38] and Tay [9] showed that compressive strength decreased for concrete mixtures containing 10%, 20%, 30%, 40% and 50% unground POFA as cement replacement. In terms of the effect of POFA on concrete properties in the long run, the researchers noted that there is no much difference in compressive strength values between the concrete containing POFA and the control mixtures. Although concrete containing POFA has lower hydration rate at earlier age and thus reduced compressive strength [38], however, POFA with fine particles of about 8  $\mu\text{m}$  as median size replacing about 20% of cement replacement has been reported to result in compressive strength higher than the corresponding value for control concrete at 90 days of curing age [26]. Increasing fineness of POFA particles to below 7.4  $\mu\text{m}$  has various advantages in terms of increased pozzolanic reaction and compressive strength up to 99% of compressive strength of the control mix at 90 days curing can be achieved [11].

Researchers have used many experimental tests to investigate the compressive strength development in early and late ages; some of them used 0.4 as constant water/binder ratio, and up to 50% as cement replacement with raw and sieved POFA as presented in Table 3. Awal and Nguong [53] reported that the strength of concrete containing fine POFA is double to that in case of coarse POFA. The high compressive strength in fineness POFA is because of the high surface area of fine particles, which contributes by increasing pozzolanic activity. Sata et al. [54] studied the properties of concrete containing 10%, 20% and 30% of fine POFA particles as cement replacements and different ratios of w/b 0.50, 0.55, 0.60, after 14 days curing. The authors claimed that the concrete mixes with 10% fine POFA as cement replacement has higher compressive strength than other mixes for all the ratios of w/b.

Ground POFA is more useful than unground POFA to improve the compressive strength of recycled aggregate concrete [15]. For the concrete mix containing 20% cement replacement with fine POFA with medium particle size (10.7  $\mu\text{m}$ ), the compressive strength was 7% lower than the control mix. Fine POFA

was responsible for increasing the compressive strength of concrete due to the high pozzolanic reaction. On the other hand, Sata et al. [10] studied effects of replacement of cement by 20% of POFA to prepare high strength concrete by using cylindrical samples with 100 mm diameter and 200 mm height. The compressive strength for concrete containing 20% POFA was higher than that in both the specimens containing 5% silica fume and the control samples. In terms of the compressive strength for light weight foamed concrete, Lim et al. [29] claimed that the concrete containing 10% and 20% POFA had compressive strengths of 7.17 and 7.06 MPa respectively; these are more than that of the control concrete, which was 6.50 MPa only.

**Table 3.** Compressive strength of concrete specimens as reported in literature.

Ref.	Compressive strength for concrete containing POFA as cement replacement								W/b
	0%	10%	20%	30%	40%	50%	60%	70%	
[55]	68.9	76.5	58.3	48.3	43.3				0.35
[12]	91.4		98.3		104.2		98.1		0.27
[25]	160					115	90	80	0.48
[9]	35.5	35.5	29.5	25.5	20.2	17.8			0.6
[56]	75	79.3	77.3	72.8	66.5				0.35
[57]	65	67.5	67	65.5					0.3
[58]						35.7	29.5	27.0	0.5
[18]	75	75	72	66.7	61.5				0.35
[38]	34.40	29.76	14.23	15.30	10.33	10.47			0.6

Johari et al. [12] showed that incorporation of ultrafine POFA in concrete as cement replacement reduces the compressive strength of high strength concrete at the early age. After one day of casting, the HSC containing ultrafine POFA with percentages of 20%, 40%, and 60% recorded relative strengths of 71.3%, 57.5% and 41.1%, respectively, of the control concrete sample. Whereas, at 7 days the compressive strengths increased to 100.6%, 97.7%, and 91.4%. The compressive strength of concrete containing various percentages of ultrafine POFA at 28 days increased to become 7.5%, 14% and 7.3% greater than the control concrete sample. Concrete containing ultrafine POFA acquired greater strength with time due to high pozzolanic reaction in POFA that produces additional amounts of C-S-H thus improving the compressive strength. Tangchirapat et al. [24] reported that the concrete containing high fineness POFA at 10%, 20%, and 30% had compressive strengths higher than that in the control concrete mix, which were 58.5, 59.5, and 58.8 respectively. This is due to the fact that high fineness POFA has high silica oxide ( $\text{SiO}_2$ ) content, this helps improve the reaction between calcium hydroxide and silica oxide to produce considerable quantity of calcium hydro silicate C-H-S gels, which leads to increasing the compressive strength in concrete samples [48]. Hussin et al. [59] reported that high pozzolans is due to the fineness POFA particles. A median particle size of ultrafine POFA is about 2  $\mu\text{m}$ , which has better specifications than normal POFA as cement replacement in the pozzolanic mineral admixture.

#### 4.2 Modulus of Rupture

Modulus of rupture is one of the methods used to measure the tensile strength of concrete. It is a measure of an unreinforced concrete slab or beam to resist failure in bending. It is measured by loading (150mm x 150mm) concrete beams with a span length at least three times the depth. Many researchers have investigated the modulus of rupture of concrete with POFA; some have found that increasing POFA proportions in concrete as cement replacement is inversely proportional and leads to decreasing the flexural strength. Lim et al. [29] showed inverse results regarding flexural strength of light weight concrete at 90 days when the cement was replaced by 10% and 20% POFA; whereas the flexural tensile strength was 25% and 23%, respectively, higher than that of the control concrete samples. Increase in the flexural strength is due to formations of additional C-S-H gels by the pozzolanic reaction resulting from high silica content in the POFA particles.

Bashar et al. [17] investigated effects of adding steel fibre in three volume fractions (0.25%, 0.5%, and 0.75%) on the concrete containing high volume of POFA as 90% cement replacement and palm oil shell (POS) as coarse aggregate; significant improvements in flexural tensile strength was noted ranging 7-18% higher than the control mix. The concrete samples with more steel fibres achieved higher value of flexural strength. The flexural strength was 8%, 9% and 12% higher for samples containing 0.25%, 0.50% and 0.75% steel fibres, respectively. Awal and Mohammadhosseini [60] mixed carpet fibres with POFA to enhance the flexural tensile strength; they observed that increase in the flexural strength was due to the control of the cracks by fibres that may have occurred otherwise in the concrete sample. Ranjbar et al. [41] reported that the self-compacting concrete containing POFA was weak in the flexural tensile strength, the weakness was due to the high porous structure in concrete and weakness of bond between paste and aggregate. Altwair et al. [61] reported that there was a significant relationship between flexural strength and the first cracking strength increasing with POFA content and water-binder ratios, whereas the crack width decreased significantly and the number of cracks increased with increasing content of POFA in concrete.

#### *4.3 Tensile Splitting Strength*

Tensile Splitting Strength of concrete is one of the significant properties of hardened concrete. The concrete is cast as a cylindrical sample to test the tensile splitting strength of concrete. The value of tensile splitting strength is necessary to identify the suitable elements in concrete structures subjected to transverse shear, effects of shrinkage and temperature, and torsion. The value is required to design the liquid retaining structures, runway slabs, roadways, and pre-stressed concrete structures [62]. Sata et al. [48] investigated different proportions of POFA ranging between 10-30% as cement replacement with constant water cement ratio at 0.28. The results indicated the increase in the tensile splitting strength value for concrete containing 10-20% POFA and higher than control mix at age 90 days, whereas the control concrete and POFA concrete was similar in compressive strength. Jaturapitakkul et al. [37] reported that the nature of pozzolanic reaction resulting from the ground POFA increased together with the fineness of POFA particles, age of mortar and cement replacement. Lim et al., [29] reported that the tensile splitting strength value for concrete containing 10% - 20% POFA is higher than the control concrete by 19% and 9%, respectively, at 90 days. This increase is because of the formation of C-H-S gel resulting from the pozzolanic reaction.

#### *4.4 Drying Shrinkage*

Drying shrinkage is the deformation in the hardened concrete mixture due to the loss of capillary water. It causes an increase in tensile stress, which may lead to cracking, internal warping, and external deflection, before the concrete is subjected to any kind of loading [63]. This occurs in the hardened concrete specimens and leads to micro-cracks formation in the concrete. This may affect adversely the durability and mechanical properties and cause hazardous damages to the structure members [32]. Tay [9] investigated the effect of concrete containing 10% - 50% POFA as cement replacement on the drying shrinkage; the drying shrinkage did not change in two cases, in the control specimens and concrete containing 10% POFA at 28 days, while the drying shrinkage in the samples with other percentages of POFA (20% - 50%) were higher than that of control mix. Tangchirapat et al. [24] reported that the drying shrinkage started at the first three months of concrete age. They measured the drying shrinkage in the starting of six months for control specimens, which was  $557 \times 10^{-6}$  micro-strain, whereas, the drying shrinkage was 525, 505 and  $494 \times 10^{-6}$  micro-strain for the concrete containing 10%, 20% and 30% POFA, respectively.

### **5. Conclusion**

The literature review has established that large quantities of palm oil waste is still being transferred into landfills and not being utilized. There is a significant concern regarding the accumulation of these wastes, which causes dangerous environmental issues. Many researches have been conducted to benefit from these wastes especially POFA in concrete production as partial cement replacement. Some researchers used



POFA with cement to benefit from its chemical and physical properties. POFA is rich in silica and alumina, which makes it suitable for replacing cement partially, the chemical and physical properties of concrete containing POFA at different percentages have been illustrated. The effects of using POFA in concrete can be summarized as:

- Workability of concrete decreases with the use of POFA as cement replacement and may require the use of admixtures
- Heat of hydration of concrete containing POFA is reduced, which is an advantage specially in the regions with higher temperature ranges
- Compressive strength of concrete decreases if unground POFA is used as cement replacement, however, the same is increased when ground POFA is used
- Modulus of rupture and tensile splitting strength of concrete have been reported to increase with partial replacement of cement by POFA due to high pozzolanic activity resulting in more C-H-S gels
- Drying shrinkage of concrete is not affected when smaller proportions of POFA are used as cement replacement, however, for higher proportions of the same, an increase in the drying shrinkage has been reported

This paper concludes that exploiting the POFA in concrete preparation should be focused upon due to its appropriate characteristics. The future recommendation is that emphasis should be laid on using high volume POFA by grinding the particles into finer sizes to prepare concrete. Further studies should be conducted to improve the POFA characteristics as well as adding some additives and further grinding to get smaller particles, which have potential to replace cement with high volume quantity of POFA.

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