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The Inclusion of Palm Oil Ash Biomass Waste in Concrete: A Literature Review

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Abstract

Oil palm ash (OPA) is a waste material produced by countries having a blooming palm oil industry. Recycling of oil palm ash is receiving increasing attention because of its huge potential in improving economic benefits and environmental awareness. Recently, it has been used as a partial replacement to cement in concrete, mortar and other cementitious materials. OPA is considered a new member of the supplementary cementing materials. Therefore, it is imperative to have a complete understanding of this material and its effects. In this chapter, a thorough literature review involving OPA will be presented. The physical and chemical properties of OPA will be listed as well as its effect when used as a partial cement replacement on the fresh state, mechanical and durability properties of a number of cementitious products. Capitalising such waste products in the production of concrete will not only benefit the recycling chain process but also produce a green product which enables the reduction of cement quantities used and also produce an energy-efficient building material.

Keywords: biomass waste, concrete, cement replacement, properties

1. Introduction

The surge in fossil fuel prices and the fear of future supply shortages alongside the increasing awareness of greenhouse gas emissions increased the shift towards the search for alternative fuels. These alternative fuels are conditioned to be technically feasible, environmentally friendly, competitive from an economic perspective and readily available [1]. Vegetable oils, which are from plant origin, are considered to be an alternative to fossil fuels. The alternative fuel is named as bio-diesel. Bio-diesel is biodegradable, non-toxic and has low CO₂ emission profiles in comparison to

conventional fossil diesel. Using bio-diesel will allow a balance to occur between agricultural economic development and the environment [2]. Various plants have been identified as a raw stock for the production of bio-diesel such as rapeseed and soybeans in the United States and palm oil and jatropha in the Asian region [3]. However, among these resources of bio-diesel, palm oil is considered to be the cheapest and has the highest oil yield per hectare of plantation [1].

Today, Malaysia is the world's largest producer and exporter of palm oil, and its palm oil industry is an important contributor to the country's gross domestic product (GDP) [4]. Before the bio-diesel boom, 90% of the oil was used in food-related commodities with the remaining 10% being used as a raw material in soap production [5]. However, after realising the potential of palm oil in producing bio-diesel, the Malaysian palm oil industry grew from a shy 400 hectares in 1920 [6] to 4.17 million hectares in 2006 and nearly 4.5 million tonnes in 2008 [7]. In 2008, about 17.7 million tonnes of crude palm oil have been produced from the 410 palm oil mills in Malaysia reaching 41% of the world's palm oil production [8].

As a result to the thriving Malaysian palm oil industry, the amount of biomass produced will increase. A single hectare of palm oil plantation can generate up to 70 tonnes of biomass residues [9]. As a rough estimate, 1 kg of palm oil results in 4 kg of biomass produced alongside it [7]. About 90 million metric tonnes of biomass is produced in Malaysia annually [10]. This biomass residue consists of empty fruit bunch, fibre, shell, wet shell, palm kernel, fronds and trunks. Each oil palm tree fruit bunch produces about 21% palm oil, 6–7% palm kernel oil, 14–15% fibre, 6–7% shell and 23% empty fruit bunch [11].

It has been a common practice for palm oil mills to burn their biomass instead of using conventional fossil fuels for heating up their boilers and generate steam [1, 5]. According to Shuit et al. [9], more than 300 palm oil mills are operated by self-generated electricity using palm oil biomass in Malaysia. In addition, the generated electricity is not only used for their internal use in crude palm oil extraction but also provided the surrounding remote areas with electricity. Due to the abundant amounts of biomass produced, Malaysia has the potential to utilise these quantities in power generation. Using such alternative fuels to partially or fully replace fossil fuels used in all Malaysian industries to generate energy will result in a significant drop in CO₂ emissions, achieving the vision to be a developed country without degrading the environment and promoting the utilisation of renewable energy in power generation.

However, the process of burning palm oil biomass will result in a new type of waste. This waste is called oil palm ash (OPA) which is causing numerous problems to the environment. OPA quantities are expected to increase in quantities due to the increasing demand for energy and the booming palm oil industry.

2. Oil palm ash (OPA)

It was mentioned earlier in the previous chapter that OPA is the result of incinerating palm oil biomass to generate necessary energy for the palm oil mill. Incineration of biomass occurs at temperatures ranging from 800 to over 1000°C. OPA is produced at a rate of 5% by weight of

burned biomass [12]. In this section, the physical and chemical properties of OPA will be discussed thoroughly. In addition, the effects of OPA integration on the properties of concrete, mortar and paste will be discussed.

2.1. Physical properties of OPA

When lower temperatures are used to incinerate the palm oil biomass, a black to dark grey OPA is produced due to the high amounts of unburned carbon [13]. Higher incineration temperatures will reduce the amounts of unburned carbon, thus producing OPA with a lighter colour and improved characteristics [14]. Therefore, every OPA is unique to its mill and there is no OPA similar to another. When received from the source, OPA is a coarse-sized particle which is at the same time porous in structure. In order to change its physical characteristics, OPA is usually ground. The grinding process not only will increase the fineness of the OPA particles but will also increase its specific gravity [15]. Grinding of OPA is done through the use of a modified Los Angeles machine [12, 13] or by ball mill [12, 16, 17]. **Table 1** lists a number of physical properties for OPA used in different studies.

2.2. Chemical properties of OPA

Due to the different production processes, every OPA is unique in its chemical composition. No OPA is chemically similar to another OPA from another source. OPAS used in different studies were compliant to a chemical composition of a Class N pozzolan [15, 19], Class C pozzolan [20] and a Class F pozzolan [21]. However, when insufficient incineration temperatures are used, impurities such as unburned shell and fibre and unburned carbon exist. Therefore, extra processing procedures are needed to enhance the properties of OPA before using it in concrete.

The usual procedure for processing OPA starts with sieving. The sieving process discards any large unburned fibre or shell. To increase OPA's pozzolanic reactivity, the sieved OPA will undergo the process of grinding. As stated earlier, grinding the OPA will create a finer substance possessing a heavier specific gravity. OPA is usually ground until a median particle size of 10 µm is achieved [14]. When the OPA is of poor quality, the grinding process will not change the

Author(s)	Unground OPA			Ground OPA		
	Specific gravity	Retained on 45-µm sieve (%)	Median particle size (µm)	Specific gravity	Retained on 45-µm sieve (%)	Median particle size (µm)
Sata et al. [12]	1.97	41.2	62.5	2.33	1.5	10.1
Tangchirapat et al. [17]	1.89	94.4	183.0	2.43	1.0	7.4
Tangchirapat et al. [15]	1.97	41.2	65.6	2.33	1.5	10.1
Megat Johari et al. [18]	2.42	—	15.76	2.50	—	2.99

Table 1. Physical properties of OPA used in different studies (Al-Mulali et al. [14]).

chemical characteristics of the OPA drastically. Therefore, the fine OPA is usually burned in an electric furnace at a temperature of 500°C for at least an hour to remove any carbon content [22]. **Table 2** lists different OPA chemical compositions utilised in a number of studies.

When compared to fly ash, OPA is known to have a higher percentage of organic residue, a higher alkali content and a larger particle size [25]. Coarse OPA is proven to be of low pozzolanic reactivity when no reduction in strength occurred. This is achieved after a curing period of 1 year is used and 10% of cement used in the production of concrete was replaced by OPA sieved through 150- μm sieve [25]. Increasing the pozzolanic reactivity of OPA is achieved through the grinding process to produce a finer particle sized ash [12]. When OPA with three different median particle sizes is used as a partial cement replacement in conventional concrete, the finest OPA with a median particle size of 7.4 μm showed a higher compressive strength than the control mix at a replacement level of 20–30% by weight of cement [17]. Mortars with cement partially replaced by coarse (55 μm), medium (25 μm) and fine (7 μm) OPA showed the same behaviour [26]. Mortar with fine OPA partially replacing cement shows superior strength in comparison to the control mortar and mortars containing the medium and coarse OPA.

In high-strength concrete, mixes containing fine OPA as a partial cement replacement exhibited the same behaviour. High-strength concrete mixes incorporating 20% of fine OPA ($d_{50} = 10 \mu\text{m}$) as a partial cement replacement showed a higher compressive strength and an increased resistance to chloride penetration, acid and sulphate attack [27]. High-strength concrete containing 20% fine OPA ($d_{50} = 10.1 \mu\text{m}$) achieved a compressive strength of 70 N/mm² at the age of 90 days proving that fine OPA is a good mineral admixture [15].

In blended cement pastes, the effect of OPA fineness and pozzolanic reaction is studied by Kroehong et al. [16]. Ground OPAs with a particle size of 15 ± 1 and $2 \pm 1 \mu\text{m}$ along with ground river sand were used to partially replace cement at levels of 10–40% by weight of cementing materials. At the age of 90 days, blended cement pastes containing 10–30% of 2- μm OPA exhibited higher compressive strengths than that exhibited by the control paste at a percentage of 105–111%. This increase was reasoned to the high pozzolanic reactivity of the 2- μm OPA.

Author(s)	Oxides present in OPA (%)									
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	K ₂ O	Na ₂ O	SO ₃	SUM	LOI
Sata et al. [12]	65.3	2.60	2.00	6.40	3.10	5.70	0.30	0.50	69.9	10.10
Tangchirapat et al. [17]	57.71	4.56	3.30	6.55	4.23	8.27	0.50	0.25	65.57	10.52
Chindaprasirt et al. [23]	63.6	1.60	1.40	7.60	3.90	6.90	0.10	0.20	66.6	9.60
Altair et al. [24]	66.91	6.44	5.72	5.56	3.13	5.20	0.19	0.33	79.07	2.30
Megat Johari et al. [23]	65.01	5.72	4.41	8.19	4.58	6.48	0.07	0.33	75.14	2.53

Table 2. OPA chemical compositions used in different studies.

2.3. The effect of OPA incorporation on the properties of concrete

In the following sections, the effect of OPA's incorporation on the properties of concrete, mortar, cement paste, high-strength concrete and aerated concrete will be discussed thoroughly.

2.3.1. Workability

In general, increasing OPA content in concrete reduces its workability. Fresh concrete with 50% of its cement replaced by coarse OPA (passing through a 150- μm sieve) achieved a slump reading of 120 mm which is lower than the 150 mm exhibited by the control mix [25]. When using the compacting factor, concrete with a 50% coarse OPA replacement showed a compacting factor reading of 0.93 which was lower than the 0.99 exhibited by the control mix [28].

Using the slump test and the amount of superplasticizer used to obtain a spread between 175 and 225 mm, high-strength concrete with increasing amounts of OPA exhibited less spread and used more superplasticizer to achieve the required spread [29]. The authors reasoned the increase in superplasticizer dose to the high porous nature of the OPA particles resulting in the absorption of a higher water quantity. Reduced workability of high-strength concrete with 20% by weight of cement is replaced by fine OPA is reasoned to the increased surface area of the OPA particles due to their grinding [27].

The increased water demand for OPA concrete to achieve a required workability limit is due to the shape and nature of the OPA particles themselves. OPA particles are known for their angularity, irregularity and their porous nature [18, 30, 31], and as a result, demanding an increased amount of water for their lubrication and by that attaining similar workability as their control mixes. Chindaprasirt et al. [30] discovered this aspect when comparing the OPA particles to those of fly ash which required less water due to their spherical shape and solid nature.

Sieved through a 300- μm sieve, OPA was used to replace cement at levels of 5, 10 and 15% by weight in conventional concrete. These OPA concrete mixes were compared to concrete with 10% replacement levels of fly ash and quarry dust also sieved through 300- μm sieve. Ahmad et al. [20] found that even with a dose of superplasticizer, OPA concrete mixes showed reduced slump readings and low compacting factors than those of the control and the fly ash mixes. The same observation is made in concrete with 50, 60 and 70% OPA replacement levels (35% retained on 45- μm sieve) and a superplasticizer dose of 2% by weight of binding material [31].

2.3.2. Setting times

The initial and final setting times of concrete incorporating OPA as a cement replacement are investigated by a number of researchers. In general, OPA concretes showed prolonged initial and final setting times [14]. Concrete containing OPA (sieved through a 150- μm sieve) as a cement replacement exhibited a delay in both initial and final setting times; however, they were within the limits stated by ASTM 150 [25]. The retardation of initial and final setting times increased with increasing OPA replacement levels [28].

The particle size of OPA plays a role in defining the setting times [17]. The authors found that concrete with 40% of its cement replaced by coarse OPA ($d_{50} = 183 \mu\text{m}$) exhibited an initial

setting time of 390 min and a final setting time of 740 min. The authors reasoned these prolonged initial and final setting times to a number of factors. These factors are reduced cement quantity and the large and porous unground OPA particles that increase the water binder ratio used in the mix. However, the authors stated that increasing the fineness of OPA decreased the setting times, making them closer to those exhibited by the control mix. High-strength concrete mixes with fine OPA ($d_{50} = 2 \mu\text{m}$) replacement levels show prolonged setting times to those exhibited by the control mix [18]. The authors reasoned this retardation to the pozzolanic reaction which is slower than cement hydration.

2.3.3. *Compressive strength*

Numerous studies investigated the effect of OPA incorporation as a cement replacement on the strength of concrete, mortar and cement paste. Increasing OPA content in concrete decreases the compressive strength [14]. Concrete with OPA (sieved through a 150- μm sieve) at replacement levels of 0–50% by weight of cement experienced a drop in compressive strength with increasing OPA content [25, 28]. Compressive strength reduction was less observed at the age of 365 days in comparison to that at 28 days due to the pozzolanic activity of the OPA. The researchers recommended an optimum OPA replacement level of 10% by weight of cement because the reduction in compressive strength is found to be 1% at the age of 1 year.

Increasing the fineness of OPA increases its pozzolanic reactivity, hence increasing the compressive strength of concrete. Chindaprasirt et al. [30] concluded that a 20% replacement level of OPA ($d_{50} = 8 \mu\text{m}$) possessed a slightly higher compressive strength than the control mix. Increasing the fineness of OPA further makes it possible to increase the replacement level used in the concrete and achieve a higher compressive strength. Concrete samples containing OPA with a median particle size of 7.4 μm at a replacement level of 30% managed to possess 99% of the control mix's strength at 90 days [17]. Fine OPA replacing 50% of cement in concrete showed double the compressive strength of concrete having half of their cement replaced by raw OPA [32].

Even when using different water cement ratios in concrete (0.5, 0.55 and 0.6), samples containing a 10% fine OPA (2% retained on a 45- μm sieve) exhibit higher compressive strengths at all water cement ratios at 14 days of age than its corresponding control mixes [29]. Fine OPA ($d_{50} = 10.7 \mu\text{m}$) at a replacement level of 20% enhanced the compressive strength of concrete with recycled aggregate in comparison to the same concrete samples without OPA [33]. High-strength concrete samples containing 20% cement replacement by fine OPA ($d_{50} = 10 \mu\text{m}$) exhibited higher compressive strengths than both the control mix and the mix containing 5% silica fume at the same age [12]. In another study, high-strength concrete samples containing OPA ($d_{50} = 10.1 \mu\text{m}$) at a replacement level of 30% exhibit higher compressive strengths than those of mixes containing Type I and Type V Portland cements at the same age [15].

Ultrafine OPA ($d_{50} = 2 \mu\text{m}$) is capable of replacing cement at a level of 60% and achieve a higher compressive strength than that exhibited by the control mix at 28 days [18]. The increase in compressive strength is due to the pozzolanic reaction between the high silica oxide content of OPA and calcium hydroxide emitted by the cement hydration. This pozzolanic reaction will produce extra amounts of calcium silicate hydrates (C-S-H); hence, an increase in compressive strength is experienced [15, 18, 27, 29].

Increasing OPA content reduces the compressive strength of aerated concrete [35]. However, it is still possible to replace cement by OPA at levels ranging from 10 to 35% without effecting the compressive strength of aerated concrete [14]. Aerated concrete sample containing fine OPA (Class F pozzolan) at a replacement level of 20% exhibits compressive strengths higher than that of the control aerated concrete mix at the same age [34]. Foamed concrete mixes containing 10 and 20% sand replacements by OPA sieved through a 600- μm sieve showed increased compressive strengths than that exhibited by the control mix due to the increase in density [31]. **Table 3** summarises the studies that investigated the effect of OPA replacement on the compressive strength.

2.3.4. Tensile strength and modulus of elasticity

High-strength concrete samples containing 10 and 20% replacement levels of fine OPA ($d_{50} = 10.1 \mu\text{m}$) exhibit higher splitting tensile strengths than their corresponding control mix at 90 days of age [29]. The authors reasoned this increase to the high fineness of OPA and its pozzolanic reaction with cement, creating increased CSH compounds. Even though a fine OPA was used, higher replacement levels of cement by OPA (50% by weight of cement) exhibit lower tensile splitting strengths than the control mix [32]. Higher tensile splitting strengths are exhibited by foamed concrete samples containing OPA (passing through a 600- μm sieve) replacing sand at 10 and 20% than those of the control mix [31].

High-strength concrete samples containing 20% of fine OPA ($d_{50} = 10.1 \mu\text{m}$) exhibited similar modulus of elasticity readings as that of the control mix [12, 29]. Concrete samples containing fine OPA (10.1 μm) at cement replacement levels of 10 and 25% by weight of cement exhibit higher modulus of elasticity readings than that of the control mix. However, concrete samples containing coarse OPA ($d_{50} = 19.9 \mu\text{m}$) exhibit lower modulus of elasticity readings than the control mix [38].

In aerated concrete samples using fine OPA (1% retained on 45- μm sieve), samples containing 20% replacement of cement by OPA exhibited higher modulus of elasticity readings than the control mix [21]. The authors reasoned this increase to the pozzolanic reaction between the fine OPA particles and the calcium hydroxide emitted by cement hydration, creating a refined and stiffer microstructure. The modulus of elasticity readings of concrete samples containing recycled aggregate and a 20% fine OPA replacement level was lower than that of the control mix and was similar to those exhibited by a concrete sample with recycled aggregate and 100% cement [33].

2.3.5. Flexural strength

Limited studies have endeavoured on studying the effects of OPA incorporation into concrete on its flexural strength. High-strength concrete samples containing OPA as cement replacements exhibit a lower flexural strength than those exhibited by the control mix [40]. However, the author states that the samples containing a 30% fine OPA replacement level exhibit flexural strengths near to that of the control mix. On the other hand, Lim et al. [31] states that foamed concrete mixes having their sand replaced by 10 and 20% of OPA (sieved through a 600- μm sieve) exhibit higher flexural strengths than those exhibited by the control mix.

Author(s)	Particle size tested (μm)	Replacement levels of OPA investigated	Tested median	Standard	Recommended particle size/replacement level
Tay [25] Tay and Show [28]	Passing through a 150- μm sieve	10–50% by weight of cement	Concrete	BS 1881	10%
Sata et al. [12]	10.0	10–30% by weight of cement	High-strength concrete	100 \times 200-mm cylinders	20%
Abdullah et al. [35]	1% retained on 45- μm sieve	10–50% by weight of cement	Aerated concrete	BS1881:116 (70.6 mm ³)	10–30%
Jaturapitakkul et al. [36]	183.0, 15.9, and 7.4	10–40% by weight of cement	Concrete	100 \times 200-mm cylinders	7.4 μm to 20%
Sata et al. [29]	10.1 μm	10–30% by weight of cement	High-strength concrete	100 \times 200-mm cylinders	20%
Chindapasirt et al. [30]	10.2 μm	20, 40, and 55% by weight of cement	Concrete	100 \times 200-mm cylinders	20%
Tangchirapat et al. [17]	183.0, 15.9, and 7.4	10–40% by weight of cement	Concrete	100 \times 200-mm cylinders	15.9 μm to 10% 7.4 μm to 20%
Chindapasirt et al. [23]	1–3% retained on 45- μm sieve	20 and 40% by weight of cement	Mortar	ASTM C39	20%
Rukzon and Chindapasirt [26]	55.0, 20.0, and 7.4 μm	20 and 40% by weight of cement	Mortar	ASTM C109 (50mm ³)	7.4 μm to 20%
Tangchirapat et al. [15]	10.1 μm	10–30% by weight of cement	High-strength concrete	100 \times 200-mm cylinders	20%
Sata et al. [37]	9.2 μm	10–30% by weight of cement	Concrete	ASTM C39	10%
Hussin et al. [21]	1% retained on a 45- μm sieve	20% by weight of cement	Aerated concrete	BS 1881:116	20%
Tangchirapat and Jaturapitakkul [38]	19.9 and 10.1	10–30% by weight of cement	Concrete	100 \times 200-mm cylinders	19.9 μm to 20% 10.1 μm to 30%
Megat Johari et al. [18]	2.06 μm	20, 40, and 60% by weight of cement	High-strength concrete	BSEN 12390–3	40%
Sata et al. [39]	13 μm	10–40% by weight of cement	Mortar	ASTM C109	10–20%
Lim et al. [31]	Passing through a 600- μm sieve	10 and 20% by weight of sand	Foamed concrete	BSEN 12390–3	10–20%

Table 3. Summary of studies investigated the effect of OPA incorporation on compressive strength.

In another study conducted by Altwair et al. [24], engineering cementitious composites (ECCs) are tested for their flexural behaviour. These ECCs are designed to exhibit enhanced ductility and toughness; therefore, they use higher amounts of cementing materials and have their coarse aggregates eliminated from their design. The ECCs in this study used different amounts of added fine OPA 0, 0.4, 0.8 and 1.2 by weight of cement and used different water

to binder ratios of 0.33, 0.36 and 0.38. The OPA that the authors use in this study was sieved through a 300- μm sieve, then ground using a ball mill and afterwards heat-treated at 450°C for 90 min to eliminate any glassy phase crystallisation and agglomeration of the OPA particles. They state that an ECC mix containing OPA at 0.4 by weight of cement and water to binder ratio of 0.36 exhibits the highest flexural strength among the conducted ECC mixes. In addition, a decrease in flexural strengths is exhibited with increasing OPA content and increasing water to binder ratio. Furthermore, ECC mixes containing OPA at 0.4 and 0.8 by weight of cement and water to binder ratio of 0.33 exhibit higher flexural strengths than the control mix at 90 days of age.

2.3.6. Drying shrinkage

Concrete samples containing cement replacements by OPA (sieved through a 150- μm) sieve show higher drying shrinkage readings than those exhibited by the control mix [25]. In addition, drying shrinkage is proportional to the increase in OPA content. Concrete samples with 50% of its cement replaced by OPA (sieved through a 45- μm sieve) exhibit a drying shrinkage reading higher by 21% than that of the control mix at the age of 90 days [32]. The authors reason this increase in drying shrinkage to the variation in moisture loss rate caused by different porosity and pore distribution.

Different sized OPA particles exhibit different readings of drying shrinkage [38]. At the age of 6 months, concrete samples having 30% of its cement replaced by coarse OPA exhibit slightly lower drying shrinkage than the control mix. On the other hand, concrete samples containing fine OPA ($d_{50} = 10.1 \mu\text{m}$) at the same replacement level of 30% exhibit lower drying shrinkage readings than both the control mix and the mixes with coarse OPA. Tangchirapat and Jaturapitakkul [38] and Tangchirapat et al. [15] reason this reduction in drying shrinkage to the pozzolanic reaction and the packing effect of the fine OPA particles, hence, transforming the large pores into smaller pores and as a result reducing the moisture loss.

Added fine OPA (1% retained on a 45- μm sieve) to aerated concrete at an addition percentage of 20% by weight of cement reduced the drying shrinkage [21]. Drying shrinkage readings of aerated concrete samples containing OPA exhibit lesser drying shrinkage readings than the plain aerated concrete samples. The authors reason this reduction in drying shrinkage to the more compact paste caused by the pozzolanic activity of the fine OPA and to its packing effect. **Table 4** summarises the studies that tested the effect of OPA on drying shrinkage.

2.3.7. Heat evolution

Using fine OPA as a cement replacement delays the time for the concrete to reach its peak temperature [29]. Concrete specimens containing 30% fine OPA cement replacement is capable of causing a 15% reduction in peak temperature in comparison to the control mix [12, 21, 41]. Fine OPA and heat-treated fine OPA exhibit different behaviours when it comes to heat evolution [42]. Cement pastes containing fine-treated OPA emit a higher heat evolution temperature than the control paste. The researchers reason this raised temperature to the high pozzolanic activity of the treated fine OPA. On the other hand, fine OPA pastes emit lower

Author (s)	OPA particle size (μm)	Replacement level investigated	Median	Effect	Recommended replacement
Tay [25]	100% passing through 150- μm sieve	10–50% by weight of cement	Concrete	Drying shrinkage increased with OPA replacement level	10% replacement slightly increased the shrinkage strain but it does not adversely affect the change in volume of concrete
Tangchirapat et al. [15]	10.1 μm	10–30% by weight of cement	High-strength concrete	Decrease in drying shrinkage with increase in OPA level	30% showed a lower drying shrinkage strain than the control mix
Abdul Awal and Nguong [32]	100% passing through 45- μm sieve	50% by weight of cement	Concrete	OPA concrete samples showed a higher drying shrinkage than the control mix	—
Tangchirapat and Jaturapitakkul [38]	19.9 and 10.1 μm	10–30% by weight of cement	Concrete	Coarse OPA up to 30% exhibited similar shrinkage to that of the control mix.	10–30% fine OPA exhibited a lower drying shrinkage than the control mix
Hussien et al. [21]	99% passing through 45- μm sieve	20% by weight of cement	Aerated concrete	OPA aerated concrete exhibited less drying shrinkage strains than the control mix	20%

Table 4. Effect of OPA incorporation on drying shrinkage readings.

temperatures compared to that of the control paste. This is reasoned to the low pozzolanic activity of the fine OPA in comparison to the treated fine OPA. The reduced pozzolanic activity is due to the decreased content of glassy phases within the particles of fine OPA in comparison to that of the fine-treated OPA.

2.3.8. Porosity, permeability and water absorption

Concrete samples containing OPA (sieved through a 150- μm sieve) show the tendency in absorbing more water with an increasing OPA content [25, 28]. Higher readings of water absorption are exhibited by concrete samples containing OPA as cement replacements in comparison to those exhibited by the control mix. The authors reason this increase in water absorption to the porous nature of concrete containing OPA. However, high-strength concrete containing fine OPA (10.1 μm) at a cement replacement level of 10% exhibits less water absorption readings than that of the control mix [43]. The authors reason this reduction in water absorption to a refined pore structure which results in a concrete sample with a reduced porosity.

High-strength concrete samples containing fine OPA ($d_{50} = 8 \mu\text{m}$) replacement levels of 20, 40 and 55% are tested for their water permeability by Chindaprasirt et al. [30]. At the ages of 28 and 90 days, high-strength concrete samples incorporating fine OPA at replacement levels of 20 and 40% by weight of cement exhibit less permeability readings than that of the control mix. In addition, samples containing fine OPA replacement levels show lower permeability readings, even though requiring higher water to binder ratios. The researchers recommend a 20%

replacement level of fine OPA as an outcome of their study. In another study, a 30% replacement level of cement by fine OPA ($d_{50} = 10.1 \mu\text{m}$) is recommended in achieving impermeable high-strength concrete [15]. The reduced permeability is attributed to the pozzolanic reaction and to the packing effect of fine OPA particles which results in filling the voids and increasing the density of the mix [30].

Concrete samples containing fine and coarse OPA replacement levels show a different behaviour when testing their permeability. Concrete samples containing coarse OPA as partial cement replacements are more permeable than the control mix at an earlier age but lower at later ages [38]. The higher permeability readings are attributed to the increased water to binder ratio to achieve the same workability as that of the control mix.

In contrast to coarse OPA, concrete samples containing fine OPA replacement levels are less permeable than the control mix. Concrete samples containing recycled aggregate and fine OPA replacement level of 20% by weight of cement show that they are less permeable than the control mix [33]. High-strength concrete samples containing partial cement replacements at levels of 20, 40 and 60% by weight of cement by ultrafine OPA ($d_{50} = 2.06 \mu\text{m}$) are tested for their absorption, permeability and porosity [18]. The authors state that the incorporation of ultrafine OPA reduced the porosity of high-strength concrete, reduced its water absorption and reduced the water permeability at the age of 28 days.

2.3.9. Carbonation

Mortars containing OPA having 3° of fineness at replacement levels of 20 and 40% by weight of cement are tested for their carbonation ingress depth [26]. The fineness of OPA particles are coarse OPA (70% retained on a 45- μm sieve), medium OPA (15% retained on the 45- μm sieve) and fine OPA (3% retained on the 45- μm sieve). The carbonation ingress depth is conducted according to RILEM's CPC18, and readings are taken at the ages of 3, 7, 14, 28 and 60 days of age. In general, OPA mortars show an increase in carbonation depth in comparison to the control mortar. However, the behaviour of OPA mortars differs according to the fineness of OPA. Mortar samples containing fine OPA show less increase in carbonation ingress depth with increasing age than mortars containing medium sized and coarse OPA. The authors reason this decrease to the better dispersion and to the filler effect of fine OPA despite its higher pozzolanic activity. This made the mortars with finer OPA incorporations denser and better to resist carbonation.

2.3.10. Chloride penetration and corrosion resistance

High-strength, high-workability concrete containing 10–30% OPA replacement levels by weight of cement are tested for their chloride penetration resistance and corrosion resistance [43]. The OPA used in this study has a median particle size of 20 μm . The chloride penetration test is conducted in accordance with ASTM 1202. Results for the chloride penetration show that chloride penetration decreases with an increasing OPA content. The authors reason this decrease in chloride penetration to the separation of large pores to the increase in nucleation sites caused by the increase in pozzolanic reaction products in the cement paste. The study states that replacing cement by fine OPA at a level of 30% by weight of cement shows increased resistance

to corrosion. The authors reason this increase to the high pozzolanic reactivity of the fine OPA and to the reduced amount of calcium hydroxide in the paste. Although the 30% replacement level is effective in increasing chloride and corrosion resistance, the researchers recommend a 20% replacement level of cement by fine OPA. This is due to the increased quantity of superplasticizer required for the 30% OPA replacement mix to achieve the required workability, hence making the mix more expensive.

However, a 60% cement replacement by ultrafine OPA ($d_{50} = 2.06 \mu\text{m}$) in high-strength concrete is more effective in resisting corrosion [18]. The 60% cement replacement by ultrafine OPA reduces the total charge passed in comparison to that of the control mix by 84%.

2.3.11. Sulphate resistance and alkali silica reaction

Concrete bars containing fine OPA cement replacements are exposed to a 5% solution of magnesium sulphate (MgSO_4) for 24 months. Results show that fine OPA concrete bars exhibit less expansion when exposed to the sulphate solution [36]. Finer OPA replacements not only cause the reduction of calcium hydroxide ($\text{Ca}(\text{OH})_2$) in the concrete but also reduce the voids between the aggregate and hydration products, creating a denser concrete. No adverse effect was found on the concrete expansion or on the compressive strength when replacing 20% of cement by fine OPA [15, 17]. High-strength concrete bars containing cement replacements of both 45- and 10- μm OPA are tested for their sulphate resistance and compressive strength loss [27]. The authors state that concrete bars containing 10- μm OPA show more resistance to sulphate attack and less reduction in compressive strength than those exhibited by the control and 45- μm concrete bars. The high sulphate resistance is attributed to the high pozzolanic reactivity of the finer OPA particles which in return reduces the $\text{Ca}(\text{OH})_2$ and reduces the amount of voids in the mix making it denser, hence, more resistant to sulphate attack. Concrete samples made from recycled aggregate show a higher resistance to sulphate attack when 20% of their cement is replaced by fine OPA [33]. The higher resistance in this case is also attributed to the reduced amounts of $\text{Ca}(\text{OH})_2$ and tricalcium aluminate (C_3A) when cement is replaced by fine OPA, hence reducing gypsum formation and ettringite re-crystallisation.

Mortar bars containing OPA having a fineness of 519 m^2/kg replacing cement levels of 10, 30 and 50% by weight of cement experience less expansion due to the alkali silica reaction (ASR) [19]. Increased suppressing of the ASR is observed with increasing OPA content. Abdul Awal and Hussin [19] reason this increased suppressing of the ASR to the pozzolanic reaction occurring between OPA's high amounts of silica with the alkalis existing in the concrete, hence limiting the amounts of alkalis reacting with aggregate.

3. Conclusion

OPA is a relatively new pozzolanic material that has been introduced in partially replacing sand or cement in manufacturing concrete, mortar, aerated concrete and high-strength concrete. The studies discussed showed that OPA needed further processing in order for it to work as a pozzolan. The further processing includes grinding to increase the fineness of OPA and heat

treatment to decrease the amounts of carbon within its particles. Although enhancing the properties of OPA is beneficial, these enhancing processes do apply increased cost. In addition, the problem with OPA is its increased demand of water when mixing. Therefore, controlling the water demand by applying superplasticizer is a good method in reducing its water demand, hence enhancing its properties. Researchers go further in the use of OPA and state that it is compulsory to use water-reducing agents when using OPA as the supplementary cementing material.

This chapter reviews the potential use of OPA as a supplementary cementing material for concrete production. The review emphasises the effects of POFA on the fresh, hardened and durability properties of concrete. Capitalising such waste products in the production of concrete will not only benefit the recycling chain process but also produce a green product which enables the reduction of cement quantities used and also produce an energy-efficient building material. This is in line with the United Nation's Sustainable Development Goals.

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