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Palm Oil Fly Ash (POFA) as a Cementitious Material in Biomass Concrete: A Feasibility Review

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Abstract

This review discussed the feasibility of using palm oil fly ash (POFA) as a cementitious material for partially replacing cement in producing concrete. Such an application is known to mitigate the emission of carbon dioxide (CO_2). Meanwhile, POFA is one of the general wastes generated from palm oil mills, and it is conventionally disposed of via landfills. Thus, using POFA to generate concrete could mitigate the depletion of raw material, i.e., limestone, used for cement.

Keywords

Biomass, Carbon Dioxide, Cementitious Material, Concrete, Palm Oil Fly Ash,

Introduction

Environmental issues are getting ever-increasingly impactful, warranting in-depth studies on it. Disaster, life losses, homeless, and poverty resulting from climate change have visibly become the daily lives of most people. In 2017, fossil fuels generated 64.5% of electricity worldwide (World Nuclear Association, 2012). However, the rapid consumption of fossil fuel for generating electricity and powering automobiles and machines has negatively impacted the environment. Burning carbon-based fuel has resulted in the emission of a large amount of carbon dioxide, expediting climate change. Besides, burning fossil fuel also produces other pollutants, such as sulphur and nitrogen oxides, that could cause acid rain. Meanwhile, it is estimated that all fossil fuels will be depleted by 2060 (Howarth, 2019).

Despite the availability of various building materials, such as steel and wood, concrete remains a primary component in construction projects globally because it can be cast into almost any shape. Besides, concrete possesses good mechanical properties, such as robust compressive strength and durability, thus giving a good performance to the building structure. In particular, the concrete's strength of compression and durability could be enhanced when reinforced with lingo cellulosic biomass (LCB), such as a combination of fly ash (FA) and palm oil fly ash (POFA). In this respect, LCB is produced primarily from plants and is categorised as a renewable energy source. Upon processing, LCB could be converted to liquid biofuels or biogas. Also, wood, garbage, and agricultural waste such as oil palm fibre could serve as solid LCB.

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However, producing concrete from cement presents a challenge to the construction industry as it is very harmful to the global environment. Since the cement is primarily composed of calcium carbonate, it emits a substantial amount of carbon dioxide (CO_2) when decomposed. Overall, 39% of the global emission of CO_2 came from the building and construction industry, substantially impacting the environment while expediting climate change. Thus, there is a growing need to develop new substances with cementitious properties that could partially replace the cement in concrete with sustainable and recyclable materials to meet the requirements of green buildings. According to the World Green Building Week, the world targeting to reach 40% less embodied carbon emissions by year 2030, and meet zero emissions of CO2 from buildings industry by year 2050.

Use of POFA as a substitute material for cement

Traditionally, electricity in Malaysian palm oil mills is generated via burning the palm oil shell and palm oil bunches. The burnt residue is POFA (Awal and Abubakar, 2011); it is deemed a common waste in Malaysia. However, sustainable development has changed the situation, and POFA is now broadly used as a substitute material for cement and aggregate with good performance (Oil et al., 2020). Thus, POFA contributes to shaping a more eco-friendlier environment by reducing agricultural waste materials from being disposed of as landfills (Hamada et al., 2021).

In general, the good pozzolanic activity of POFA enables it to reduce the usage of cement in concrete (citation). Besides, the high fineness of POFA suppresses the expansion of concrete due to the alkali-silica reaction, thus enhancing the concrete's performance (Syaizul et al., 2019). Experimental studies indicated that when Portland cement-CEM I 52.5R in the concrete was replaced with 2.5% to 20.0% POFA, the resultant concrete's compressive strength was decreasing with increase in adding POFA (Ash, 2018). Figure shows compressive strength results.

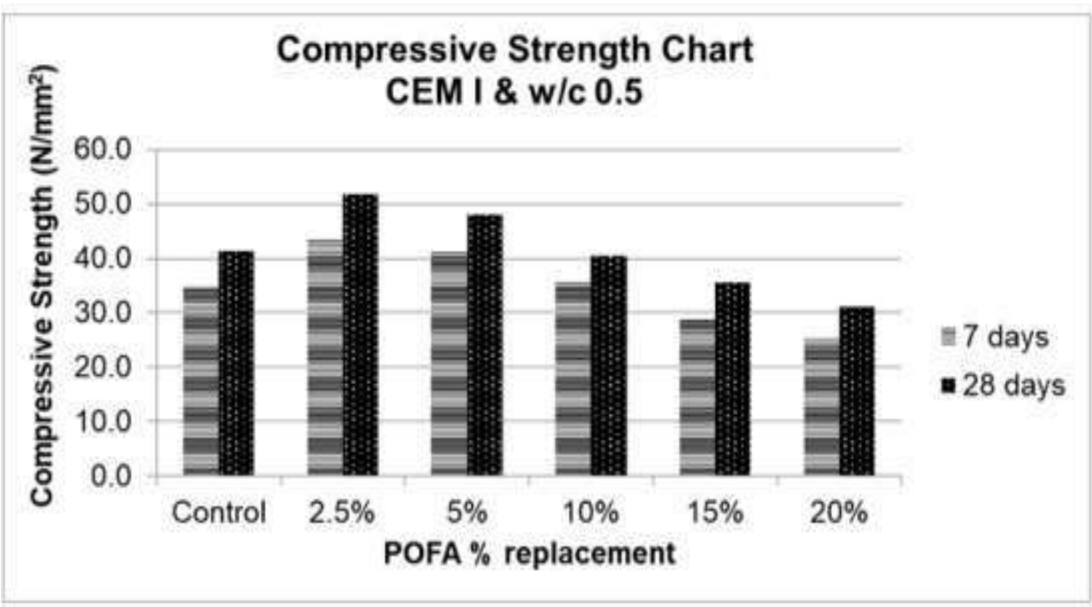

Figure 1. Compressive of Concrete after adding with POFA (Ash, 2018)

Meanwhile, grinding increases the surface area POFA and reduces its particle size. Thus, it is divisible into unground (UNPOFA) and ground POFA (GPOFA). Also, grinding increases its pozzolanic activity due to an increment in specific gravity and fineness of particles (Jaturapitakkul et al., 2007). Based on the outcome of grinding, the particle size of POFA could be classified into large, medium, and small. Overall, the study of POFA as a cementitious material is getting increasingly widespread. Table 1 shows the prevalence of such studies for the past five years or so.

Table 1. Studies on POFA as cementitious materials since 2018.

Reference	Description
Alnahhal et al., 2021	Synthesizing sustainable lightweight foamed concrete using POFA to replace cement
Jamellodin et al., 2021	Physical properties of blended cement concrete incorporated with POFA and eggshell powder
Kusumastuti et al., 2021	Converting POFA into foamy geopolymer for lightweight construction material by the incorporation of aluminum powder
Mohammadhosseini et al., 2020	Creep and desiccating shrinkage performance of concrete composite composing of waste polypropylene carpet fibres and PFA
Hamada et al., 2020	Effects of nano-POFA and nano-eggshell powder on concrete
Djamaluddin et al., 2020	Industrial experiment on fired clay bricks incorporated with POFA as a sustainable building material
Oil et al., 2020	Experimental study on the mechanical and durability performance of POFA aggregates and concretes Environmental advantages of assimilating POFA in cement concrete and mortar
Mustapha et al., 2019	The effect of fly ash and silica fume on self-compacting high-performance concrete
Alabduljabbar et al., 2020	Producing green and sustainable concrete with carpet fibres waste and POFA
Alyousef et al., 2021	The production of green concrete composites composing of metalized plastic waste fibers and POFA
Imran et al., 2018	Effects of POFA on the consistency and setting time of concrete
Sidek et al., 2018	The production of POFA as a cement the substitute using powder and liquidation technique
Hamada et al., 2018	Properties of fresh and hardened sustainable concrete with POFA as a substitute for cement
Ash, 2018	POFA as a substitute for cement in concrete
Hamada et al., 2018)	The current state of using POFA in concrete

Chemical composition of POFA

Table 2 shows the chemical compositions of POFA, with silicon dioxide (SiO_2) as the primary component. Other components of POFA include aluminium oxide (AI_2O_3), iron III oxide (Fe_2O_3), calcium oxide (CaO), magnesium oxide (MgO), sodium oxide (Na_2O), potassium oxide (K_2O), and sulphur trioxide (SO_3). In general, the reported content of SiO_2 in POFA ranges between 43% and 71%, giving POFA particles good pozzolanic properties to produce high-quality concrete. Such a high variation in the chemical composition of POFA is primarily due to varying preparation conditions, such as varying burning temperatures, burning quantities of palm oil parts to produce POFA from different mills, season to adopt the POFA from mills and vary part of palm oil tree burned in mills.

Table 2. Chemical properties of POFA.

Reference	Chemical content (%)								SiO_2 + Al_2O_3 + Fe_2O_3 (%)	Loss on ignition (%)
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3		
Rajak et al., 2021	54.80	7.24	4.47	14.00	4.14	-	-	0.71	66.51	8.50
Jamellodin et al., 2021	53.30	1.90	1.90	9.20	4.10	-	6.10	-	57.10	-
Kusumastuti et al., 2021	65.58	1.54	4.28	14.92	1.03	-	10.99	-	71.40	-
Adewunmi & Salami, 2020	66.91	6.44	5.72	5.56	3.13	0.19	5.20	0.33	79.07	2.30
Alabduljabbar et al., 2020	62.6	4.65	8.12	5.7	3.52	-	9.05	1.16	75.37	6.25
Khankhaje et al., 2017	43.60	8.50	10.10	8.40	4.80	-	3.50	2.80	62.20	18.00

The silica content contributes primarily to the pozzolanic reaction and is considered a suitable partial replacement for cement. In comparison, the component of (SiO2 + AI2O3 + Fe2O3) ranges between 57.1% and 79.1% of the total composition of POFA, representing the formation of additional calcium-hydro-silicate (C-H-S) gels in a concrete mixture. A higher silica content affects the pozzolanic reaction, producing extra C-H-S gels to yield a durable and denser mortar (Lim et al., 2015). In this respect, POFA shows relatively high values of SiO2 and Al2O3 (Table 2).

Table 3. Chemical composition of OPC and POFA

Item	Reference	Chemical content (%)							
		SiO_2	AI_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3
POFA	Average value from Table 2	57.79	5.05	5.77	9.63	3.45	0.19	6.97	1.25
OPC	The Constructor, 2021	17 - 25	3 - 8	0.5 - 6.0	60 - 67	0.1 - 4.0	0.5 -1.3	0.5 -1.3	1 - 3

The iron content of OPC and POFA is within nearly the same percentage range.

Physical Properties of POFA

Table 4 shows the physical properties of POFA, which also vary substantially due to different preparation conditions. In general, high burning temperatures change the particles from dark black to grey. The pozzolanic activity of POFA surges during the carbon burning because the reduction of carbon increases the fineness of POFA (Awal, Shehu and Ismail, 2015) .Also, the surface area of POFA particles increases when the fineness of the particles is increased by grinding. Meanwhile, POFA particles are spherical. Its specific gravity is less than that of cement (Awal et al., 2015). Unlike UGPOFA, GPOFA could resist high thermal deterioration because its fine particles act as micro-fillers effectively to prevent concrete degradation (Skariah et al., 2017). Among the three oil-palm-based materials, GPOFA has the smallest particle size, followed by and UGPOFA. The unburnt carbon causes high absorption of water and superplasticicer, thus minimising the concrete workability. Treating GPOFA at high temperatures (up to 500 ^{o}C) for one hour could remove the carbon particles to obtain fineness POFA (Chandara et al., 2010; Megat Johari et al., 2012). The particles could then be collected using a 45-µm sieve.

Table 4. Physical properties of POFA.

Reference	Specific gravity	Surface area	Blain fineness (m2/kg)	Retained on sieve No 325 (%)/ 45 µm sieve (%)	Median particle size (d50 µm)	Soundness (mm)
Amran et al., 2021	2.04	104	-	96	12.3 (average)	1
Hamada et al., 2020	2.52	1.962	-	-	6.85	-
Alyousef et al., 2021	2.42	-	4930	-	-	2.0
Alabduljabbar et al., 2020	2.42	-	4930	-	-	2.0
Mohammadhosseini et al., 2017	2.42	-	49.3	33	-	2.0
Bashar et al., 2016	2.2		1720	-	18.46	-
Lim et al., 2015	2.42	-	3999	4.98	1.69	-

Compressive strength of POFA

The compressive strength is measured by breaking the concrete specimen with the compression testing machine. The compressive strength of concrete is dependent on several factors, such as the water-cement ratio, strength of concrete, quality of concrete material, and the quality control in the production of concrete (Sidek et al., 2018). Table 5 shows that replacing cement in the concrete with 2.5 to 20% POFA generally increases the concrete's compressive strength. However, further increment of POFA reduces the compressive strength consistently (Munir, 2015).

Table 5 - Compressive strength of concretes containing POFA as a replacement for cement.

Reference	Compressive strength of concretes containing POFA as a replacement for cement on day 28 (MPa)							W/cm	W/b
	0% (OPC)	10%	20%	30%	40%	50%	60%		
Alnahhal et al., 2021	48	4.0	4.8	4.2	-	-	-	-	0.35
Hamada et al., 2020	62.7	64.8	62.1	58.2				0.37	-
Mohammadhosseini et al., 2020	48	-	42	-	-	-	-	0.47	-
Alyousef et al., 2021	45	-	48	-	-	-	-	0.48	-
Sidek et al., 2018	31	37	-	-	-	-	-	0.61	-
Khankhaje et al., 2017	14	13	11	10	-	-	-	0.54	-

Benefits of added POFA

Over the years, numerous building materials were mixed with biomass and tested, and some of them were classified as "smart materials”(Amun et al., 2018).For example, biomass aggregate, lightweight foamed concrete using POFA, self-sensing structural materials, smart self-healing materials, and etc. In this respect, POFA emerges as one of the most popular cementitious materials to partially replace cement in the concrete, primarily due to its outstanding physical properties and chemical properties. These properties give POFA the following benefits:

1. **Reduced hydration heat and drying shrinkage** – Drying shrinkage generally occurs when the concrete specimen solidifies and desiccates (Alsubari et al., 2014) in the early days of curing in the first months with nearly 70% of drying shrinkage (Tangchirapat et al., 2009).

2. **Resistance to chloride and acid attack-** When exposed to aggressive substances from the austere environment, reinforced concrete structures deteriorate (Liu et al., 2017). In particular, chloride ions rapidly corrode the steel bars incorporated into the concrete when the chloride concentration exceeds a threshold level (Mujedu et al., 2020). Experimental studies showed that adding POFA into the concrete conferred better resistance against acid and alkaline attacks (Oil et al., 2020).

3. **Resistance to sulfate attack** – When cube specimens of concrete were submerged in a 5% magnesium sulphate ($MgSO_4$) and aged for 360 days, they lost 8.3%, 7.8%, and 7.2% compressive strength, respectively for Self Compacting Concrete (SCC) containing 10%, 15% and 20% POFA compared to the control with 9.6% POFA (Ranjbar et al., 2016). The high resistance to sulphate attack for POFA-containing SCC was attributable to the pozzolanic property of POFA. The drying process reduced the quantity of free $Ca(OH)_2$ liberated from the hydration of cement to form additional C-S-H gel, improving the pores to produce a denser concrete (Ranjbar et al., 2016).

4. **Reduction of landfill stress for POFA** – In 2019, the agriculture sector contributed 7.1% (RM101.5 billion) to the Malaysian Gross Domestic Product (GDP). Oil palm was the primary player, making 37.7% of the total agricultural contribution, followed by other agriculture (25.9%), livestock (15.3%), fishing (12.0%), forestry and logging (6.3%), and rubber (3.0%; Department of Statistics, 2020). However, in the meantime, due to the abundant production of POFA, the waste disposal problem from the palm oil industry was also increasing correspondingly. Besides, due to a shortage of land, the Malaysian government also faced the problems of allocating more landfills for disposing of concrete waste (Suraya Hani et al., 2015). Thus, using POFA as a partial replacement for cement for producing concrete would reduce the need for landfilling the oil palm waste.

Conclusions

The use of POFA in cementitious material should be widely implemented in the construction industry since the technology of incorporating POFA into the concrete has matured with numerous studies conducted in the past ten years. The burden of disposing of cement and POFA as landfills could be mitigated by using POFA as a partial replacement for cement in concrete. Besides, with the fully utilize the waste created from palm oil mill, it is obvious in benefit the economic and environment. However, different mills are likely to generate POFAs with varying properties and particle sizes, which might be challenging for concrete manufacturers to adopt for their production. Thus, further study is essential to examine issues of standardizing the production of POFA for example time of burning, size of mill, ingredient to burn, method to burn and etc.

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